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Technical Notes & Surgical Techniques

Continuous positive airway pressure alters cranial blood flow and cerebrospinal fluid dynamics at the craniovertebral junction

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ABSTRACT

Purpose: To investigate the impact of continuous positive airway pressure (CPAP) applied by a full-face fitted mask at 15 cmH_2O on total cerebral blood flow (tCBF), jugular venous flow (tJVF) and cerebrospinal fluid (CSF) flow.
Materials and methods: Axial 2D phase-contrast MRI measurements were acquired at the C2–C3 vertebral level for 23 healthy male awake subjects at baseline (without) and with CPAP applied. CSF flow was quantified within the spinal subarachnoid space and tCBF was quantified based on the summation of blood flow within the left and right internal carotid and vertebral arteries. tJVF was quantified based on the summation of blood flow within the left and right jugular veins. Heart rate, transcutaneous carbon dioxide ($PtcCO_2$) and oxygen saturation were continuously monitored during the MR protocol.
Results: CPAP decreased the pulse amplitude (PtPPA) of tJVF by 21% ($p = 0.004$). CSF stroke volume (SV) and PtPPA also decreased by 20% ($p = 0.003$) and 15% ($p = 0.005$), respectively. Change in tCBF SV and PtPPA was not significant. However, the timing of maximum systolic tCBF occurred significantly earlier under CPAP. CSF flow and tJVF waveforms showed significant spatial and temporal differences in waveform feature points, and spectral analysis revealed a decrease in the first harmonic of tJVF under CPAP ($p = 0.001$). Under CPAP, a 5% decrease in $PtcCO_2$ ($p = 0.003$) and 9% increase in HR ($p = 0.006$) were measured. However, these HR and $PtcCO_2$ changes were not correlated with any changes in arterial, venous or CSF flow dynamics.
Conclusion: Application of CPAP via a full-fitted mask at 15 cm H_2O was found to have a significant effect on intracranial venous outflow and spinal CSF flow at the C2 vertebral level in healthy adult-age awake volunteers. CPAP can be used to non-invasively provoke changes in intracranial and CSF flow dynamics.

1. Introduction

The coupling of cerebrospinal fluid (CSF) pressure fluctuations and the cardiovascular system has long interested researchers [1–3]. A full understanding of this coupling is thought to be important to understand the pathophysiology of cerebrovascular disorders such as stroke, interstitial fluid transport within the brain [4,5], and craniospinal disorders such as type I Chiari malformation, syringomyelia and hydrocephalus [6–9]. A number of studies have sought to understand the CSF dynamics in the spinal subarachnoid space (SSS) and its importance for the overall intracranial balance between the arterial, venous, and CSF flow pulsations [10–12]. Researchers have postulated that under normal conditions the healthy SSS may act as a "notch filter" that dampens incoming cerebral blood flow (CBF) pulsations to supply smooth blood flow to the neural tissue [13,14]. In addition, Martins et al. [15] showed that the spinal dural sac is a dynamic structure, readily changing its capacity in response to intra-abdominal pressure fluctuations.

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Non-invasive 2D phase-contrast magnetic resonance imaging (2D PC MRI) enables measurement of the CSF and CBF system fluid flow [16,17] and has also been used to estimate venous flow in the jugular and intracerebral veins as well as the major sinuses [12]. According to the Monro–Kellie doctrine [12], the arterial, venous, CSF and brain tissue compartments co-exist in a state of dynamic equilibrium throughout the cardiac cycle [18–20]. A change in the volume in one component requires a change in the volume in either one or both of the other two compartments. Schmid Daners et al. [21] showed using 2D PC MRI that the coupling of cerebral arterial inflow and CSF dynamics is age and sex dependent. Other studies have focused on the cerebral venous system [20,22]. El Sankari et al. [22] simultaneously compared the venous flow, arterial and CSF flows of patients with multiple scleroses to age and sex matched healthy adults. Results documented complex and heterogeneous venous drainage pathways and a decrease in CSF flow oscillations.

The interaction between intrathoracic pressure and intracranial pressure (ICP) due to posture [23], abdominal pressure changes [24] and coughing [25] has been reported in the literature. These pressure changes are transmitted from the abdomen into the CSF system through the dural venous sinuses and epidural venous plexus [26]. Published data have shown physiologic variations in the dural venous sinus drainage that can occur either under specific respiratory mechanisms such as Valsava maneuver [27] or with posture changes [28]. Thus, it is possible to manipulate the intrathoracic pressure by a number of non-invasive maneuvers that in turn modify the intracranial system as a whole. One method to non-invasively alter intrathoracic pressure is with the use of continuous positive airway pressure (CPAP), the most widely accepted treatment for sleep apnea. CPAP acts as a pneumatic "splint" by producing a positive pressure, thereby preventing upper airway collapse during sleep.

While CPAP use has become routine, the full physiological effect of its use on CBF, venous flow and CSF dynamics is not fully understood [29,30]. Considering that a rise of the intrathoracic pressure increases the jugular venous pressure, CPAP could have an effect on CBF by reducing the cerebral perfusion pressure [31]. Concomitantly, changes in the blood flow volume due to the increased intrathoracic pressure hinder cerebral venous drainage via the jugular veins [32]. In human volunteers CPAP breathing has been shown to increase lumbar CSF pressure [33] and reduce CSF peak velocity in the aqueduct of Sylvius [34].

