Quantitative comparison of 4D MRI flow measurements to 3D computational fluid dynamics simulation of cerebrospinal fluid movement in the spinal subarachnoid space

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Abstract— **Computational fluid dynamic (CFD) simulations have provided detailed information about the complex flow and pressure field within the cerebrospinal fluid (CSF) system. The solutions of these simulations are sensitive to boundary conditions and thus need validation with *in vivo* measurements. However, validation of CFD flow results and MRI CSF flow measurements have been limited to through-plane pcMR measurements. Recent advancements in MRI flow measurement technology has enabled measurement of the 4D flow field within the spinal subarachnoid space (SSS), superior sagittal sinus and ventricles of the brain. Alterations in cerebrospinal fluid (CSF) dynamics have been associated with neurological symptoms and formation of Syringomyelia in patients with Chiari malformation and spinal stenosis. In these patients, analysis of morphology alone has proved to be insufficient in explaining the absence or presence of symptoms. In the present study, we compare quantitatively 4D flow measurements to CFD analysis within the SSS (C1-T1, cervical spinal segment) of a healthy volunteer without any lesions at the craniocervical junction or the cervical spinal canal.**

I. Introduction

CEREBROSPINAL fluid (CSF) moves within the spinal canal and in the subarachnoid and ventricular spaces of the cranial[1]. This fluid protects the brain from injury and delivers nutrients and protein to/from brain surface along with the removal of waste products[1]. CSF moves in the complicated set of cranial and spinal cavities in a pulsatile manner.

Alterations in the CSF dynamics can lead to neurological disorders such as Chiari malformation, Syringomyelia and hydrocephalus. In patients with these diseases, analysis of morphology alone is insufficient in explaining the absence or presence of symptoms[2]. Single-slice 2D phase contrast flow imaging in sagittal or axial orientation has been used for quantification of subarachnoid obstruction and in trying to unravel the mechanisms of associated syringomyelia formation [2-4]. However, 2D measurements have poor spatial and temporal resolution and will not allow analysis of complex flow patterns. Recent studies have performed computational fluid dynamics (CFD) simulations in order to represent three-dimensional flow fields in the CSF fluid region [5-10]. CFD provide good information for the global understanding of CSF dynamics but their clinical application is still limited. Over the last few years time-resolved three-directional velocity encoded phase contrast MR imaging (4D MRI) has increasingly been appreciated for its potential for in vivo analysis of complex flow phenomena[11]. A first evaluation of the applicability of this technique was performed by A. C. Bunck et al., in which 4D MRI measurements were qualitatively and quantitatively compared with 2D MRI measurements [2].

The purpose of this study was to evaluate the applicability of cardiac triggered 4D MRI sequence for assessing the CSF dynamics at the craniocervical junction and the cervical spine in one healthy and to compare this technique with a 3D CFD simulation of the CSF flow done on the same geometry.

II. Methods

A. In Vivo Measurements

4D MRI CSF velocity measurements in the SSS of one healthy volunteer (Patient 1) were obtained using the protocol developed by A. C. Bunck et al. [2] on a 1.5 T MRI (Fig. 1). The subject was asked to lie in the supine position in the scanner bed with a standard 16-channel head and neck coil (Philips). CSF flow measurements were performed in

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the SSS from the C1 to T1 level with the following imaging parameters: venc = 10-15 cm/s, TE = minimum (5.4-6.3 ms), TR = minimum (8.6-9.5 ms), flip angle = 5°

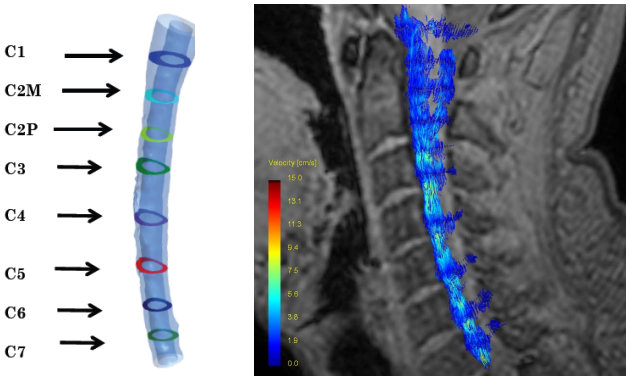

Fig.1. Level of 4D MRI measurements in the SSS (left) and 3D systole sagittal velocity map of CSF in the cervical subarachnoid space of Patient 1 (right).

