MRI-Based Assessment of Acute Effect of Head-Down Tilt Position on Intracranial Hemodynamics and Hydrodynamics

Shota Ishida, MS,[1,2] Tosiaki Miyati, PhD, DMSc,[1]* Naoki Ohno, PhD,[1] Shinnosuke Hiratsuka, MS,[3] Noam Alperin, PhD,[4] Mitsuhito Mase, MD, PhD,[5] and Toshifumi Gabata, MD, PhD[6]

Purpose: To quantify the acute effect of the head-down tilt (HDT) posture on intracranial hemodynamics and hydrodynamics.

Materials and Methods: We evaluated the intracranial physiological parameters, blood flow-related parameters, and brain morphology in the HDT (–6° and –12°) and the horizontal supine (HS) positions. Seven and 15 healthy subjects were scanned for each position using 3.0 T magnetic resonance imaging system. The peak-to-peak intracranial volume change, the peak-to-peak cerebrospinal fluid (CSF) pressure gradient ($PG_{p\text{-}p}$), and the intracranial compliance index were calculated from the blood and CSF flow determined using a cine phase-contrast technique. The brain volumetry was conducted using SPM12. The measurements were compared using the Wilcoxon signed-rank test or a paired *t*-test.

Results: No measurements changed in the –6° HDT. The $PG_{p\text{-}p}$ and venous outflow of the internal jugular veins (IJVs) in the –12° HDT were significantly increased compared to the HS ($P < 0.001$ and $P = 0.025$, respectively). The cross-sectional areas of the IJVs were significantly larger ($P < 0.001$), and the maximum, minimum, and mean blood flow velocity of the IJVs were significantly decreased ($P = 0.003$, < 0.001, and $= 0.001$, respectively) in the –12° HDT. The mean blood flow velocities of the internal carotid arteries were decreased ($P = 0.023$). Neither position affected the brain volume.

Conclusion: Pressure gradient and venous outflow were increased in accordance with the elevation of the intracranial pressure as an acute effect of the HDT. However, the CSF was not constantly shifted from the spinal canal to the cranium.

Level of Evidence: 2

Technical Efficacy: Stage 1

J. MAGN. RESON. IMAGING 2018;47:565–571.

Invasive procedures are typically used for monitoring the intracranial physiology despite the risk of complications and morbidity.[1,2] Magnetic resonance imaging (MRI)-based techniques can noninvasively provide physiological information on the brain, such as cerebral blood flow (CBF).[3] Flow measurements using phase-contrast (PC) MRI may quantitatively assess intracranial physiological parameters, such as the intracranial volume change (ICVC), the cerebrospinal fluid (CSF) pressure gradient (PG), and the intracranial compliance index (ICCI). Previous reports using PC cine MRI showed that the intracranial biomechanical properties were altered in patients with idiopathic normal pressure hydrocephalus,[4–6] Chiari malformation,[7] and idiopathic intracranial hypertension.[8]

Intracranial hydrodynamics and cerebral hemodynamics are strongly affected by body posture due to gravitational hydrostatic pressure changes.[9,10] Notably, most neuroradiological examinations are conducted in patients in a horizontal supine position (HS). However, cephalad fluid shifts are driven by a loss of the hydrostatic pressure in the head-

View this article online at wileyonlinelibrary.com. DOI: 10.1002/jmri.25781

Received Feb 14, 2017, Accepted for publication May 18, 2017.

*Address reprint requests to: T.M., Division of Health Sciences, Graduate School of Medical Sciences, Kanazawa University, 5-11-8, Kodatsuno, Kanazawa, Ishikawa, 920-0942, Japan. E-mail: ramiyati@mhs.mp.kanazawa-u.ac.jp

From the [1]Division of Health Sciences, Graduate School of Medical Sciences, Kanazawa University, Ishikawa, Japan; [2]Radiological center, University of Fukui Hospital, Fukui, Japan; [3]Department of Radiology, Shiga University of Medical Science Hospital, Shiga, Japan; [4]Department of Radiology, University of Miami, Miami, Florida, USA; [5]Department of Neurosurgery and Restorative Neuroscience, Graduate School of Medical Sciences, Nagoya City University, Aichi, Japan; and [6]Department of Radiology, Kanazawa University Hospital, Ishikawa, Japan.