In the present study, we hypothesized that acute pressure changes in the chest caused by the application of CPAP would alter intracranial and spinal CSF flow dynamics in the following manner: 1) venous flow dynamics would be noticeably altered and 2) the stroke volume (SV) and pulsation of the spinal CSF would decrease. We tested our hypothesis by applying CPAP at 15 cm H_2O in 23 healthy male volunteers and measured physiological alterations using a 2D PC MRI protocol to quantify blood flow in the left and right internal carotid arteries (ICAs), left and right vertebral arteries (VAs), left and right jugular veins (JVs) and CSF flow at the C2–C3 level of the cervical spinal canal with CPAP applied. Baseline measurements without CPAP applied followed the initial recording with the CPAP using identical imaging protocols. Using these measurements the influence of CPAP on total cerebral blood flow (tCBF), total jugular venous (tJVF) and spinal CSF flow was assessed in terms of flow based metrics and spectral content of the flow waveforms.

2. Materials and methods

2.1. Ethics statement

Healthy, young, non-smoking male volunteers, with no history of pulmonary, cardiac, neurological, cerebral disease, spinal trauma or diagnosed sleep apnea, were invited to participate in the study by advertisement at the local university hospital of Lausanne, Centre Hospitalier Universitaire Vaudois (CHUV) and École Polytechnique Fédérale de Lausanne in Switzerland. The study was carried out in accordance with the Declaration of Helsinki (1989) and was approved by the Swiss Human Research Ethics Committee of Vaud. The MR data acquisition was performed at the Centre d'Imagerie BioMédicale (CIBM) Department of Radiology, CHUV in Lausanne. Before the MR exams, written informed consent was obtained for all volunteers. MR data were anonymized prior to data post-processing.

2.2. In vivo 2D PC MR measurements

23 healthy male volunteers, aged 24 ± 2.1 years with a mean body mass index (BMI) of 22.9 ± 2.51 kg/m^2 were scanned on a 3 T MRI scanner (Siemens Magnetom Trio Tim, Siemens, Erlangen, Germany) with a standard 4-channel phased array carotid coil (Magnet Mach NET 4CHN, Siemens A Tim Coil), placed adjacent to the left and right ICAs and a neck coil (Neck matrix, 4CHN, Siemens) with CPAP (S8 AutoSet Spirit™ II, ResMed Inc, Poway, CA) applied at 15 cmH_2O through a fitted full-face mask MIRAGE QUATTRO® (ResMed®, ResMed Inc, Poway, CA) in a specific order following a structured protocol. The measurements were performed during the afternoon at atmospheric pressure in the MR scanner room with controlled temperature at least two hours after the last meal and caffeinated drink. A medical doctor was present throughout testing. Subjects were awake during the entire MRI protocol in the supine position with their necks in a neutral orientation.

Both anatomy and 2D PC MR images were acquired. A set of T2-weighted turbo spin-echo sagittal images defined the anatomy in the upper cervical spine. Fluid flow acquisition planes, oriented perpendicular to the nominal flow direction, were selected based on a mid-sagittal scan at the C2–C3 subarachnoid space (Fig. 1A). Both left and right ICAs, left and right VAs and left and right JVs were imaged by 2D PCMRI simultaneously within the same slice oriented orthogonal to the spinal cord axis at the C2–C3 cervical level (Fig. 1B). Imaging parameters for the arterial and jugular flow measurements were as follows: 0.7 mm isotropic in-plane resolution, 5 mm slice thickness, 124 × 114 acquisition matrix, 20° flip angle, 814 Hz/Px bandwidth, 190 × 112 field of view (FoV), 59.4% FoV phase, 256 base resolution, 100% phase resolution, 80 cm/s thru-plane velocity encoding (VENC) and TR = 20 ms and TE = 6.5 ms, which resulted in a temporal resolution of 20 ms. The minimum TR available was used to optimize temporal resolution, and the minimum TE available was used to optimize signal-to-noise ratio and to reduce intravoxel phase dispersion. All scans were prospectively triggered with electrocardiographic (ECG) gating. The number of heart phases acquired was adapted to the cardiac frequency and fixed to 35 phases for all the subjects.

CSF flow measurements were performed at the same location as the vascular flow measurements (Fig. 1C) with the imaging parameters identical to those of the vascular flow measurements, except with a VENC of 10 cm/s and 15° flip angle. Overall scan time was 8–10 min with CPAP and 8–10 min without CPAP applied, depending on the heart rate. The entire examination was approximately 45 min.

2.3. Physiologic monitoring

Transcutaneous partial pressure of carbon dioxide ($PtcCO_2$), oxygen saturation (SaO_2) and heart rate (HR) were monitored throughout the exam with a 'Tosca 500' system (Radiometer Basel AG, Basel, Switzerland) using a sensor applied at the top surface of the foot. MRI measurements under CPAP were obtained first after the $PtcCO_2$ level return to baseline (±2 mmHg) or at least 15 min of CPAP use. Following the MRI measurements with CPAP, the mask was removed and the same protocol repeated without CPAP to obtain the 'baseline' measurements. Following MR examination, all subjects were asked to rate their anxiety level under CPAP from a scale of 0–3 where 0 refers to 'not at all anxious', 1 refers to 'slightly anxious', 2 refers to 'moderately anxious' and 3 refers to 'highly anxious'.