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TECHNICAL NOTE

Visualization of Cerebrospinal Fluid Motion in the Whole Brain Using Three-dimensional Dynamic Improved Motion-sensitized Driven-equilibrium Steady-state Free Precession

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The feasibility of the 3D dynamic improved motion-sensitized driven-equilibrium steady-state free precession (3D dynamic iMSDE SSFP) was evaluated for visualizing CSF motion and the appropriate parameters were determined. Both flow phantom and volunteer studies revealed that linear ordering and the shortest acquisition duration time were optimal. 3D dynamic iMSDE SSFP provides good quality imaging of CSF motion in the whole brain and enables visualization of flow in arbitrary planes from a single 3D volume scan.

Keywords: *cerebrospinal fluid, flow dynamics, dynamic improved motion-sensitized driven-equilibrium steady-state free precession*

Introduction

Cerebrospinal fluid (CSF) motion has been studied by phase contrast (PC) magnetic resonance imaging (MRI), and is now used widely in clinical practice.[1–4] The more recently developed time-spatial labeling pulse (Time-SLIP) technique also plays a key role in CSF studies.[5,6] Combining these two methods has achieved detailed visualization of CSF motion, including swirl motion, in most CSF cavities.[7,8] However, these techniques have some drawbacks. The primary drawback of the PC approach is its time-consuming acquisition, especially when the method is used in a time-resolved and 3D manner, whereas in the Time-SLIP technique, the process of setting the excitation slab and inversion time is relatively complicated.

We proposed a novel imaging method, dynamic improved motion-sensitized driven-equilibrium steady-state free precession (dynamic iMSDE SSFP), which conveniently visualizes entire CSF motion in the acquired imaging plane.[9] This method uses motion-sensitized gradients (MSGs) that modify the signal from flowing spins by dephasing their macroscopic magnetization, and thus can be used to label flowing spins. CSF motion is visualized by subtracting images acquired without MSG labeling from those acquired with MSG labeling. Because this method does not require pulse triggering or complex post-processing, it has the advantage of enabling visualization of entire CSF motion in the entire brain, in the acquired imaging plane, in a short period of time. However, this method has some limitations. First, a large region cannot be obtained because only one slice can be acquired. Second, image resolution is insufficient for detecting a connection between the CSF space and a small lesion. Therefore, dynamic iMSDE SSFP requires improvement as a 3D imaging method. 3D imaging offers image reconstruction in any orientation, which is helpful in evaluating complex CSF motion in whole CSF space. However, two problems associated with 3D imaging are that a wide range (i.e., the whole brain) must be excited at once; and that it extends the acquisition duration time, which may reduce the effectiveness of MSG preparation. Therefore, it is unclear whether 3D imaging with MSGs can detect flowing spins. Here we propose a novel method for visualizing CSF motion in the whole brain using 3D dynamic iMSDE SSFP. The purpose of this study was to determine the appropriate parameters for *k*-space ordering and acquisition duration time for detecting flowing spins using MSGs, and to evaluate the feasibility of 3D dynamic iMSDE SSFP for visualizing CSF motion in the whole brain.

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Materials and Methods

This study protocol was approved by the Institutional Review Board of Tokai University Hospital (IRB No. 13R-066). All of the volunteers and the patient were examined after obtaining appropriate written informed consent, consistent with the terms of our Institutional Review Board's approval form.

Magnetic resonance imaging

All MRI examinations were performed on a 1.5T scanner (Ingenia R5.3.1; Philips Healthcare, Best, the Netherlands), operating at a maximum slew rate of 160 mT/m/ms and a maximum gradient strength of 66 mT/m. A 15-channel receive-only dS Head Spine coil was used to cover the whole brain area.

The basic principle of 3D dynamic iMSDE SSFP is illustrated in Fig. 1. In this sequence, eight consecutive sets of whole-brain 3D balanced turbo field-echo (3D bTFE) are obtained, with and without MSG preparation. A motion-sensitized contrast image is created by subtracting images without MSGs (MSGs-off) from those with MSGs (MSGs-on). An MSGs-off image is selected and used for the subtraction. The basic parameters for 3D dynamic iMSDE SSFP were as follows: 3D bTFE with iMSDE, field of view = 250 mm, voxel size = 0.49 × 0.49 × 0.5 mm, repetition time (TR) = 4.12 ms, echo time = 2.1 ms, flip angle = 60°, sensitivity encoding factor = 3 (phase) and 2 (slice), TFE factor = 300, acquisition duration time [e.g., (TFE factor: 300) × (TR: 4.12 ms) = 1236 ms], number of signal averages = 1, T_2prepTE = 20 ms, flow VENC = 1 cm/s, direction of MSGs = 3 axes (MSGs were simultaneously applied in 3 axes), dynamic scan = 8 (MSGs-off: 1, MSGs-on: 7), and total scan time = 5 min 18 s.

