Cerebral Venous Flow and Pulsatility in Older Adults: A 4D-Flow MRI Study

Introduction

Imagine a plumber given only a blueprint of the pipe system to diagnose a problem—unable to test which pipes carry water or what the pressure is. Neurology research faces a similar challenge: the cerebral venous system is well mapped anatomically, but its physiology—flow and pressure—remains poorly understood, particularly regarding how it functions in health and disease

Essential to brain health is the homeostasis between three main constituents competing for space inside the scull: the brain tissue, the arterial – and - venous blood, and the cerebral spinal fluid (CSF). Any volume increase in one of these constituents requires an equal decrease in volume in another. If not, intracranial pressure (ICP) will rise. This is known as the Monroe-Kelly doctrine and this principle is the basis for understanding the pathophysiology CSF- and hemodynamic disorders such as idiopathic normal pressure hydrocephalus (INPH) and idiopathic intracranial hypertension (IIH). The venous system may play a critical role in both these diseases since it interacts with the CSF- system during each cardiac cycle: With each heartbeat, expansion of the arterial pulse leads to a transient intracranial pressure rise that propagates through the CSF and compresses CSF-immersed veins, expelling blood toward the dural sinuses. Conversely, the dural sinuses are the principal site of CSF absorption. Consequently, sinus pressure sets the lower limit of CSF pressure (i.e., ICP) required for CSF outflow.

Dural sinus pressure is determined by venous flow and outflow resistance—i.e., by anatomy (which governs resistance) and by flow rate. Both anatomy and flow can be quantified with four-dimensional flow MRI (4D-flow), which assesses arterial and venous flow simultaneously across the cardiac cycle. While the anatomy of the venous system is highly variable and well documented, little is known about how anatomical variability affects venous hemodynamics. Moreover, knowledge of the hemodynamics of veins that interact directly with CSF, such as the cortical veins and the vein of Galen, is limited as well. Specifically, what constitutes normal flow patterns and which features characterize signs of pathology remain unclear. Large population-based studies are scarce and are needed to establish reference data for future research.

Objective: quantify venous blood flow in a large, population-based cohort using 4D-flow MRI, including CSF-immersed veins (cortical veins, vein of Galen) and major dural-sinus outflow pathways; relate venous flow to total arterial inflow across common anatomical variants; and identify patterns characteristic of INPH-like gait disorders.

Methods

4D-flow MRI examinations of 762 volunteers from a population-based cohort of older adults (mean age 75 ± 5 years; 52% female) with self-reported gait disturbances were included. Following neurological examinations, 689 had no neurological gait disorder (Group 1) and 73 had INPH-like gait disorder (Group 2). Blood flow, pulsatility, and cross-sectional areas were assessed at the arterial inflow (defined as the sum of flow rates in the internal carotid arteries (ICAs) and the basilar artery (BA)) and throughout the venous outflow pathways. The venous system was assessed at several locations along the major outflow pathways, from the rostral-most segment of the superior sagittal sinus to the mid-segment of the sigmoid sinus. In addition, large cortical veins (typically the vein of Trolard and the vein of Labbé) and the vein of Galen were assessed.

Results/Discussion

The distribution of transverse sinus drainage patterns—70% symmetrical, 25% right-sided dominant, and 5% left-sided dominant—was consistent with previous anatomical studies and did not differ between groups. The proportion of blood flow in relation to arterial inflow was higher in symmetrical than in asymmetrical drainage patterns, indicating greater reliance on accessory outflow pathways for the latter.

The cross-sectional areas of the intracranial sinuses were larger in Group 1 than those previously reported in younger cohorts[1] (areas estimated from diameter). This finding, combined with the fact that total cerebral blood flow declines with age[5], suggests that dural sinus pressure may decrease with increasing age. This finding is particularly interesting because elevated dural sinus pressure is strongly associated with IIH, a disorder that predominantly affects women of childbearing age and is rare in the elderly. Similarly, when comparing flow and cross-sectional areas between Group 1 and Group 2, smaller cross-sectional areas were found in Group 2 in the cortical veins and dural sinuses, despite similar flow rates between the groups. In addition, reduced flow pulsatility was observed in Group 2, consistent with lower intracranial compliance commonly associated with INPH.

Conclusion

To our knowledge, this is the first study to present venous blood flow and pulsatility in relation to common dural sinus configurations and large cerebral veins in a large, population-based cohort. We present reference values for flow, pulsatility, and cross-sectional areas across the cerebral venous system. Furthermore, this study demonstrated flow patterns consistent with decreased intracranial compliance for INPH-like gait disorders, whereas those with non-neurological gait disorders showed the opposite pattern.

1. Paudel, S., Sah, R., Singh, R. K., Kayastha, P. & Katwal, S. Dural Venous Sinus Variations Observed in Magnetic Resonance Venography at a Tertiary Care Hospital: An Observational Study. *J. Nepal Med. Assoc.* **62**, 720–724 (2024).
2. Anand, A. *et al.* A retrospective anatomical study of the cerebral dural venous sinus outflow pathways utilizing three-dimensional rotational venography. *Brain Circ.* **8**, 38–44 (2022).
3. Peterson, K. A. *et al.* Angiographic cerebral venous sinus calibers and drainage patterns in patients with normal intracranial pressure and idiopathic intracranial hypertension. *J. Neurointerv. Surg.* **13**, 958–963 (2021).
4. Rohr, A. *et al.* The entire dural sinus tree is compressed in patients with idiopathic intracranial hypertension: A longitudinal, volumetric magnetic resonance imaging study. *Neuroradiology* **54**, 25–33 (2012).
5. Xing, C. Y. *et al.* Distribution of cardiac output to the brain across the adult lifespan. *J. Cereb. Blood Flow Metab.* **37**, 2848–2856 (2017).