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Biomechanical modeling and Magnetic Resonance Imaging to investigate CSF flow physiology

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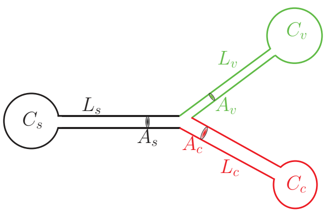
Abstract/Objective

Nowadays Phase contrast Magnetic Resonance Imaging (PC-MRI) is the only sensor able to measure in physiological conditions blood and cerebrospinal fluids (CSF) flow dynamics during cardiac cycle at different levels of the craniospinal system [1]. Combining modelling and in Vivo PC-MRI measurments of CSF Flow at the cervical Spinal (Q_s) and Aqueduct of Sylvius (Q_v) or Sub-Arachnoidal cerebral (Q_c) levels makes it possible to compute Intracranial pressure (ICP) as well as get a deep insight into the LCS dynamical system. Inertia has been neglected in most of previous LCS models. Our simple model show that inertia plays a crucial role in particular in the optimal LCS flow amplitudes and phases.

The Cerebro-Spinal Model

We modelled the cerebro-spinal sytem as a bifurcation of 3 rigid tubes of length L_k and section A_k, $k \in \{s, v, c\}$, filled of cerebro-spinal fluid (CSF) of density ρ and dynamic viscosity μ, and ended with 3 compliant compartments. The subscripts $\{s, v, c\}$ represent respectively the spinal subarachnoid space (SAS), the ventricular space and the cerebral SAS.



The governing equations

Assuming that the spinal flow rate $Q_s = Q_{\max} e^{i\omega t}$ is known, we obtain that the flow rate Q_k, with $k \in \{c, v\}$, is solution of the following differential equation:

$$T_I \frac{d^2 Q_k}{dt^2} + \frac{dQ_k}{dt} + \frac{1}{T_C} Q_k = F_k Q_s \qquad (1)$$

which introduces 2 characteristic times depending only on the fluid characteristics, and ventricular and cerebral SAS parameters as follows:

$$T_I = \frac{\rho \sum_{i=c,v} \frac{L_i}{A_i}}{\sum_{i=c,v} \sigma_i} \text{ inertial time} \qquad T_C = \frac{\sum_{i=c,v} \sigma_i}{\sum_{i=c,v} \frac{1}{C_i}} \text{ compliant time}$$

where $\sigma_k = \frac{8\pi\mu L_k}{A_k^2}$ if we assume a parabolic velocity profile. The forcing term, $F_k Q_s$ represents the spinal flow Q_s modulated by the collateral branch reactance and resistance factor F_k given by:

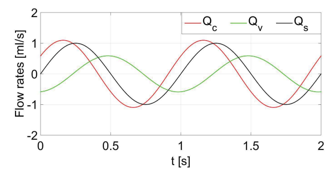
$$F_c = \left[\left(\frac{1}{C_v} - \frac{\rho L_v}{A_v}\omega^2\right) + i\omega\sigma_v\right] / \sum_{i=c,v} \sigma_i, \qquad F_v = \left[\left(\frac{1}{C_c} - \frac{\rho L_c}{A_c}\omega^2\right) + i\omega\sigma_e\right] / \sum_{i=c,v} \sigma_i$$

Natural angular frequency of the model: $\Omega = \frac{1}{\sqrt{T_I T_C}}$

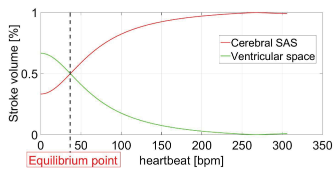
Model Analysis

$\Omega/\omega = 1.0713$

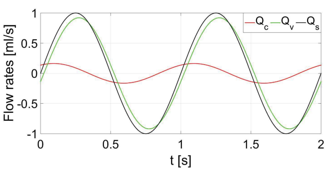
Flow rates in the cerebro-spinal system

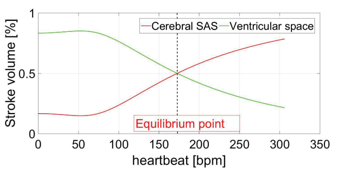


Stroke volumes as a function of the heartbeat

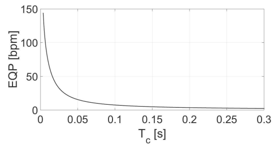


$\Omega/\omega = 3.302$





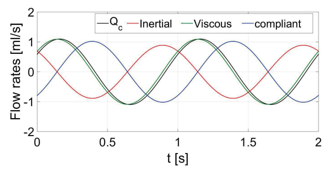
Stroke volume equilibrium (EQP) as a function of T_c



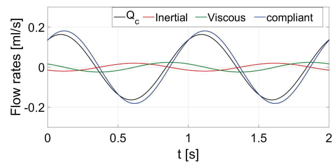
Relative importance of inertial/viscous/compliant effects

$$\underbrace{T_I \frac{d^2 Q_k}{dt^2}}_{\text{inertial}} + \underbrace{\frac{dQ_k}{dt}}_{\text{viscous}} + \underbrace{\frac{1}{T_C} Q_k}_{\text{compliant}} = F_k Q_s$$

$\Omega/\omega = 1.0713$



$\Omega/\omega = 3.302$



Three behaviors

$\Omega/\omega \approx 1$	viscous (OPTIMAL)
$\Omega/\omega \gg 1$	compliant
$\Omega/\omega \ll 1$	inertial

Frequency/compliance effects

EQP becomes higher as T_c becomes smaller

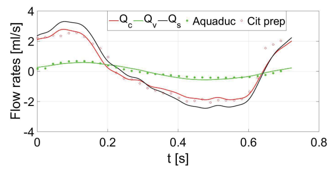
Ventricular space leads at frequency < EQP

Cerebral SAS leads at frequency > EQP

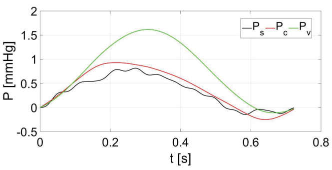
Patient specific simulations

Healthy case $\Omega/\omega = 1.4426$

Model (straight lines) MRI data (symbols)

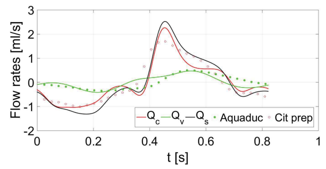


Computed ICP



Hydrocephalus symptoms $\Omega/\omega = 2.7454$

Model (straight lines) MRI data (symbols)



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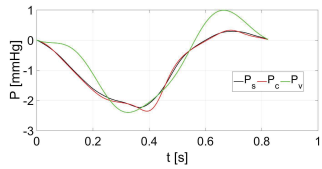

Discussion

The flows are optimal when inertia and compliance cancels each other, i.e when cardiac angular frequency equals the natural angular frequency of the coupled LCS system. A reduced global compliance induces a ventricular compartment more active, even if the relative compliance ratio remains the same. The 2 characteristics parameters Ω and EQP may be used to find the specific patient parameters, as compliances, based on flow rates data.

References

[1] Baledent, O. and Idy-Peretti, I. *Investigate radiology* **36** (7), p. 368-377, 2001.