Flow phantom study

The flow phantom (Fig. 2a) comprised acrylic tubes filled with 0.9% saline flowing at a constant rate of 0.55 ± 0.02 cm/s, embedded in superabsorbent polymer (FF350 Daiken Medical Co., Ltd., Osaka, Japan). The 0.9% saline was 23 ± 1.5°C same as room temperature. We investigated the optimal *k*-space ordering (*XY* plane) and acquisition duration time required to detect flowing spins using the MSG method. The signal intensities of the saline flowing in the tube were measured for various *k*-space orderings (linear ordering, low–high ordering) and acquisition duration times (1236, 1649, and 2061 ms) in longitudinal section, for MSGs-off and MSGs-on. Regions of interest (ROIs) were placed on the tube in longitudinal section by one of the authors (T.H). A circular ROI of >200 pixels was drawn on the first of the dynamic images (Fig. 2b).

Human study

Five healthy volunteers (age range, 25–46 years; mean age, 36.1 ± 4.2 years) underwent 3D dynamic iMSDE SSFP. We determined the optimal acquisition duration time (1236 or 2061 ms) and evaluated the visualization of CSF motion in the 3D sagittal source images, in transverse and coronal multiplanar reconstruction (MPR) images and minimum intensity projection (min-MIP) images of this 3D volume scan.

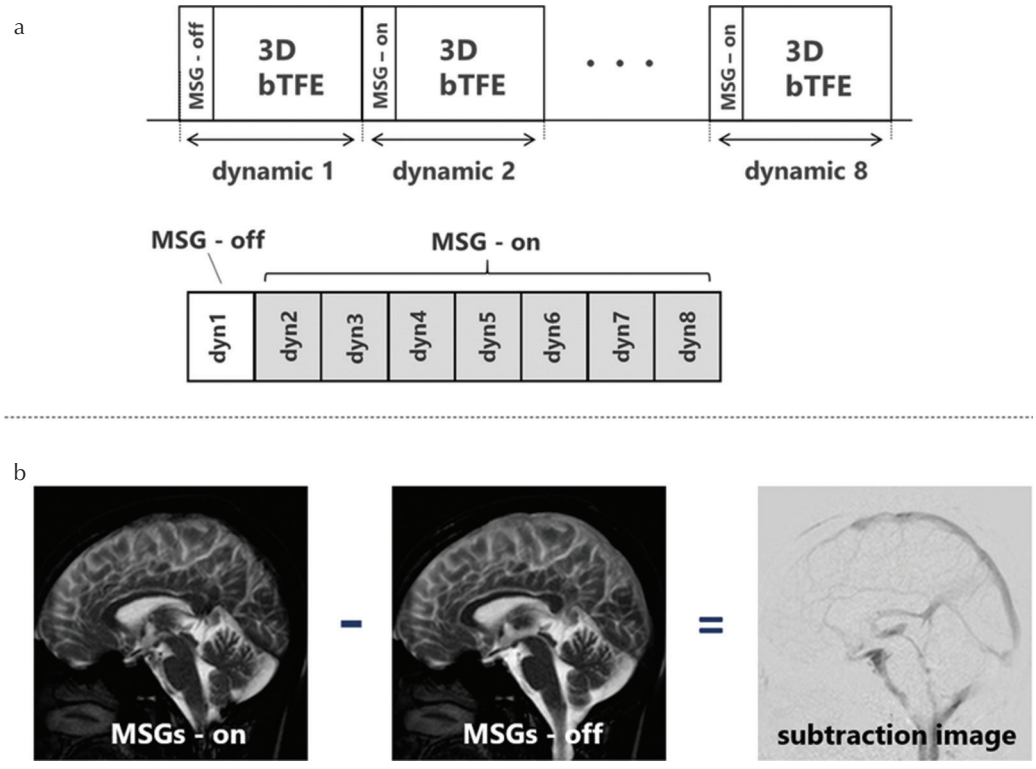

Fig. 1 Schematic overview of the 3D dynamic improved motion-sensitized driven-equilibrium steady-state free precession (iMSDE SSFP) sequence. (**a**) Eight consecutive sets of whole-brain 3D balanced turbo field-echo (3D bTFE) acquisitions are obtained with and without motion sensitized gradient (MSG) preparation. (**b**) A motion-sensitized contrast image (subtraction image) is created by subtracting the image without MSGs (MSGs-off) from that with MSGs (MSGs-on). The MSGs-off image of the first set is used for the subtraction.

