Improved Visualization of Cervical CSF Flow using Balanced Steady State Free Precession Phase Contrast MRI

E. J. McCormack[1], M. R. Egnor[2], P. E. Roche[3], M. E. Wagshul[3]

[1]Biomedical Engineering, Stony Brook University, Stony Brook, NY, United States, [2]Neurosurgery, Stony Brook University, Stony Brook, NY, United States, [3]Radiology, Stony Brook University, Stony Brook, NY, United States

Introduction

Noninvasive measurements of cerebrospinal fluid (CSF) flow in the brain with MR imaging have enabled an increased understanding of life threatening intracranial flow-related disorders. For these measurements, velocity imaging of CSF flow has typically been achieved with phase contrast MRI (PC-MRI), which utilizes incoherent gradient echoes, for which all transverse magnetization is destroyed after each acquisition. A new type of velocity imaging with balanced steady-state free precession is inherently flow compensating, and has been reported to generate high signal from flowing spins [1]. The technique presented by Markl *et al* for combining PC-MRI with balanced Steady State Free Precession (PC-SSFP) to visualize blood [2], which uses slice select gradient inversion in alternate echo trains, has been implemented in this study to improve the speed and accuracy of CSF flow measurements. With the long longitudinal relaxation time of CSF, PC-MRI yields a very small signal, due to the need for high temporal resolution and short TR's. PC-SSFP produces a much higher signal due to its ability to maintain magnetization in the transverse plane even with a short TR. Signal from CSF, at the level of the craniocervical junction (CC), in magnitude images acquired with non-balanced gradient echo techniques is typically iso-intense or dark compared to the surrounding tissue, but PC-SSFP yields CSF signal which is easily depicted and maintained throughout all phases of the cardiac cycle, yielding a higher, more uniform SNR than can be achieved with conventional phase contrast imaging. The goal of this study was to test whether PC-SSFP can improve the SNR in CSF flow images over PC-MRI.

Methods

In vivo velocity imaging of the brain was conducted on a 1.5T Philips Intera with retrospective peripheral pulse gating on seven consenting healthy adult volunteers to compare PC-SSFP (TE/TR = 6.5/13, FOV = 15-18cm, 18 cardiac phases, 1NEX) with PC-MRI (TE/TR = 8/14, FOV = 15-18cm, 18 cardiac phases, 2NEX). Both sequences were acquired in the transverse orientation to visualize flow through the Aqueduct of Sylvius and at the level of CC, with Venc of 5 cm/s. Intensity variation in b-SSFP is produced by interecho dephasing [3], and PC-SSFP inherently imparts dephasing of the spins as a function of their velocity. This affect is a strong function of flip angle, and therefore a series of PC-SSFP scans was run with flip angles ranging from 30-80 degrees to determine the optimum flip angle. Total acquisition time for PC-SSFP was less than 2 minutes, whereas the total acquisition time for PC-MRI was longer due to the need for two averages in order to achieve adequate SNR. Because of the V*enc* (5cm/s) required to visualize slower CSF flow, the lowest achievable TR was 13ms, longer than those used by Markl, where the TR was 3-5ms for V*encs* of 50-150cm/s. Signal variation in magnitude images throughout the cardiac cycle, SNR and accuracy of velocity waveforms were analyzed for both imaging methods in all volunteers.

Results

As depicted in Figure 1, fully balanced PC-SSFP can greatly enhance the signal from flowing CSF, as well as maintain constant signal throughout the cardiac cycle, even with the pulsatile nature of CSF flow. Adversely, the total CSF signal throughout cardiac phases for PC-MRI is on average three times less and varies greatly throughout the cardiac cycle. Moreover, the resulting signal to noise ratios as a function of the cardiac cycle increased three-fold for PC-SSFP. It is important to note that this relative SNR increase is actually equivalent to 4.2 due to the averaging necessary in the PC-MRI acquisitions. As seen in Figure 2, SNR over 3 times that in PC-MRI was observed for balanced PC-SSFP, with minimal signal variation. Relative SNR gain for PC-SSFP over PC-MRI for all volunteers ranged from 2.8-3.7, without accounting for the averaging in the PC-MRI scans. A 50 degree flip angle for the 5cm/s encoding velocity yielded the highest SNR with the least variation compared to the other flip angles tested, and therefore signal and SNR for this flip angle is reported. When imaging the flow at the craniocervical junction, posterior subarachnoid space (SAS) flow becomes somewhat turbulent due to the confined space and the mixing of flow from the 4^{th} ventricle and the SAS, leading to some signal dropout in PC-MRI velocity images. In one subject, for example, the peak flow rate calculated with PC-MRI in the posterior SAS measured 0.5cc/s, whereas with the PC-SSFP sequence the peak rate was 1.0cc/s. The difference between the two measurements is due to the superior inherent flow compensation in PC-SSFP. Since PC-SSFP images maintain high uniform signal both anterior and posterior to CC throughout the cardiac cycle, total flow can be calculated more accurately. In the aqueduct and anterior CC, excellent agreement was found for velocity waveforms in both imaging methods, both in terms of the shape and amplitude of the velocity waveforms.

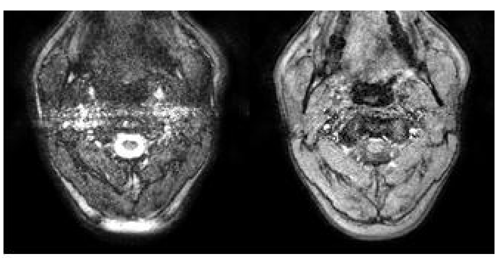

Figure 1. Magnitude images in the axial plane from the temporal center of the cardiac cycle at the level of C2 for PC-SSFP (left) and PC-MRI (right).

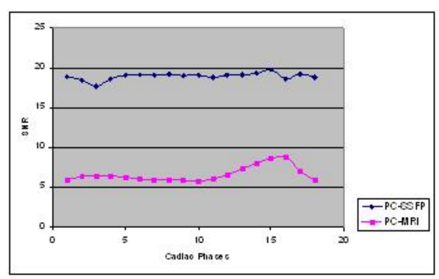

Figure 2. SNR gain as a function of cardiac phase. PC-SSFP yields 3 times higher SNR with less relative signal variation than PC-MRI.

Conclusions

With the enhanced flow region depiction throughout the entire cardiac cycle, balanced PC-SSFP can greatly improve the accuracy of CSF flow measurements which are important for understanding disorders of intracranial flow. For example, Alperin *et al* have presented a novel method for measuring ICP and intracranial elastance changes using the CSF pressure gradient and the Navier-Stokes relationship with PC-MRI [4]. With balanced PC-SSFP, these measurements can be calculated more efficiently, and more accurately since net flow waveforms will include the entire SAS. These results illustrate that measuring intracranial flow for evaluating intracranial disorders with PC-SSFP may offer better diagnostic capabilities due to the improved efficiency and flow region delineation for quantification. Furthermore, with an SNR increase of three, SENSE techniques could be used to speed up the acquisition time so that CSF flow images could be acquired in less than 1 minute and therefore be added to routine clinical imaging protocols. PC-SSFP shows promise for replacing PC-MRI sequences with regard to better visualization of CSF flow and improved SNR.

References

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