Magnetic Resonance Imaging Technique for Visualization of Irregular Cerebrospinal Fluid Motion in the Ventricular System and Subarachnoid Space

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BACKGROUND: **Many studies have shown that cerebrospinal fluid (CSF) behaves irregularly, rather than with laminar flow, in the various CSF spaces. We adapted a modified previously known magnetic resonance imaging technique to visualize irregular CSF motion. Subsequently, we assessed the usefulness and clinical significance of the present method.**

MATERIALS AND METHODS: **Normal CSF motion in 10 healthy volunteers was visualized with the dynamic improved, motion-sensitized, driven-equilibrium steady-state free precession technique. Subsequently, CSF motion visualization with a modified sequence was applied to 3 patients.**

RESULTS: **In healthy volunteers, we achieved visualization of the irregularity of CSF flow in the ventricles and spinal canal, whereas CSF motion was diminished in the peripheral part of the intracranial subarachnoid space. In one case, we confirmed the patency of the patient's third ventriculostomy fenestration site. In the other, we verified the usefulness of the proposed sequence for determining the communication between the ventricle or subarachnoid space and the cyst.**

CONCLUSIONS: **Using the present sequence, we obtained images that accentuated CSF motion, which is largely composed of irregular motion. This method does not require pulse triggering or complex post-processing of images and allows visualization of CSF motion in a short period of time in selected whole imaging planes. It can therefore be applied clinically to diagnose various diseases that cause abnormalities in the CSF space.**

INTRODUCTION

Radioisotopes traditionally have been used for the imaging of cerebrospinal fluid (CSF). Through radioisotope studies, CSF flow has been interpreted in the following manner: CSF produced by the choroid plexus within the ventricles flows unidirectionally in the caudal direction from the lateral ventricle to the fourth ventricle, subsequently is drained from the fourth ventricular exit, circulates around the spinal cord and over the surface of the brain, and eventually is absorbed by the arachnoid granulations, which are present near the venous sinuses. These are established concepts in the literature.

Numerous experimental findings, however—as well as novel insights obtained by molecular, cellular, and neuroimaging approaches—indicate that our understanding of CSF physiology is reaching new horizons. In fact, CSF flow is now thought to be

Key words
- Balanced steady-state free precession
- Cerebrospinal fluid
- Cerebrospinal fluid motion
- Improved motion-sensitized driven-equilibrium
- Magnetic resonance imaging

Abbreviations and Acronyms
AP: Anterior-to-posterior
Balanced SSFP: Balanced steady-state free precession
CSF: Cerebrospinal fluid
Dynamic iMSDE SSFP: Dynamic improved motion-sensitized driven-equilibrium steady-state free precession
FH: feet-to-head
iMSDE: Improved motion-sensitized driven-equilibrium
MRI: Magnetic resonance imaging
MSG: Motion-sensitized gradient
PC: Phase contrast
RF: Radiofrequency
RL: Right-to-left
SSFP: Steady-state free precession
Time-SLIP: Time-spatial labeling pulse

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much more complex than a simple displacement from the choroid plexus to the major intracranial venous sinuses.[1-4] With the application of magnetic resonance imaging (MRI) to the evaluation of CSF flow dynamics, these historical concepts of CSF flow need to be revised. Noninvasive observations that use MRI have led to the discovery of facts that now supersede historical concepts.[5-7] Surprisingly, the net CSF flow through the Sylvian aqueduct in hydrocephalic patients with hydrocephalus has been found to be directed mainly in the caudal cephalic direction with filling of the third ventricle.[8] This reverse direction of flow contradicts previously established concepts in the literature. Notable examples of such discoveries include the irregular movement of CSF within the ventricles and the nonlaminar motion of CSF between the adjacent ventricles.

As a result of these findings, the use of the term "CSF flow," which represents the circulation of CSF akin to the flow of a river, has changed to "CSF motion" or "CSF movement." Phase contrast (PC) is a longstanding methodology and has been used widely in MRI studies of CSF. Currently, PC allows us to quantitatively analyze velocity and pressure gradient in the CSF space.[9-16] Recent progress in the time-resolved, 3-dimensional PC technique has revealed that CSF displays irregular motion in most of the intracranial CSF spaces.[5] The time-spatial labeling pulse (time-SLIP) technique also has played a key role in CSF studies.[6] This technique observes the travel of water protons in the labeled CSF region and thus demonstrates the pathway of the CSF. Through the combination of these 2 methods, the elucidation of CSF dynamics has progressed significantly in recent years, and this clarification has shown that CSF exhibits irregular motion in most of the CSF cavities. Thus, the 2 existing methods may complement each other and allow better visualization of CSF motion than either method alone.

