Respiratory influence on intracranial pressure gradients and aqueductal flow in normal pressure hydrocephalus

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Abstract

Phase contrast MRI does not take into account the role of respiration on cerebrospinal fluid (CSF) flow. We used in vivo pressure measurements from two locations in the intracranial space to calculate a pulsatile pressure gradient. This pressure data was used as input to an idealized model of the aqueduct to calculate CSF flow. We found the cardiac and respiratory cycle to contribute equally to CSF flow. The total flow volume was dominated by respiration, and all subjects showed variability in pressure gradients over time resulting also in variability in CSF flow.

Background

- Idiopathic normal pressure hydrocephalus (iNPH) is neurodegenerative disorder characterized by gait ataxia, urinary incontinence and dementia.
- iNPH patients have been reported to have greater cerebrospinal fluid (CSF) flow in the aqueduct, resulting in a greater aqueductal stroke volume (ASV).
- ASV measured with phase contrast MRI has been proposed as a biomarker for shunt surgery [1]. The biomarker has remained controversial, provides data only from a short time-period and does not take into account the role of respiration.
- In this study we quantified the pulsatile pressure gradients, computed aqeuductal flow and separated the signals into their cardiac and respiratory component.

In vivo pressure measurements were used as input to the CFD model

In 9 iNPH patients, over a period of 12-15 hours, we simultaneously measured intracranial pressure (ICP) in the lateral ventricle and in the subdural space [2]. We included a total of 102 6-minute windows, a typical time window for an MRI scan. For each 6-minute window, the Fourier transform was computed, and the cardiac and respiratory frequencies were quantified together with the corresponding amplitudes. For each time window, we approximated the pulsatile pressure gradient as

$$\nabla p(t) = a_0 \sin(2\pi f_0 t) + a_1 \sin(2\pi f_1 t), \tag{1}$$

where f_0 and f_1 are the frequencies and a_0 and a_1 are the amplitudes of the respiratory and cardiac cycle from a given 6-minute window.

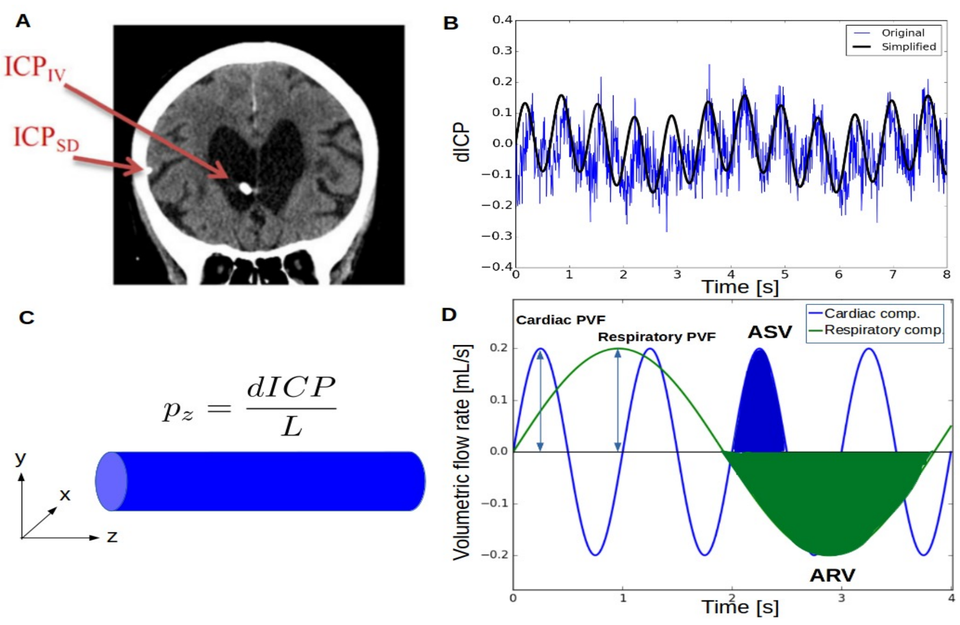


Figure 1: Schematic of the methodology. **A:** Placement of the two sensors during pressure measurements. **B:** Analysis and simplification of the pressure difference signal. **C:** Computational Fluid Dynamics with the estimated pressure gradient as a driving force. **D:** Quantification of peak volumetric flux (PVF) and flow volumes, derived from the CSF flow signal.

The pressure gradient from eq. (1) was used as a driving force to compute CSF flow according to the 1D Navier-Stokes equations in cylindrical coordinates. The aqueduct was assumed to have a radius of 2 mm, with zero gradient and the centerline, and no-slip at the outer walls.