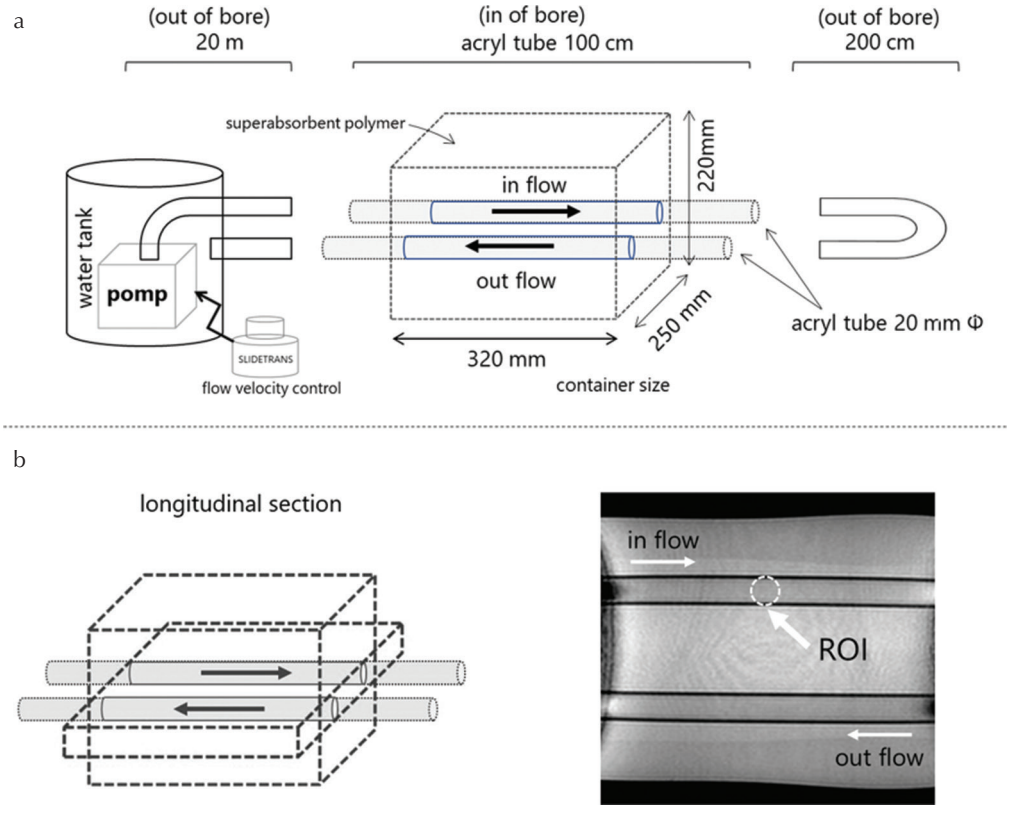

Fig. 2 Diagrams showing the construction of the flow phantom and placement of the region of interest (ROI). (**a**) The flow phantom comprised acrylic tubes embedded in superabsorbent polymer. The tubes were filled with saline flowing at a constant rate of 0.55 ± 0.02 cm/s. (**b**) The circular ROI (of >200 pixels) was set in a longitudinal section of tube on an image of the first set.

Five radiological technologists (mean years of experience, 16 ± 5.1) rated the visibility of CSF motion on each image on a 5-point scale using the following criteria: (1) unsatisfactory quality and observer not confident due to no visualization of CSF motion in the entire range, (2) poor quality and observer not confident due to a lack of visualization of CSF motion in wide regions, (3) fair quality and observer confident due to visualization of CSF motion in limited regions, (4) good quality and observer confident due to visualization of CSF motion in wide regions, and (5) excellent quality and observer highly confident due to visualization of CSF motion in the entire range.

After the initial parameters had been set, 3D dynamic iMSDE SSFP was obtained in a patient who had undergone endoscopic third ventriculostomy (ETV) for aqueduct obstruction.