2D phase contrast MRI measurements were obtained at the craniospinal junction (C1) and midportion of T1 to establish the flow boundary conditions for the CFD simulation. A high resolution T2-weighted 3D, turbo spin-echo sequence (image resolution: 0.8mm isotropic) was used to define the anatomic SSS boundaries.

B. CFD simulation

A rigid wall CFD simulation was performed in the SSS from the C1 to T1 level using solver CFX (Ansys, Canonsburg, PA). The three-dimensional anatomy of the SSS was reconstructed from the T2 weighted MRI images of the SSS with a manual segmentation using ITK Snap (Fig. 2) [12].

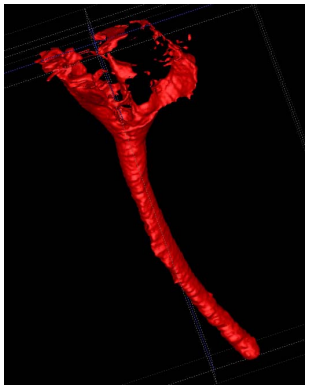

Fig.2. 3D reconstruction of Patient's 1 geometry from the 3D MRI images

A computational mesh with $1.9*10^6$ elements was generated based on the 3D geometry using the ICEM CFD software. The geometry was cut at the region of interest (C1-T1) as indicated on the data obtained by A. C. Bunck. CSF was modeled as an incompressible Newtonian fluid with the same density and viscosity as water at body temperature [5, 6] and the SSS was modeled as a rigid wall.

III. RESULTS

In the present study 4D MRI measurements of CSF flow in the spinal subarachnoid space of a healthy volunteer were compared to CFD simulation. Fig. 3a shows the comparison of the peak CSF velocity results (diastole: upper part of the graph and systole: lower part of the graph) between the 4D MRI flow acquisition and the 3D CFD simulation. Figues 3b and 3c depict the results of the peak CSF velocity (diastole and systole) and the cross-sectional area obtained from the 4D MRI and the CFD, respectively for Patient 1.

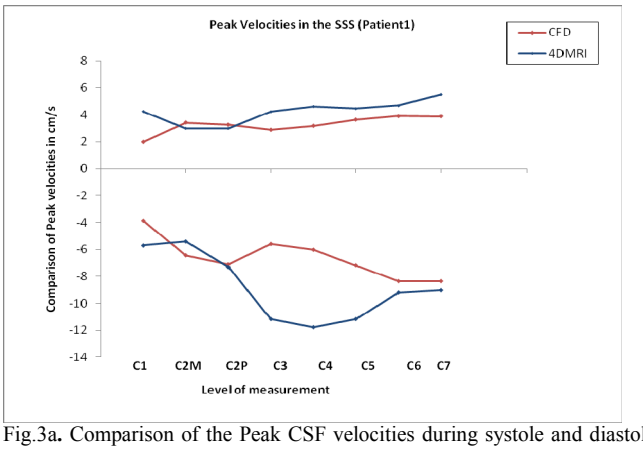

Fig.3a. Comparison of the Peak CSF velocities during systole and diastole between the 4D MRI and the CFD