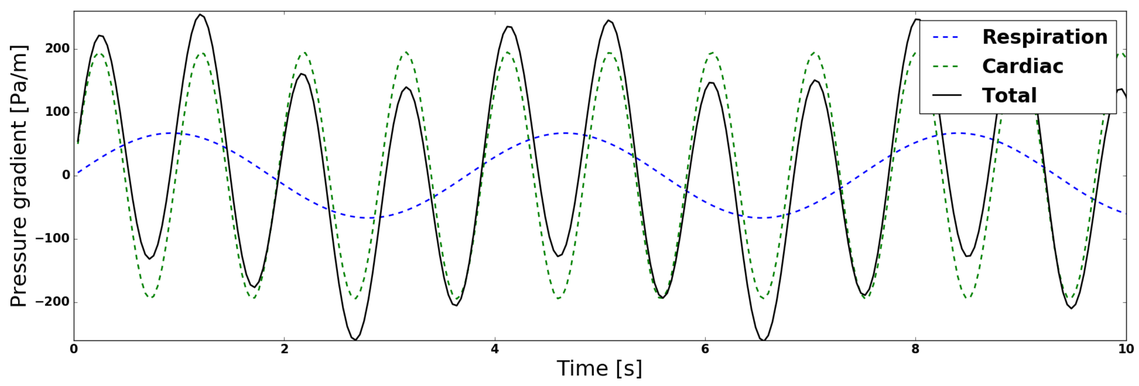
Intracranial pressure gradients were dominated by the cardiac cycle while CSF flow was evenly regulated by the two components

With the pressure gradient in eqn. (1), the CSF volumetric flux was found to be on the form:

$$v(t) = A_0 \sin(2\pi f_0 t) + A_1 \sin(2\pi f_1 t + \phi) \tag{2}$$

Respiratory			Cardiac		
f_0 [Hz]	a_0 [Pa/m]	A_0 [mL/s]	f_1 [Hz]	a_1 [Pa/m]	A_1 [mL/s]
0.27	67	0.26	1.03	195	0.25

Table 1: Cohort average frequency of the respiratory (f_0) and the cardiac (f_1) component with the corresponding pressure gradients (a_0,a_1) and CSF peak volumetric flux (A_0,A_1)



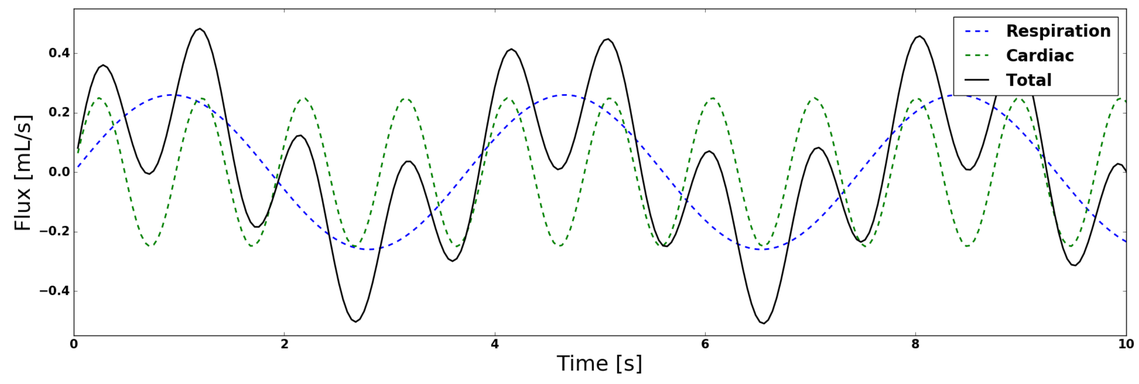


Figure 2: The average pressure gradient (upper) and the corresponding flow (lower), split into the respiratory (blue) and cardiac (green) component. The pulsatile pressure gradient is dominated by the cardiac cycle, while CSF flow is evenly regulated by the two components.

we defined the aqueductal respiratory volume (ARV) and the ASV as

$$\text{ARV} = \int_0^{\frac{1}{2f_0}} A_0 \sin(2\pi f_0)\mathrm{d}t, \qquad \text{ASV} = \int_0^{\frac{1}{2f_1}} A_1 \sin(2\pi f_1)\mathrm{d}t \tag{3}$$

On cohort average the ARV was 360 μL, and the ASV was 81 μL. The standard deviations were 152 μL and 45 μL respectively. At the patient level, the standard deviation for the set of 6-minute windows was 181 μL for ARV and 38 μL for ASV on average, reflecting individual variability over time.

Conclusions

- Pulsatile pressure gradients of approximately 200 Pa/m were dominated by the cardiac cycle, while aqueductal CSF flow was evenly dominated by the cardiac and respiratory cycle.
- Flow volume over one respective cycle was dominated by respiration, and each individual patient showed considerable variation in CSF flow over time. Hence, ASV derived from a single MRI acquisition should be used with great care to select patients for shunting.

References

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[2] P. K. Eide and T. Sæhle. Is ventriculomegaly in idiopathic normal pressure hydrocephalus associated with a transmantle gradient in pulsatile intracranial pressure? *Acta neurochirurgica*, 2010.