Statistical analysis

In the phantom study, one-way repeated-measures analysis of variance with Bonferroni correction for multiple comparisons was used to compare the signal intensities in each ROI for each of the *k*-space ordering and acquisition duration time parameters. In the human study, the rated scores of the five readers were averaged according to the two acquisition duration time parameters, and these were compared using Friedman's test and Holm's multiple-comparison test. Statistical analysis was performed using MedCalc version 12.2.1 (MedCalc Software, Mariakerke, Belgium). *P*-values <0.05 were considered to indicate statistically significant difference.

Results

Flow phantom study

Figure 3 shows the results of signal intensity according to *k*-space ordering for MSGs-off (Fig. 3a) and MSGs-on (Fig. 3b). The signal intensities for MSGs-off with linear ordering were significantly higher than those with low–high ordering for all acquisition duration times (all $P < 0.05$). However, the signal intensities for MSGs-on were not significantly different between linear and low–high ordering (all $P > 0.05$).

Figure 4 shows the results of signal intensity according to acquisition duration time for MSGs-off (Fig. 4a) and MSGs-on (Fig. 4b). Shortening the acquisition duration time significantly decreased the signal intensities for MSGs-on for both linear and low–high ordering (all $P < 0.05$). However, signal intensities for MSGs-off were not significantly different in terms of ordering (all $P > 0.05$).

Human study

Figure 5 shows the results of the visual assessment of CSF motion in the volunteer study. Scores were significantly higher for acquisition duration time of 1236 ms than for acquisition duration time of 2061 ms, on all images (all $P < 0.05$).

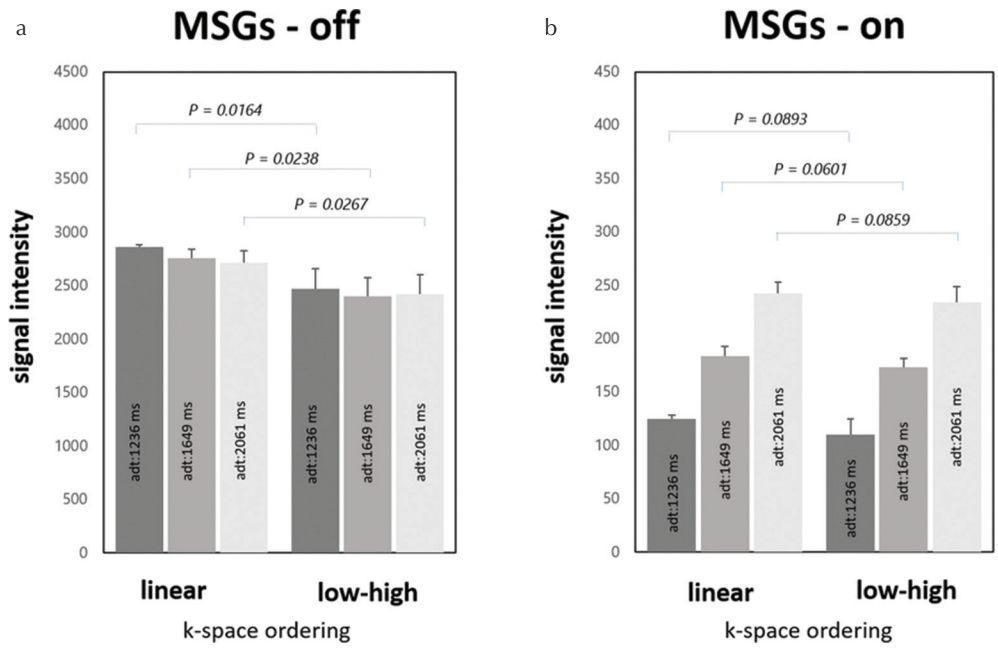

Fig. 3 Bar graph of signal intensity according to *k*-space ordering, for without motion sensitized gradients (MSGs; MSGs-off) (**a**) and with MSGs (MSGs-on) (**b**). The signal intensities for MSGs-off with linear ordering were significantly higher than those with low–high ordering (all $P < 0.05$) for each acquisition duration time (ADT). For MSGs-on, the signal intensities were not significantly different between linear and low–high ordering (all $P > 0.05$). Accordingly, the differences in signal intensity between MSGs-off and MSGs-on were greater with linear ordering than with low–high ordering.

