Fluid Structure Interaction Model Analysis of Cerebrospinal Fluid in Patients with Continuous - Flow Left Ventricular Assist Devices

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Objective

CSF circulation includes directed and pulsatile flow throughout the cerebral ventricular system as well as the brain and spinal subarachnoid spaces, cisterns, and sulci. Novel research insights have proven that the traditional physiology of CSF circulation is more complex than previously understood by describing the role of lymphatic pathways for drainage of CSF along astrocytes and their aquaporins and the overall fluid exchange between CSF and interstitial spaces. We have to improve our understanding as it may have clinical relevance to understand neurodegenerative and immunological diseases of the brain and spinal cord. Our study aims to utilize a computation Fluid Structure Interaction (FSI) model to characterize behavior of CSF pressure and flow in patients with continuous - flow left ventricular assist device where arterial pulse is greatly diminished or absent.

Methods

- We used modified principles of Reymond's (1-D) dimensional model to simulate arterial segments within the brain and spinal cord and couple the cardiovascular system with the cerebrospinal fluid system using computational fluid dynamics. (***Figures A – C***)

- We constructed the CSF motion and fluid dynamic simulation for our Fluid Structure Interaction model using the same approach as described by *Gupta et al., 2010*. We modelled the pulse wave propagations for our model using the equations and calculations depicted below, and incorporated the boundary condition values based on their MRI studies. For our model we established low pulse wave to represent patients with continuous flow left ventricular assist device. (***Figures D – F***)

Equations for flow behavior in our FSI model based on *Gupta et al., 2010.*

$$\dot{A} + (uA)' = \psi$$

$$\dot{u} + \left(\frac{u^2}{2} + \frac{P}{\rho}\right)' = \frac{\mu}{\rho}u'' - \frac{K_v}{A}u - K_{head}u^2 sign(u) + \frac{u\psi}{A}$$

$$CSF\ generation: \quad \dot{m} = m_{bulk} + m_{pulse}$$

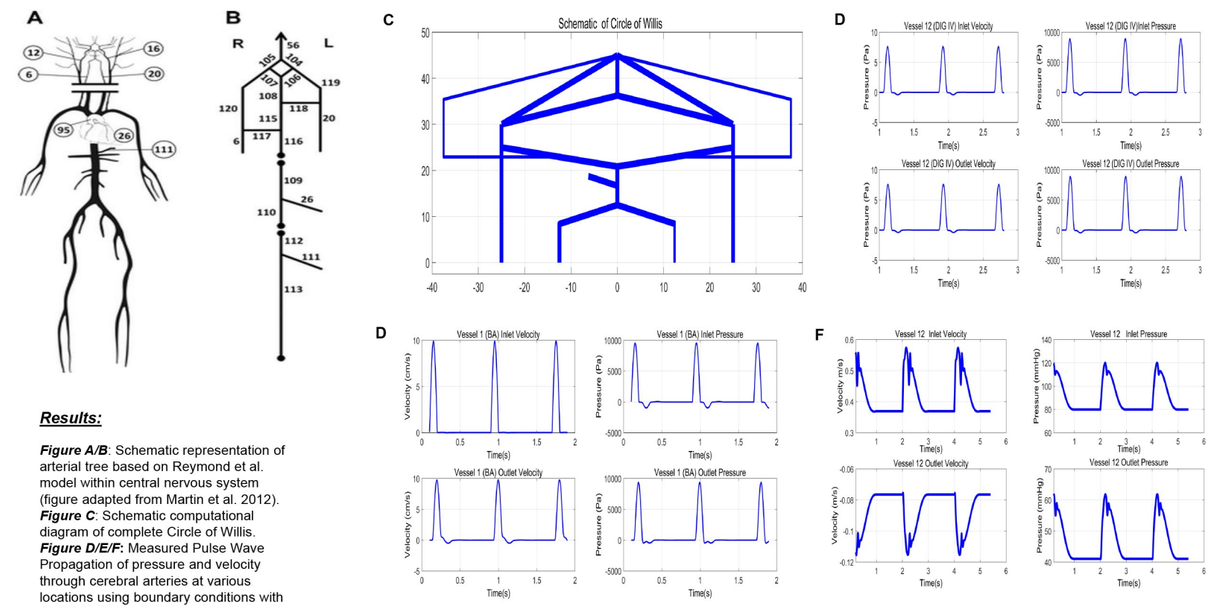
m_{bulk} = 600ml/day;

m_{pulse}(t)=

$$\alpha\left[\sin\left(\omega t - \frac{\pi}{2}\right) - 0.5\cos\left(\omega t - \frac{\pi}{2}\right)\right]$$