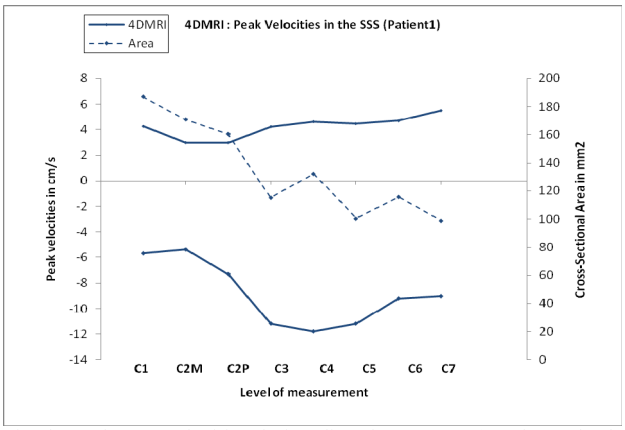

Fig.3b. Peak CSF velocities during diastole(upper part) and systole (lower part) and cross-sectional area obtained from the 4D MRI

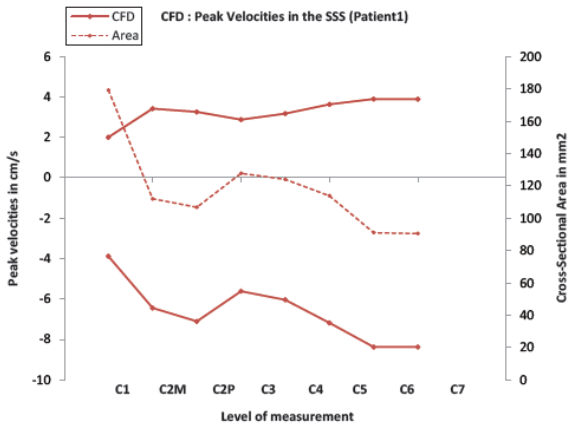

Fig.3c. Peak CSF velocities during diastole (upper part) and systole (lower part) and cross-sectional area obtained from the CFD

The peak systolic velocity obtained from the 4D MRI was 8.86 ± 3.44 cm/s and the diastolic was 4.22 ± 1. 3 cm/s. The peak systolic velocity obtained from the CFD was 6.6 ± 2.7 cm/s and the diastolic was 3,3 ± 1,3 cm/s. CFD peak systolic velocities revealed lower values than 4D MRI results. The maximum difference can be observed at levels C3 and C4. For the CFD, changes in peak systolic velocities strongly correlate with changes in cross-sectional area. On the contrary, 4D MRI did not show such a strong correlation. This is probably due to the wall deformation that we obtain from the 4D MRI, whereas in the CFD a rigid wall is assumed. Moreover, the cross-sectional area between the two methods is quite similar at levels C1 and from C3 to C7. There was a decrease in the average flow over space as measured from 4D MRI, because of the wall deformation (Fig. 4).

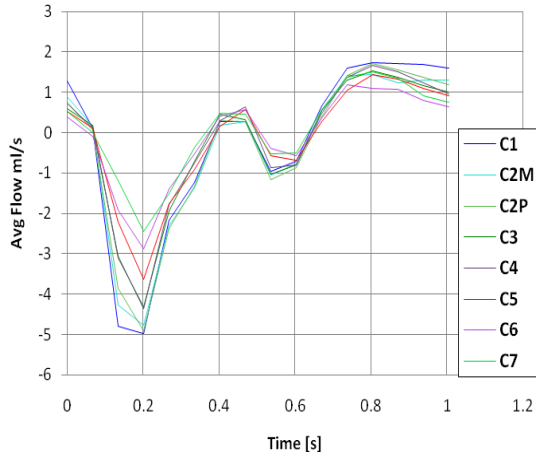

Fig.4. 4D MRI mass flow over a heart beat at different plane locations in the spinal canal

The CFD simulation on the contrary assumes rigid walls resulting in a constant mass flow over planes. At peak systole, the mass flow reached 328 ml/min and is constant over space. The stroke volume was 2.96 ml/s. The cross-sectional area between the two methods is quite similar at levels C1 and from C3 to C7. However, the difference at levels C2M and C2P is unexpected. Hydraulic Diameter measured with CFD is strongly correlates with CFD cross-sectional area, as expected (Fig. 5). The Reynolds Number gradually increases along the spinal canal within the range [300-417] (Fig. 6).