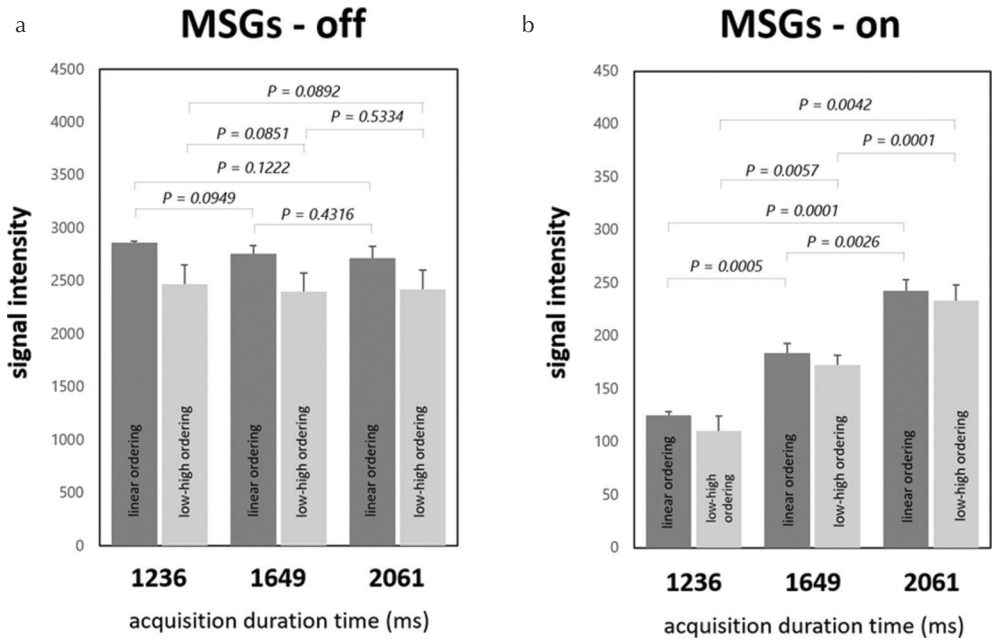

Fig. 4 Bar graph of signal intensity according to acquisition duration time, for MSGs-off (**a**) and MSGs-on (**b**). For MSGs-on, the signal intensities decrease with shortened acquisition duration time ($P < 0.05$), but those for MSGs-off are not significantly different (all $P > 0.05$). Accordingly, the differences in signal intensity between MSGs-off and MSGs-on were greater at the shorter acquisition duration time.

Figure 6 and Movie 1 show representative 3D iMSDE SSFP images in a volunteer. (The movies are available online.) The video demonstrates that 3D dynamic iMSDE SSFP enables visualization of CSF motion in the whole brain and the display of images in arbitrary planes. MPR and min-MIP images could visualize CSF motion simultaneously at multiple sites.

Figure 7 and Movie 2 show CSF motion dynamics in the post-ETV patient. 3D dynamic iMSDE SSFP provided CSF motion-sensitized contrast images from a single 3D volume scan. The CSF motion at multiple sites and the patency of the fenestration site could be demonstrated simultaneously in a single scan.

Discussion

Three dimensional dynamic iMSDE SSFP was able to provide the images with high resolution CSF motion of whole brain in a single 3D volume scan. This method has the advantage of display CSF motion at multiple sites (e.g., both the foramen of Monro and the cerebral aqueduct) in a single scan, which cannot be achieved with 2D dynamic iMSDE SSFP. In addition, because the source images of this method are anatomical images, this method can provide CSF dynamics and anatomical images from a single 3D volume scan, thus enabling detailed assessment of the CSF passageways.

