Quantifying the Effect of Posture on Intracranial Physiology in Humans by MRI Flow Studies

Noam Alperin, PhD, Sang H. Lee, MS, Anusha Sivaramakrishnan, MS, and Stephen G. Hushek, PhD

Purpose: To quantify the effect of posture on intracranial physiology in humans by MRI, and demonstrate the relationship between intracranial compliance (ICC) and pressure (ICP), and the pulsatility of blood and CSF flows.

Materials and Methods: Ten healthy volunteers (29 ± 7 years old) were scanned in the supine and sitting positions using a vertical gap MRI scanner. Pulsatile blood and CSF flows into and out from the brain were visualized and quantified using time-of-flight (TOF) and cine phase-contrast techniques, respectively. The total cerebral blood flow (tCBF), venous outflow, ICC, and ICP for the two postures were then calculated from the arterial, venous, and CSF volumetric flow rate waveforms using a previously described method.

Results: In the upright posture, venous outflow is considerably less pulsatile (57%) and occurs predominantly through the vertebral plexus, while in the supine posture venous outflow occurs predominantly through the internal jugular veins. A slightly lower tCBF (12%), a considerably smaller CSF volume oscillating between the cranium and the spinal canal (48%), and a much larger ICC (2.8-fold) with a corresponding decrease in the MRI-derived ICP values were measured in the sitting position.

Conclusion: The effect of posture on intracranial physiology can be quantified by MRI because posture-related changes in ICC and ICP strongly affect the dynamics of cerebral blood and CSF flows. This study provides important insight into the coupling that exists between arterial, venous, and CSF flow dynamics, and how it is affected by posture.

Key Words: cine phase contrast; upright posture; CSF flow; CBF; cerebral venous outflow; intracranial compliance and pressure


BODY POSTURE strongly affects intracranial hydrodynamics and cerebral hemodynamics. Yet quantitative data on posture-related changes in parameters such as intracranial compliance (ICC), intracranial pressure (ICP), and cerebral blood flow (CBF) in humans is scarce because of the invasiveness and risk associated with measurements of ICC and ICP, and because most neuroimaging studies used for CBF measurement are constrained to the supine posture. Invasive measurements in a previous study of head-injury patients (1) documented lower ICP and mean blood pressure in the carotid arteries, and relatively unchanged cerebrovascular resistance and CBF when the patient’s head was elevated at 30°. Studies on the effect of posture on cerebral venous outflow are more abundant. Angiographic studies in nonhuman primates demonstrated that the internal jugular veins (IJVs) are the main pathway for venous outflow in the supine position, while in the upright posture the IJVs collapse and venous outflow occurs mainly through secondary veins such as the vertebral, epidural, and deep cervical veins, which compose the vertebral venous plexus (2,3). Dilenge and Perrey (3) postulated that the closing and opening of the vertebral plexus are related to changes in CSF pressure in the cervical region. Studies in humans utilized color-coded duplex sonography to quantify the effect of posture on cerebral venous outflow (4–7). Valdueza et al (4) reported lower total venous outflow in the upright posture compared to the supine posture (280 mL/min vs. 740 mL/min), and that the respective average volumetric flow rates through the IJVs were 70 mL/min and 700 mL/min. A more recent sonography study demonstrated that the cross-sectional area of the right jugular vein is not maximal in the supine position and can increase further when changing to the Trendelenburg (head-down) position (5). Cross-sectional area measurements of the right jugular vein have also been used to demonstrate that application of positive-pressure breathing (PPB) reverses the collapse of that IJV in the sitting position (6). A mathematical model was proposed to explain how an increase in central venous pressure reverses the collapse of the IJVs in the upright posture (7). Using ultrasound, Doeppe et al (8) found that approximately 6% of subjects had predominantly nonjugular venous drainage in the supine position as well.

The link between posture-related changes in cerebral hemodynamics, intracranial hydrodynamics, and patterns of venous drainage are not known, and the effect of body posture on the dynamics of cerebral blood and cerebrospinal fluid (CSF) has not been measured pre-
viously. In this study we report the first measurements of cerebral blood and CSF flow dynamics in the upright posture in humans, using an open gap MRI scanner. We further characterize differences between supine and upright postures in the same subjects. Finally, the study aims to quantify changes in CBF, ICC, and ICP between the upright and supine postures, and explain the relationships between these parameters and the dynamics of blood and CSF flows measured by a cine phase-contrast MRI technique.