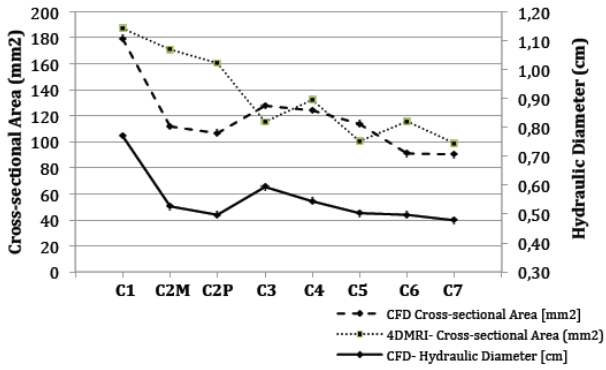

Fig.5. Geometry characterization of Patient 1

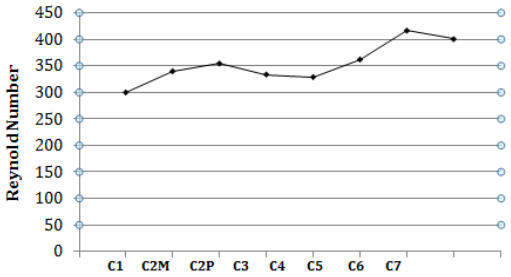

Fig.6. Evolution of Reynolds number through the various planes of the SSS of Patient 1

IV. Discussion

In the present study, two techniques were used to analyze three-dimensional flow patterns of the CSF within the spinal subarachnoid space: the computational fluid dynamics and the newly applied 4D MRI technique. Results of both techniques applied to the same SSS geometry, were compared in order to evaluate their application for clinical needs.

The subarachnoid spinal cavity in which the CSF flows has an annular geometry resulting in complicated hemodynamic analysis. Results have shown that at regions C2M and C2P, the cross-sectional areas were quite different (60 mm^2 higher estimation in 4DMRI than in CFD). For the other levels, the difference was negligible. Manual segmentation of the geometry could have introduced these errors. Also, geometry cutting and plane positioning were done with some approximations. It is important to evaluate these differences since these values also influence velocity values.

Peak CSF flow velocities at systole and diastole were measured at the different levels of the spinal cavity, extending from the Foramen Magnum to the Thoracic Region. Comparison between the two techniques was only performed for one healthy volunteer. Minimum diastole velocities were shown to be slightly lower in CFD than in

4D MRI (± 2cm/s); however they followed similar evolution over the level of the spinal cavity. The peak systolic velocities varied more significantly between the two techniques (± 6cm/s), reaching a maximum difference at the levels C3 and C4. This difference is most probably due to the rigid-wall assumption that has been made for the CFD simulation. This effect is thus a main drawback of the CFD simulation in the assessment of CSF flow. Moreover, CSF peak flow and stroke volume obtained from CFD remain constant over space as there is no energy loss due to wall-deformation. On the contrary, 4D MRI shows that the flow decreases with distance from the skull along the spinal cavity.

From the CFD simulation, the Reynolds number was evaluated along the different cervical vertebrae in order to characterize fluid dynamics of CSF. Reynolds number globally increases with length, as the cross-sectional area and the related hydraulic diameter have tendency to decrease. The overall range for Patient 1 was 300-417 which remains under the critical level of 2100, meaning that the flow is laminar over the whole cycle independent whether the patient presents abnormalities or not.

These preliminary results show that both 3D CFD simulations and 4D phase contrast MR imaging are powerful tools to analyze cerebrospinal fluid dynamics in the spinal subarachnoid space. Compared to 2D MRI techniques, they give time and space resolved information, which is essential to detect flow abnormalities in patients with Chiari-malformation and syringomyelia. From the results, CFD simulations present main drawbacks that need to be improved in the future. On the contrary, the 4D MRI technique assesses CSF dynamics *in vivo* and therefore is closer to reality. As such, a 4D MRI approach offers a comprehensive analysis of CSF flow dynamics and may lead to a more thorough understanding of the pathophysiology of several craniospinal disorders.

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