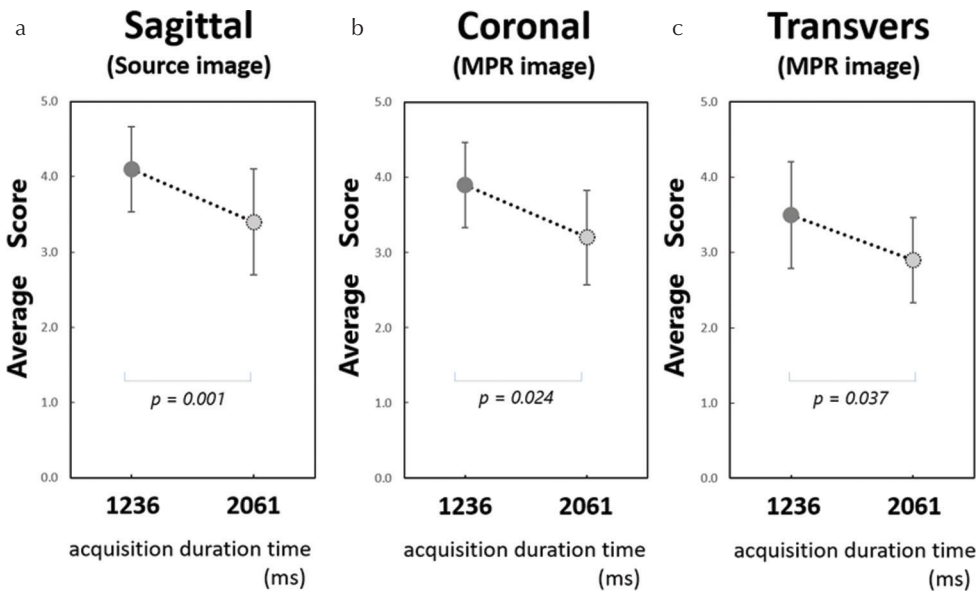

Fig. 5 The results of visual assessment of cerebrospinal fluid flow on the 3D sagittal source images (**a**), coronal multiplanar reconstruction (MPR) images (**b**), and transverse MPR (**c**) images. The scores for the acquisition duration time of 1236 ms are significantly higher than those for 2061 ms, on all images (all $P < 0.05$).