**MATERIALS AND METHODS**

**Data Acquisition**

Ten healthy volunteers (three males and seven females, mean age = 29 ± 7 years) with no known history of neurological problems were imaged in both upright and supine positions in a Signa SP/i 0.5T vertical gap MRI scanner (GE Medical Systems, Milwaukee, MN, USA). The imaging protocol was approved by the institutional review board and informed consent was obtained from all subjects. The vertical gap allows the subject to be positioned seated upright with the upper cervical spine at the magnet isocenter, as shown in Fig. 1. The subject in the seated position is held in place by a combination of foam and inflatable pads attached to rails anterior and posterior to the patient’s head. An 8” × 10” flex coil was used in a transmit/receive mode for the upright position, and in receive mode for the supine position. A time interval of at least 10 minutes between the two scans allowed the volunteers to adjust to the change in posture. Venous outflow through the IJVs and the vertebral plexus was visualized using a two-dimensional time-of-flight (2D-TOF) technique with the following MRI scanning parameters: TR = 36 msec, FA = 50°, FOV = 15 cm, and slice thickness = 1.8 mm.

Two retrospectively gated cine phase-contrast scans were used to measure pulsatile arterial inflow, venous outflow, and CSF flow between the cranium and the spinal canal. A scan with high velocity encoding (VENC = 80 cm/second) and scanning parameters TR = 19 msec, FA = 25°, FOV = 16 cm, matrix size = 256 × 256, average of four excitations, and slice thickness of 8 mm were used to quantify blood flow. A second scan with low VENC (7–9 cm/second) was used to quantify the slower CSF flow and venous flow in the vertebral plexus. The parameters for the lower VENC scan were similar to those use for the high VENC scan, except that TR = 26 msec and FA = 30°. Imaging planes were selected to be perpendicular to the direction of the flow. The high VENC scan was located above the carotid bifurcation, and the low VENC scan was located at the level of mid C2.

**Measurements of CBF and CSF Flow Dynamics**

Each of the two cine phase-contrast MRI scans generates a set of 32 velocity-encoded images of the pulsatile flow during one cardiac cycle, with pixel values proportional to velocity. The volumetric flow rate (VFR) through a blood vessel or the CSF space was obtained by integrating velocities through the lumen’s cross-sectional area. A previously reported automated lumen segmentation technique, pulsatility-based segmentations (PUBS), was used to delineate the boundary of the lumens for improved measurement accuracy and reproducibility (9). A cardiac-cycle-averaged VFR was then calculated for each of the four vessels that carry blood to the brain (i.e., the right and left internal carotid and vertebral arteries). The total CBF (tCBF) was obtained by summation of the average VFR of these four vessels. Venous outflow was quantified in the following venous pathways: the IJVs, vertebral veins, epidural veins, and deep cerebral veins. Averages and fractional SDs of the tCBF, venous flow through the IJVs, and venous pulsatility index (the amplitude of the venous outflow waveform normalized by that of the arterial inflow waveform) in each posture, and the percentage changes between the supine and the sitting positions were then obtained to determine statistical significance.

CSF flow during the cardiac cycle was measured from the low-VENC phase-contrast image series. Since the CSF flow is bidirectional (i.e., outflow toward the spinal canal occurs in systole, and reverse flow occurs during diastole), the amount of CSF volume that flows back and forth (oscillatory CSF volume) is obtained by inte-
grating the absolute values of the CSF flow waveform over the cardiac cycle and dividing the sum by 2.

MRI-Based Derivation of Intracranial Compliance and Pressure

The details of the MRI-based method used to measure ICC and ICP, noninvasively, by MRI and validations with nonhuman primates, flow phantom, computational fluid dynamics simulations, healthy human subjects, and small number of patients have been previously described (10 –12). Briefly, intracranial compliance (defined as the ratio of volume and pressure change, dV/dP) is calculated from measurements of the small phasic change in the intracranial volume and pressure that occur naturally with each heartbeat due to the pulsatile nature of the blood flow (10). This approach is analogous to the invasive pressure-volume response method for measurement of ICC proposed by Marmarou et al (13), whereby a known small volume of fluid is injected into the CSF space causing a temporary increase in ICP. ICC is then calculated from the ratio of the injected volume and the pressure change.