- We performed computational fluid dynamic simulations for our 1-D dimensional Fluid Structure Interaction Model that represents the CSF circulation system. ***(Figure G-J)***

Results

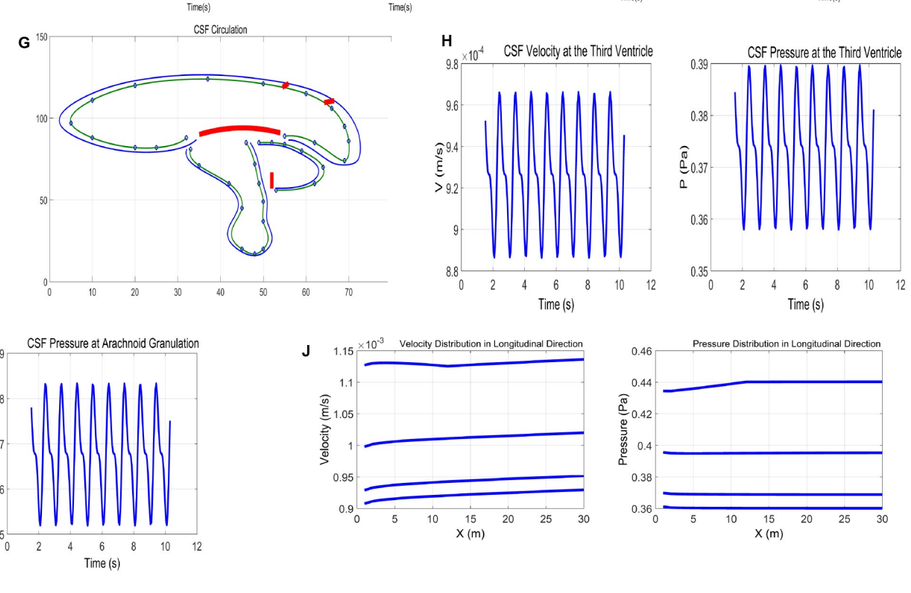


Results:

Figure A/B: Schematic representation of arterial tree based on Reymond et al. model within central nervous system (figure adapted from Martin et al. 2012). ***Figure C***: Schematic computational diagram of complete Circle of Willis. ***Figure D/E/F:*** Measured Pulse Wave Propagation of pressure and velocity through cerebral arteries at various locations using boundary conditions with diminished pulse to represent continuous flow left ventricular assist device patient.

Figure G: Schematic representation of CSF circulation system, with some boundaries depicted in red (i.e. arachnoid granulations). ***Figure H/I:*** Low pulse computational simulation of CSF at third ventricle and arachnoid granulation respectively- amplitude of pressure and velocity affected, but overall flow rate unchanged.

Figure J: Velocity and pressure profiles in the longitudinal direction of low pulse CSF simulation at the boundaries obtained at the third ventricle.



Discussion

Based on computations from our Fluid Structure Interaction model we were able to predict the pressure and flow within the cardiovascular system and in the cerebral ventricular system for a patient with continuous – flow left ventricular assist device with presumed low arterial pulse. The preliminary CSF flow analysis demonstrate amplitude changes for velocity and pressure, but did not reveal an overall effect on flow rate. To our knowledge, our 1-D dimensional fluid structure model for the investigation of CSF dynamics in patients with continuous-flow left ventricular assist devices is an original application within this clinical environment.

Future Directions

- Utilize in-vivo data from our institutional phase contrast MRI as boundary conditions for our Fluid Structure Interaction model
- Based on conditions above, coordinate patient specific computational fluid dynamic simulations for 1D, 2D, and 3D simulations
- Extend our FSI model to better understand the modernized view of CSF flow which includes bi-directional fluid exchange with the extracellular space, perivascular flow, and lymphatic drainage
- Construct computational model of mechanical behavior of the CSF system using 3D printing technology and couple cardiovascular pulse flow with a continuous-flow left ventricular assist device in-vitro
- Cognitive testing of patients with Continuous – Flow Left Ventricular Assist Device at our institution.

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