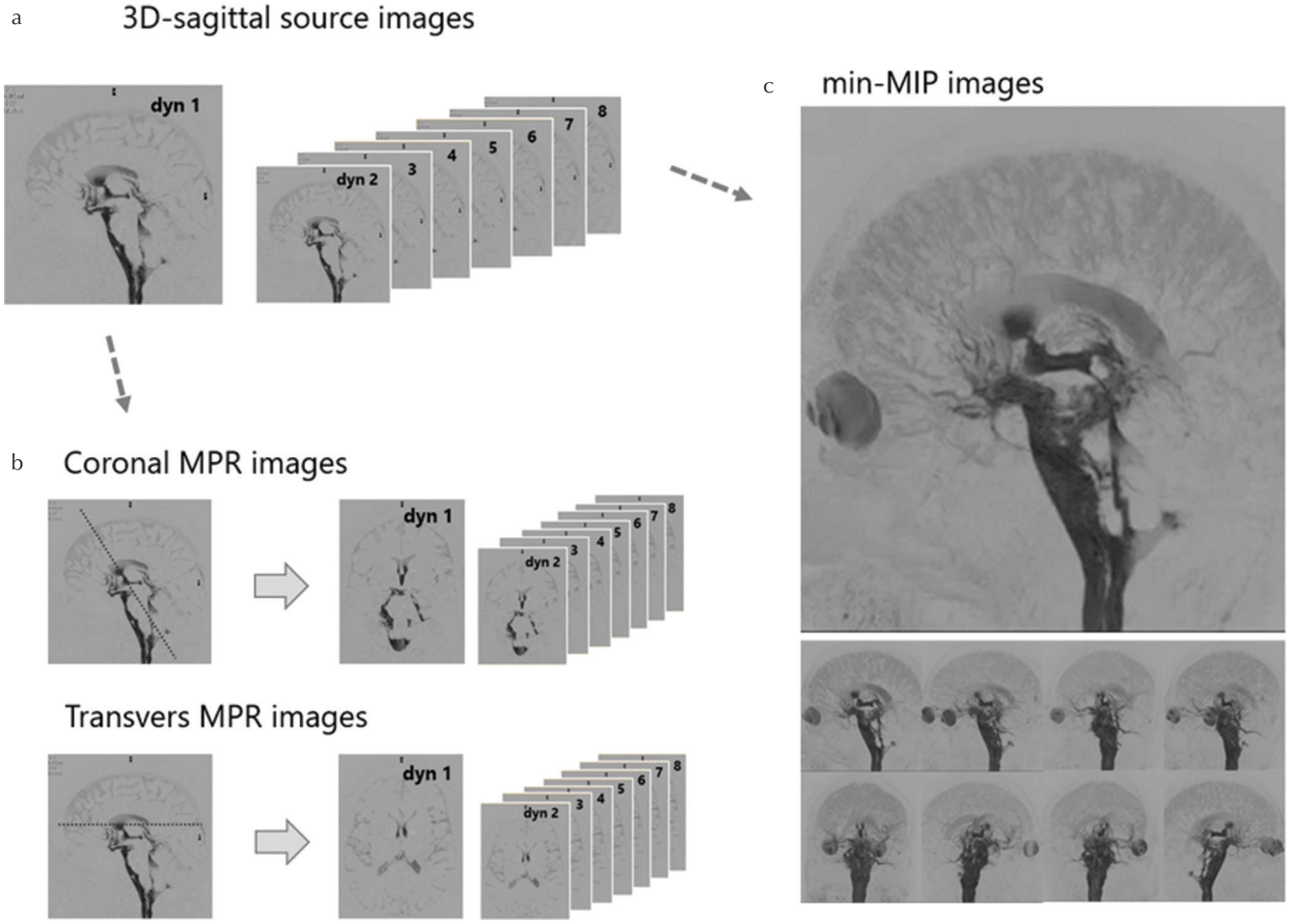

Fig. 6 3D dynamic improved motion-sensitized driven-equilibrium steady-state free precession (iMSDE SSFP) images in a healthy 28-year-old male. The 3D dynamic iMSDE SSFP source images (**a**) are used as the basis for arbitrarily selectable sectional images. Multiplanar reconstruction (MPR) (**b**) and minimum intensity projection (min-MIP) images (**c**) enable visualization of cerebrospinal fluid (CSF) motion in the lateral ventricles, third ventricle, fourth ventricle, ventral surface of the brain stem, and cisterna magna simultaneously, in a single scan. (The movie is available online.)