With the MRI method, intracranial volume change (ICVC) during the cardiac cycle is measured noninvasively from the point-by-point difference between arterial blood inflow, venous blood outflow, and CSF volumetric flow rates into and out of the cranial vault, as described in Eq. [1] and the condition described by Eq. [2]:

\[
\text{ICVC}(t) = |Q_A(t) - Q_V(t) - Q_{CSF}(t)| \Delta t \tag{1}
\]

\[
\text{ICVC}(T) = \sum_{\text{Cardiac cycle}} |Q_A(t) - Q_V(t) - Q_{CSF}(t)| \Delta t = 0 \tag{2}
\]

where \(Q_A(t)\) is the arterial volumetric inflow rate, \(Q_V(t)\) is the venous volumetric outflow rate, \(Q_{CSF}(t)\) is the rate of CSF oscillatory volumetric flow through the foramen magnum, and \(T\) is the time period of one cardiac cycle. Equation [2] formulates the condition of constant (i.e., zero change) cardiac cycle-averaged intracranial volume. The pressure change during the cardiac cycle is calculated from the amplitude of the CSF pressure gradient waveform, which is obtained using the Navier Stokes relationship between spatial and temporal derivatives of the CSF velocities and the pressure gradient, as previously described by Urchuk and Plewes (14). A mean ICP (MR-ICP) value is then derived based on a linear relationship that exists between the intracranial elastance (the inverse of compliance) and ICP (13). The maximal ICVC during the cardiac cycle, an intracranial

Figure 2. MR venography of the neck veins from one of the subjects obtained in the supine (left) and upright (right) postures. MIPs are shown at the top, and one of the axial source images is shown at the bottom. Both the right and left jugular veins (white arrow heads) are visualized in the supine position, while in the upright posture the left IJV is fully collapsed and the right IJV (arrow head) is nearly fully collapsed. The venous drainage in the upright posture is redistributed to the epidural, vertebral, and deep cerebral veins (white arrows).

Figure 3. One of the high-VENC phase-contrast MR images obtained in the supine (left) and upright (right) postures. Black pixels indicate inflow into the cranium (arteries) and white pixels indicate outflow (veins). In the supine posture, the dominant venous drainage is through the jugular veins (arrow heads), and in the upright posture the dominant flow is through the vertebral veins (white arrows).
compliance index, and the MR-ICP value at the two postures were calculated for each subject. The averages and standard deviations (SDs) of these parameters, and the percentage change in these parameters between the two postures were then obtained to determine statistical significance.

**Statistical Testing**

The statistical significance of differences in the hemodynamic and hydrodynamic parameters between the two postures were calculated using a single-tailed, paired t-test, with $P < 0.05$ considered to indicate a statistically significant difference. The test was implemented using the standard t-test worksheet function in Microsoft Excel 2002.

**RESULTS**

A shift of the venous outflow from the IJVs to secondary venous pathways, which is associated with complete or partial collapse of the IJVs, occurred in the upright posture. There was a total bilateral collapse of the IJVs in three of the subjects, while only the nondominant IJV collapsed in five of the subjects. In the other two subjects, only a partial bilateral collapse occurred. The TOF MR images of the neck veins obtained from one of the subjects at the two postures are shown in Fig. 2. The maximum intensity projection (MIP) 3D reconstructions and the raw images shown demonstrate differences in venous outflow between the supine and sitting postures. In the supine position, the flow is primarily through the IJVs, while in the upright posture the IJVs are collapsed and drainage occurs through secondary veins. In the example shown, only the upright position shows measurable venous outflow in the epidural veins, vertebral veins, and deep cervical veins. The corresponding high-VENC phase-contrast images from the same subject are shown in Fig. 3. In these images, white pixels represent velocity in the craniocaudal direction (i.e., venous flow) and black pixels represent flow in the opposite direction (i.e., arterial flow). In the supine position high flow velocities are seen mainly in the IJVs, while in the sitting posture high flow velocities are seen mainly in the vertebral veins. An example of the low-VENC phase-contrast images used to quantify CSF flow and venous flow through the epidural veins is shown in Fig. 4. This image demonstrates the significant increase in venous flow velocities through the epidural veins and reduced CSF flow velocities during the upright position compared to the supine position.