The primary drawback of the PC approach is that it is time consuming, especially when the method is used in a time-resolved, 3-dimensional manner. The drawback of the time-SLIP technique is that it involves a relatively complicated process for labeling the CSF. Thus, we propose a simple imaging technique that uses MRI to assess the irregular CSF motion in the CSF cavities.

In the present study, we propose a modified imaging method, dynamic improved motion-sensitized driven-equilibrium steady-state free precession (dynamic iMSDE SSFP), which conveniently visualizes CSF motion in the entire imaging plane, similar to the PC method. This dynamic iMSDE SSFP is a modified imaging method that takes consecutive images using both improved motion-sensitized driven-equilibrium (iMSDE) and balanced steady-state free precession (balanced SSFP) and allows for the observation of CSF fluid dynamics with signal change. Balanced SSFP and iMSDE are both sequences that are recognized widely by radiologists. Balanced SSFP is a rapid imaging technique that is superior in allowing the visualization of blood and water, whereas iMSDE is suitable for visualizing irregular spin. In the present study, we combine these 2 methods and describe an imaging sequence that is useful in elucidating the pathology of conditions such as hydrocephalus and cysts, which neurosurgeons often encounter. We present the details of the dynamic iMSDE SSFP method used to identify irregular CSF motion in the ventricular and subarachnoid spaces as well as a discussion of the clinical usefulness of dynamic iMSDE SSFP.

METHODS

This research was approved by the Internal Review Board of Tokai University Hospital (IRB No. 13R-066). All volunteers were examined after appropriate informed consent was obtained, consistent with the terms of our institutional internal review board's approval form.

In this study, we investigated the usefulness of dynamic iMSDE SSFP in 10 healthy male volunteers between 23 and 58 years old (mean = 37 ± 11 years) and in 3 patients with the following conditions: 1 with obstructive hydrocephalus caused by a cyst of the quadrigeminal cistern, 1 after a third ventriculostomy, and 1 before and after surgery to remove the wall of an arachnoid cyst in the posterior fossa.

The principles governing of the iMSDE are described elsewhere.[17] To summarize, iMSDE uses the decreased signal that arises from phase dispersion of the spin caused by irregularity of CSF, which happens especially where CSF passes through small foramen, or in the large chamber. A lower signal is displayed when great irregularity (turbulence) of CSF motion is present.[18]

A 1.5-T clinical magnetic resonance scanner (Achieva R3.2, Philips Medical Systems, Best, Netherlands) with a 6-channel phased array, receive-only head coil was used. The acquisitions were conducted with and without the iMSDE preparation for each subject. **Figures 1** and **2** shows the entire scan configuration. An iMSDE technique was implemented on the scanner. The iMSDE preparation consists of a spatially nonselective hard 90° excitation pulse, 2 refocusing pulses weighted in a Malcolm Levitt's composite pulse opposing phase-pair scheme to compensate for imperfections in the shape of the radiofrequency (RF) pulse,[17-19] and a hard 90° flip back pulse (**Figure 1**). All the refocusing pulses were composite hard pulses (90x-180y-90x) to provide further correction for errors in the amplitude of the excitation RF field. Bipolar designed motion-sensitized gradients (MSGs) were placed between these RF pulses to dephase the magnetization of the flowing spins. Additional bipolar gradients identical to the block of bipolar gradients used in the prepulse were inserted in front of the first 90° excitation pulse to optimize eddy current cancellation.[17] For iMSDE preparation, the following parameters were used: preparation delay (interval between [90 degrees + x] and [90 degrees − x] pulses), 20 milliseconds; velocity encoding equivalent to the applied MSGs, 5 cm/s; and directions of MSGs (feet-to-head [FH], anterior-to-posterior [AP], and right-to-left [RL]). The total duration of the preparation was approximately 55 milliseconds.

The following were used for steady-state free precession (SSFP) acquisition: sequence, balanced turbo field-echo; slice thickness, 10 mm; field of view, 250 × 250 mm; acquisition matrix, 208 × 208; reconstruction matrix, 256 × 256 (voxel size, 0.98 × 0.98 × 10 mm); repetition time/echo time, 3.5/1.73 milliseconds; flip angle, 90°; readout bandwidth, 1068.4 Hz/pixel; reduction factor, 2.0; turbo field-echo factor (number of phase encodings after a preparation process), 107; pause duration, 406 milliseconds; and number of acquisitions, 1. These settings led to the temporal resolution of dynamic scans of 835 milliseconds. Such an acquisition was repeated 15 times with iMSDE *off* and 15 times with iMSDE *on* as a set of dynamic scans in the