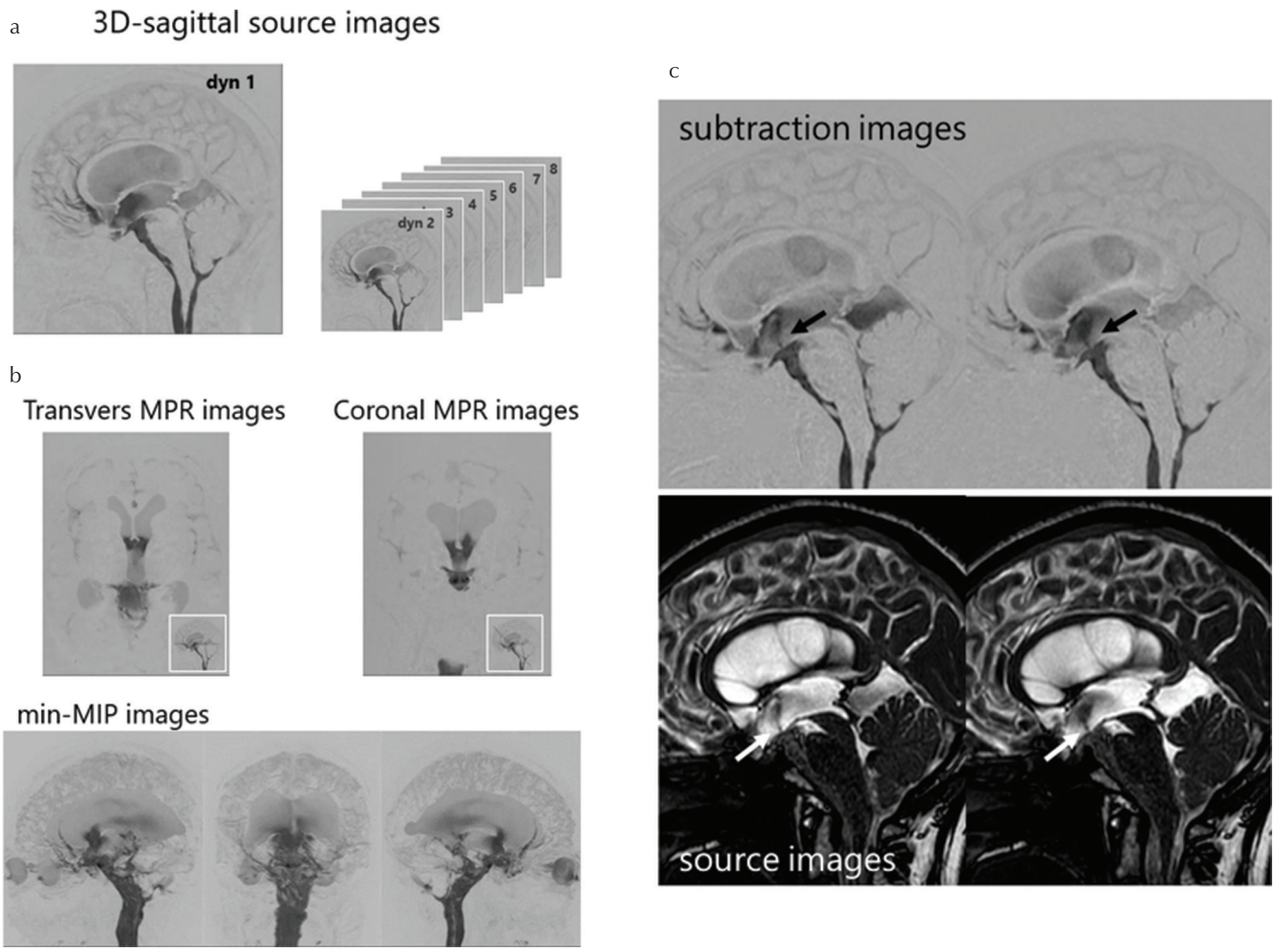

Fig. 7 3D dynamic improved motion-sensitized driven-equilibrium steady-state free precession (iMSDE SSFP) images in a 33-year-old female after endoscopic third ventriculostomy. 3D dynamic iMSDE SSFP sagittal source images (**a**) and transverse, coronal, and minimum intensity projection (min-MIP) images (**b**) show cerebrospinal fluid (CSF) motion. The subtraction and source images (**c**) clearly demonstrate the patency of the fenestration site (arrows) and display CSF motion in multiple sites such as the foramen of Monro and cerebral aqueduct in a single scan. (The movie is available online.)

Recently, Taoka et al.[10] suggested that the CSF signal distribution of b = 500 s/mm^2 diffusion-weighted image reflects the movement of water molecules, which is similar to 3D dynamic iMSDE SSFP, observing the CSF dynamics using signal decrease due to gradients magnetic fields. Although these two methods cannot be evaluated quantitatively, they are convenient methods that can provide rough information on CSF dynamics.

Linear ordering and the shortest acquisition duration time enabled optimal detection of flowing spins by MSGs in both the flow phantom and human studies. Because the 3D dynamic iMSDE SSFP method visualizes flowing spins by subtracting the MSGs-off signal intensities from the MSGs-on signal intensities, maximizing the difference between these signal intensities results in the most effective CSF flow images. In the flow phantom study, linear ordering and the shortest acquisition duration time (1236 ms) provided the best images. Because of the steady state, the signal intensities of linear ordering were higher than those of low–high ordering on MSGs-off.[11] Longer acquisition duration times increased the signal intensities of MSGs-on because they allowed rephasing of the spins. In the volunteer study, images with the shortest acquisition duration time were rated higher than those with the longer acquisition duration time, which is good agreement with the results of the flow phantom study. This result may also be due to rephasing of the spins with extension of the acquisition duration time. Therefore, acquisition duration time is an important parameter influencing signal intensity differences between MSGs-off and MSGs-on.

There are some limitations to the present 3D dynamic iMSDE SSFP study. First, because setting the shortest acquisition duration time extends the total scan time, the possibility of misregistration due to subjects head motion also increased. Furthermore, the scan time of this method is 5 min 18 s. Therefore, the CSF dynamics obtained by this method is a kind of indirect information of CSF motion. Second, the

steady flow in the phantom may not be identical to intracranial CSF motion. Third, this method requires attention to banding artifacts due to SSFP. Fourth, in this study, there was no velocity aliasing, but there is a possibility of velocity aliasing at flow VENC 1 cm/s. Therefore, optimization of the flow VENC will be needed in the further study. Fifth, the volunteers consisted of relatively young adults. Thus, this study could not reflect age-related changes. Furthermore, we assessed only one clinical subject. This method should be assessed in patients with various intracranial abnormalities. Finally, in addition to the PC and Time-SLIP methods, a novel technique using multi-spin echo acquisition cine imaging technique has been reported for observing CSF motion.[12] The 3D dynamic iMSDE SSFP technique should be compared with these three techniques in the future.

Conclusion

Three dimensional dynamic iMSDE SSFP could provide CSF-motion and anatomical images of the whole brain in a single 3D volume scan. Linear ordering and the shortest acquisition duration time were the optimal parameters for detecting flowing spins by MSGs.

Conflicts of Interest

Makoto Obara and Tetsuo Ogino are the employees of the Philips Electronics Japan Ltd. The remaining authors have no other conflicts of interest related to this submission personally.

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