A lower tCBF was measured in the sitting posture in each of the 10 subjects. The average and SD of the tCBF in the supine and upright postures were $825 \pm 166$ and $724 \pm 127$ mL/minute, respectively. The mean and SD percentage reduction in tCBF was $12\% \pm 7\%$. The average and SD of mean venous flow through the IJVs in the supine and upright postures were $614 \pm 143$ and $304 \pm 261$ mL/minute, respectively. The percentage of the venous drainage through the IJVs in the supine and upright positions were $75\% \pm 14\%$ and $42\% \pm 34\%$, respectively.

Waveforms of VFR of arterial inflow and venous outflow from one of the subjects are shown in Fig. 5. Arterial inflow (open circles) and venous outflow (filled circles) during the cardiac cycle in the supine position are shown on the left and in the sitting position on the right. The arterial VFRs are slightly lower in the sitting pos-

![Figure 4](image1.png)

**Figure 4.** Low-velocity-encoding MR phase images obtained in the supine (left) and upright (right) postures. The images demonstrate flow during the systolic phase where CSF flows into the spinal canal (white pixels are velocity in the cranio-caudal direction). The CSF space (arrow) and the epidural veins (arrow heads) are in the center of the image. CSF flow velocities are higher in the supine position (left) and venous flow through the epidural veins is significantly larger in the sitting posture (right).

![Figure 5](image2.png)

**Figure 5.** MRI-based measurements of the arterial inflow (open circles) and venous outflow (filled circles) volumetric flow waveforms during the cardiac cycle in the supine (left) and sitting (right) postures. Note the slightly lower arterial flow rates in the sitting position. The amplitude of the arterial waveform at the two postures is similar. In contrast, the amplitude of the venous flow is much smaller (less pulsatile flow) at the upright posture due to higher cerebral vascular compliance.
ture. However, the overall shape (dynamics) and amplitude (the difference between the maximum and the minimum) in the two postures are similar. In contrast, the shape and the amplitude of the venous flow differ considerably between the two postures: the venous flow is much less pulsatile and the systolic peak is further delayed with respect to the arterial peak in the upright position.

Waveforms of the CSF flow in the two postures are shown in Fig. 6. The CSF flow waveforms are plotted together with the net transcranial blood flow (arterial-venous (A-V)) to demonstrate how the CSF flow is driven by the net blood flow. Note that in the supine position the CSF flow waveform “follows” the A-V flow waveform more closely—an indication of a lower intracranial compliance.

The intersubjects average and SD of the tCBF, venous outflow through the IJVs, the oscillatory CSF volume, maximum ICVC during the cardiac cycle, intracranial compliance index, and derived MR-ICP values are summarized in Table 1. Compared with the supine position, in the sitting position, on average, the oscillatory CSF volume is smaller by a factor of 2.4, the ICVC is larger by a factor of 1.8, the intracranial compliance is larger by a factor of 2.8, and the MR-ICP is lower by a factor of 2.4. All these changes are statistically significant at a P-value of 0.002 or smaller.

**DISCUSSION**

A comprehensive characterization of the cerebral hemodynamics, venous outflow, and intracranial hydrodynamics in healthy subjects in the supine and sitting positions was performed using a vertical gap MRI scanner. Statistically significant differences between the supine and sitting positions were documented and quantified. On average, approximately 50% of the venous outflow through the IJVs in the supine position shifts to secondary venous channels (e.g., epidural, vertebral, and deep cervical veins in the sitting position), while overall venous outflow is reduced by only 12% (in steady state, the total venous outflow equals the tCBF). These results are not in agreement with previously reported results of an approximately 75% reduction in total venous outflow and 90% reduction in venous flow through the IJVs in the sitting posture (4). This difference can be explained by the large intersubject variability in venous drainage distribution and the better reproducibility and accuracy of MRI-based VFR measurements.

The relationship between the dynamics of the venous outflow and the arterial inflow is influenced by the biomechanical state of the cerebrovascular system. A significant decrease in the pulsatility of the venous outflow was found, while the pulsatility of the arterial inflow was relatively unchanged. Since the cerebrovascular compartment can be regarded as the conduit for the blood flow through the brain, an increase in the conduit’s compliance will result in a larger attenuation of the flow pulsatility (i.e., less pulsatile venous outflow), as illustrated in Fig. 7. The most likely cause for increased cerebrovascular compliance is a reduction in the volume of blood that resides in the cerebral vasculature in the upright posture, since gravity preferentially redistributes blood volume to the lower part of the body.

