Improvements in Cerebrospinal Fluid Flow Measurements With Phase Contrast Balanced Steady State Free Precession

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ABSTRACT

To overcome limitations in obtaining accurate quantitative information with phase contrast gradient echo sequences (PC-GRE) for cerebrospinal fluid (CSF), a new technique is presented, phase contrast balanced steady state free precession (PC-bSSFP), which can improve the accuracy of CSF flow measurements. CSF images acquired with PC-GRE suffer from very low signal to noise ratios (SNR), due to the requirement of short repetition times (TR) for adequate temporal resolution, and the long relaxation rate of CSF. Furthermore, CSF is often turbulent, causing phase dispersion and further signal loss. PC-bSSFP can overcome these limitations due to its high SNR and robustness against signal loss from turbulent flow. In order to establish the reliability of PC-bSSFP, a comparison of CSF flow measurements from various regions of the brain, acquired with the PC-GRE and PC-bSSFP is presented.

INTRODUCTION

The 2D cine phase contrast gradient echo (PC-GRE) has often been used to quantify intracranial CSF flow, and has revealed the possible inappropriate emphasis on bulk CSF flow in models of hydrocephalus and in the treatment of intracranial flow disorders, such as hydrocephalus. Recent investigations of normal and abnormal intracranial CSF flow dynamics have emphasized the need for quantifying intracranial CSF flow in multiple regions in the brain, as opposed the aqueductal stroke volume alone, which has been studied aggressively in the past. It was recently hypothesized that ratios of stroke volumes from multiple measures represent a more sensitive measure of global CSF dynamics for charactering diseases of CSF flow (1). The need for multiple CSF flow measurements require high accuracy of CSF net flow not only in the aqueduct, but also in the prepontine cistern and in the anterior and posterior subarachnoid space (SAS) at the level of C2. Accurate CSF flow measurements for the laminar aqueductal flow can often be attained with PC-GRE, but in other larger CSF flow regions, their geometries and/or influence from ventricular outflow cause CSF flow to become turbulent. Along with the short repetition time requirement in cardiac gated imaging and the long relaxation rate of CSF, the phase dispersion due to higher order flow results in very low signal to noise ratios (SNR) for CSF flow imaging, resulting in lost flow information. A new technique, balanced steady state free precession (PC-bSSFP), has recently been evaluated for measuring blood flow. Because the contrast in SSFP sequences is a ratio of T_2/T_1, it is especially advantageous for CSF imaging, and the high SNR can be utilized to improve the CSF flow measurements, even in the presence of turbulent flow. With this new technique, accurate CSF flow measurements can be made within many CSF flow regions in the cranium for improved accuracy for measurements of global CSF flow dynamics.

METHODS

The PC-SSFP sequence was developed using Philips sequence development software (version R10.3, Philips Medical Systems, Cleveland, OH) for use on a Philips 1.5T Intera scanner, modeled after the gradient inversion technique first implemented by Markl *et al* (2), and optimized to measure the much slower CSF velocities. To validate the correlation of the CSF flow measurements with PC-bSSFP and PC-GRE, a flow phantom was created and transverse flow through a tube was repeatedly measured. A comprehensive CSF flow study consisting of thirteen healthy volunteers was undertaken to fully evaluate PC-SSFP CSF flow measurements within four CSF flow regions, the aqueduct, prepontine cistern, and anterior and posterior SAS at the level of C2, compared to the same regions measured with PC-GRE. Magnitude and flow masks were created for each region of interest for accurate calculations of net flow waveforms and stroke volumes as well as for quantifying the percentage of the CSF space demonstrating pulsatile flow in each region for both techniques. SNR was measured in the cervical CSF regions and the variation in SNR was calculated throughout the cardiac cycle.

RESULTS

Excellent agreement in velocity measurements was found in the flow phantom experiments ($R^2>0.99$). Figure 1 displays the improvement in stroke volumes measured in complex CSF flow regions in the cranium, as well as the similarity of the aqueduct stroke volumes. PC-SSFP measured 24.4%±12.1% ($p<0.05$) more CSF flow in various CSF regions, determined by the presence of pulsatile CSF flow compared to the total CSF region, and stroke volume measurements increased by 22.4%±12.8% ($p<0.05$) for PC-SSFP. An average *gain* in SNR of 5.02±0.15 ($p<0.01$) was observed in PC-SSFP magnitude images compared to PC-GRE, as well as more consistent signal throughout the cardiac cycle.

CONCLUSIONS

We have introduced a new technique for quantifying CSF flow in the brain, and presented a detailed analysis comparing this technique, PC-bSSFP, to the standard PC-GRE technique. The results clearly demonstrate reliability of the PC-bSSFP flow measurements, improvements in quantification of net CSF flow, and dramatically increased SNR. Through mathematical analysis for modeling communicating hydrocephalus and computer simulations, Egnor *et al* (3) showed that a redistribution of CSF between CSF spaces in the cranium can lead to the ventricular dilation that is characteristic of hydrocephalus. Therefore, a complete analysis of CSF dynamics requires visualization of CSF flow in multiple locations. However, this study reveals that PC-GRE typically generated less than 50% of the total CSF flow information in the prepontine cistern, while PC-bSSFP produced flow information for the majority of the CSF in that region. Similar flow losses were seen in the anterior and posterior subarachnoid flow regions at level of C2, resulting in severe underestimations of net CSF flow in many CSF regions, and degrading accurate measures of global CSF dynamics. The findings of this study illustrate the superiority of PC-bSSFP compared to PC-GRE for quantifying intracranial CSF flow, supported the by dramatically increased SNR, improved accuracy of flow measurements, better CSF flow region delineation, and improved quantification of net CSF flow in the more complex CSF regions, such as the prepontine cistern and in the cervical subarachnoid space.

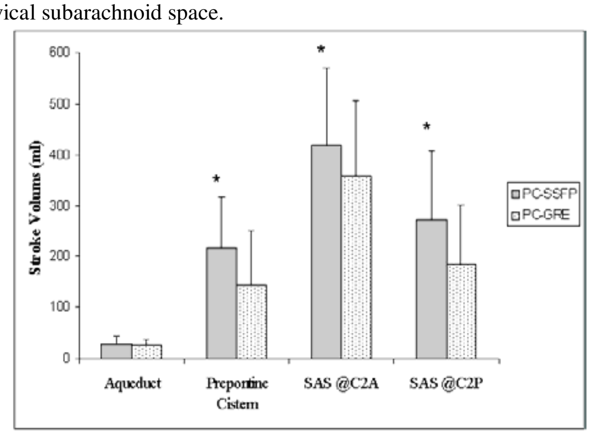

Figure 1. Summary of CSF stroke volumes for the four CSF flow regions. ($p<0.05$)

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