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# BIOMECHANICAL MODELING AND MAGNETIC RESONANCE IMAGING TO INVESTIGATE CSF FLOW PHYSIOLOGY



Patricia Cathalifaud<sup>(1)</sup>, Mokhtar Zagzoule<sup>(1)</sup> & Olivier Balédent<sup>(2)</sup>

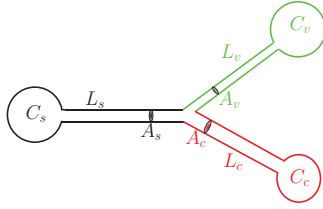
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(2) BioFlowImage, CHU Amiens-Picardie, Amiens, France

## 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 measurements of CSF Flow at the cervical Spinal ( $Q_s$ ) and Aqueduct of Sylvius ( $Q_v$ ) or Sub-Arachnoid 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 system 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  $\rho$  and dynamic viscosity  $\mu$ , 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:

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

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

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

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:

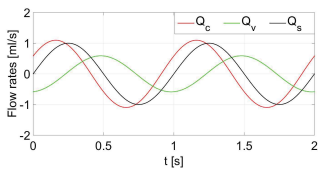
$$F_c = \left[ \left( \frac{1}{C_v} - \frac{\rho L_v \omega^2}{A_v} \right) + i\omega\sigma_v \right] / \sum_{i=c,v} \sigma_i, \quad F_v = \left[ \left( \frac{1}{C_c} - \frac{\rho L_c \omega^2}{A_c} \right) + i\omega\sigma_c \right] / \sum_{i=c,v} \sigma_i$$

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

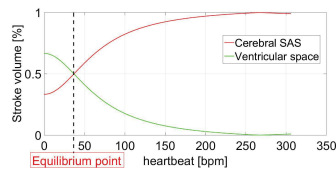
## Model Analysis

$$\Omega/\omega = 1.0713$$

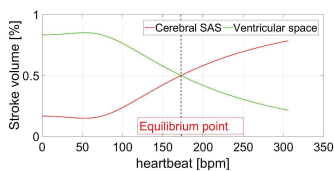
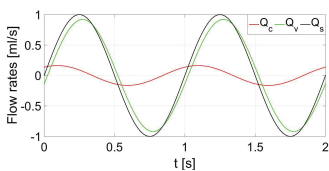
Flow rates in the cerebro-spinal system



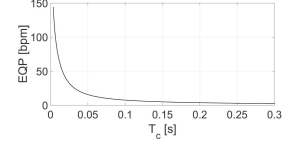
Stroke volumes as a function of the heartbeat



$$\Omega/\omega = 3.302$$



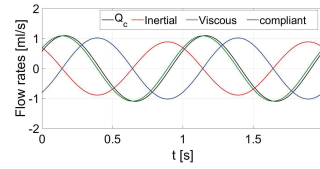
Stroke volume equilibrium (EQP) as a function of  $T_c$



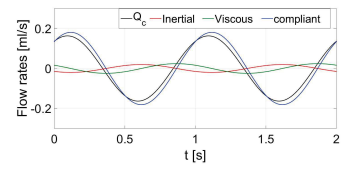
Relative importance of inertial/viscous/compliant effects

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

$$\Omega/\omega = 1.0713$$



$$\Omega/\omega = 3.302$$



Frequency/compliance effects

EQP becomes higher as  $T_c$  becomes smaller  
**Ventricular space** leads at frequency < EQP  
**Cerebral SAS** leads at frequency > EQP

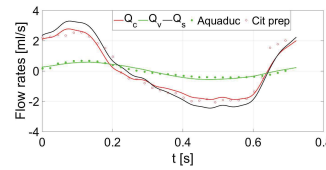
### Three behaviors

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

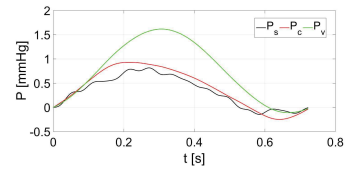
## Patient specific simulations

Healthy case  $\Omega/\omega = 1.4426$

Model (straight lines)  
MRI data (symbols)

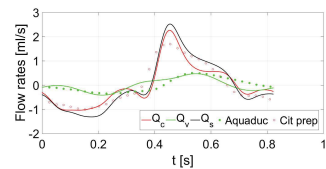


Computed ICP

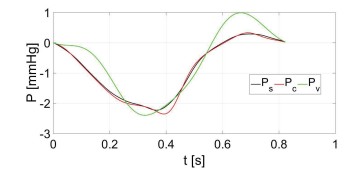


Hydrocephalus symptoms  $\Omega/\omega = 2.7454$

Model (straight lines)  
MRI data (symbols)



Computed ICP



## 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  $\Omega$  and EQP may be used to find the specific patient parameters, as compliances, based on flow rates data.

## References

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