The effect of body posture on the intracranial hydrodynamics is dramatic. The differences between the supine and upright postures include a 1.8-fold increase in the ICVC, a 2.4-fold reduction in the CSF oscillatory volume, and a large increase (2.8-fold) in the intracranial compliance index with a corresponding decrease in pressure. All of these changes are consistent with a more compliant intracranial compartment in the upright posture. Since ICP and intracranial elastance are an exponential function of intracranial volume (13), a reduction in intracranial volume results in reduced elastance (increased compliance). Therefore, increased ICC with corresponding decrease in ICP implies that smaller amounts of blood and CSF reside in their respective intracranial compartments, in the upright posture.

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Supine (Mean ± SD)</th>
<th>Upright (Mean ± SD)</th>
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<tbody>
<tr>
<td>tCBF (mL/minute)</td>
<td>825 ± 166</td>
<td>724 ± 127</td>
</tr>
<tr>
<td>Venous flow in IJVs (mL/minute)</td>
<td>614 ± 143</td>
<td>304 ± 261</td>
</tr>
<tr>
<td>Venous pulsatility index</td>
<td>0.61 ± 0.15</td>
<td>0.35 ± 0.10</td>
</tr>
<tr>
<td>Osc. CSF volume (mL)</td>
<td>0.55 ± 0.12</td>
<td>0.23 ± 0.11</td>
</tr>
<tr>
<td>Max. ICVC (mL)</td>
<td>0.48 ± 0.15</td>
<td>0.89 ± 0.44</td>
</tr>
<tr>
<td>Intracranial compliance index</td>
<td>7.3 ± 2.6</td>
<td>20.2 ± 10.7</td>
</tr>
<tr>
<td>MR-ICP (mmHg)</td>
<td>10.6 ± 3.6</td>
<td>4.5 ± 1.82</td>
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*All differences are statistically significant with a P value of 0.002 or smaller.*
The increased ICC in the upright posture is also consistent with the larger amplitude of the net transcranial blood flow (A-V) in the sitting position than in the supine position (Fig. 6). This is the result of the reduced pulsatility of the venous outflow along with a relatively unchanged arterial inflow dynamics. A larger net transcranial blood flow results in a larger increase in blood volume during the systolic phase. However, because of reduced volumes of blood and CSF in the cranial vault in the sitting position, the blood entering the cranium during the systolic phase can be more easily accommodated even with less CSF being displaced into the spinal canal. The combination of a smaller amount of CSF that leaves the cranium with each cardiac cycle, and a larger net transcranial inflow explains the larger maximal ICVC measured in the sitting position.

MRI-based measurements of CSF and blood flow dynamics provide a clearer picture of posture-related changes in the intracranial physiology. An accepted textbook explanation for a lower ICP in an upright posture is that "venous flow is increased in that position and this avoids compression of the jugular veins" (15). Since in steady state the mean venous outflow equals the mean arterial inflow, the total venous outflow (as is the tCBF) is actually slightly reduced in the upright posture. The increases in ICC and corresponding lower ICP in the upright position are therefore most likely the result of a lower mean intracranial volume caused by reduced volumes of CSF and blood in the cranium. A shift of both blood and CSF out of the cranium occurs during the transition from the supine to the upright position.

The ability to noninvasively quantify the effect of posture on intracranial physiology may lead to the development of new diagnostic tests to evaluate functions such as regulation of CBF and ICP, and the effect of pathologies on these functions. There is already evidence for abnormal venous drainage (e.g., predominantly nonjugular venous drainage with partial or complete IJVs collapse in the supine position) in idiopathic intracranial hypertension patients (16). Therefore, the role played by posture-related changes in venous drainage, and how they may relate to hemodynamic and hydrodynamic changes in both healthy and disease states need to be further evaluated. MRI studies of posture-related neurophysiologic changes may potentially augment anatomical findings with important physiological parameters for a more complete, noninvasive picture of cerebral physiology.

REFERENCES