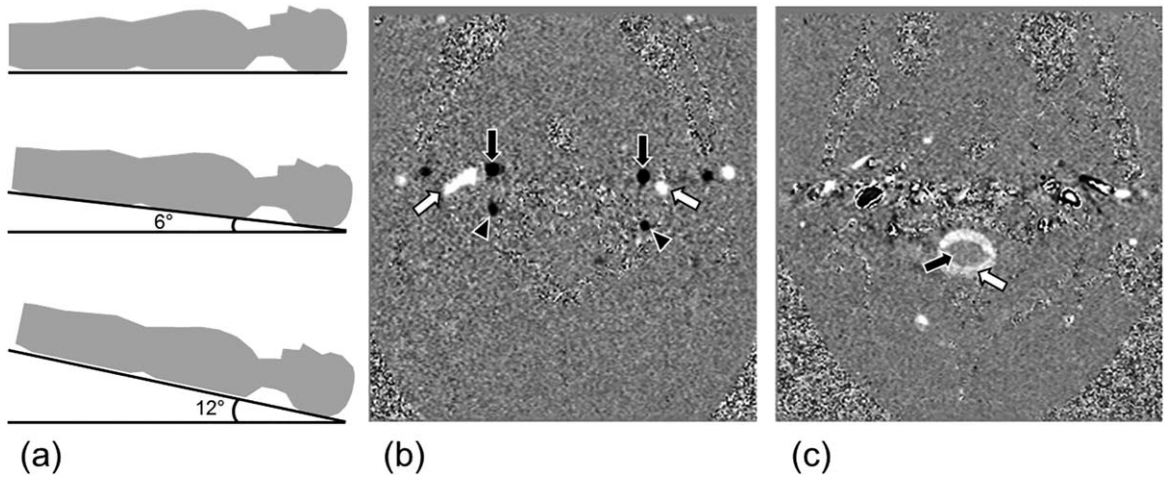

FIGURE 1: Schematic diagrams of the three different tilt angle positions and velocity-mapped phase images: (a) horizontal supine position (top), slight head-down tilt position (middle), and moderate head-down tilt position (bottom), (b) velocity-mapped phase image with a VENC of 90 cm/s for blood flow, and (c) VENC of 7 to 10 cm/s for CSF flow measurements. (b) ICA = internal carotid artery (black arrow), VA = vertebral artery (black arrowhead), IJV = internal jugular vein (white arrow); and (c) CSF (white arrow), cord (black arrow).

down tilt position (HDT).[11] An HDT, in which the physiological responses are similar to those in microgravity environments, is exploited for the ground-based evaluation of intracranial conditions in space.[11] A previous report using sonography showed that the cross-sectional area (CSA) in the right internal jugular vein (IJV) was significantly increased in the HDT position.[12] Sun et al reported that CBF velocity was decreased in the HDT.[13] A recent study reported that cerebral hemodynamics changed during an HDT using PC MRI.[14] MRI-based measurements enabled us to noninvasively observe the posture-related changes in the intracranial physiology. Furthermore, the HDT is easily implemented inside of the bore of a general MRI scanner. While cerebral hemodynamics, intracranial hydrodynamics, brain tissue volumes, and brain morphology are linked to one another,[15] these parameters have been separately studied and reported. CSF flow dynamics in the HDT have not been previously investigated. We hypothesized that a comprehensive MRI-based assessment of intracranial physiology associated with the HDT will provide more detailed information on the biodynamical faculties of the brain.

Materials and Methods

Subjects and Data Acquisition

This prospective study was approved by our Institutional Review Board. All data acquisitions and analyses were performed in healthy male volunteers with no known history of neurological disease. The purpose and procedures of our investigation were fully explained to all subjects, and the study was performed only after we obtained informed consent from each volunteer.

We used three different tilt angle positions, ie, HS of 0°, a slight HDT (sHDT) of –6°, and a moderate HDT (mHDT) of –12° (Fig. 1a). The subjects were scanned using the following pulse sequences immediately after a posture change to the sHDT or mHDT from the HS.

On a 3.0 T MRI (Signa HDxt, GE Healthcare, Milwaukee, WI), the retrospective electrocardiogram-synchronized PC cine MRI was used to obtain transcranial blood flow, CSF flow, and spinal cord displacement in each tilt angle position (seven men in the sHDT study, 23 ± 1 years; 15 men in the mHDT study, 23 ± 1 years). A transverse imaging plane was set perpendicular to the flow direction at the mid C2 level. PC MRI was performed using the following parameters: repetition time (TR) 11 msec, echo time (TE) 4 msec, slice thickness 5 mm, field of view (FOV) 140 mm, matrix size 256, flip angle (FA) 20°, and number of signal averaged (NSA) 1. The velocity encoding (VENC) was set at 90 cm/s for blood flow and 7–10 cm/s for CSF flow. Subsequently, 3D fast spoiled gradient-echo (3D-FSPGR) was performed with a TR 6.8–7.0 msec, TE 2.5 msec, slice thickness 1 mm, FOV 230–256 mm, matrix size 256, FA 12°, and NSA 1 (seven men in the sHDT study, 23 ± 1 years; eight men in the mHDT study, 23 ± 1 years).

Calculation of Intracranial Physiological Parameters

We used pulsatility-based segmentation[16] to automatically delineate the lumen boundaries of the internal carotid arteries (ICAs), vertebral arteries (VAs), and IJVs on velocity-mapped phase images (Fig. 1b,c). The *ICVC* was calculated using Eqs. (1) and (2):

$$ICVC(t) = [Q_A(t) - Q_V(t) - Q_{CSF}(t)]\Delta t \quad (1)$$

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

where Q_A(t) is the arterial volumetric flow rate, Q_V(t) is the venous volumetric flow rate, Q_{CSF}(t) is the CSF oscillatory flow, and T is the time period of one cardiac cycle.

The peak-to-peak *ICVC* during the cardiac cycle ($ICVC_{p\text{-}p}$) was calculated from Eq. (3):

$$ICVC_{p-p} = ICVC_{max} - ICVC_{min} \quad (3)$$

where the $ICVC_{max}$ and $ICVC_{min}$ are the maximum and minimum *ICVC* during the cardiac cycle, respectively.

Next, we assumed that CSF is a Newtonian fluid, and calculated the craniospinal CSF *PG* during the cardiac cycle from a simplified Navier-Stokes equation[17]:

$$PG = -\rho\left(\frac{\partial V}{\partial t} + V \cdot \nabla V\right) + \mu \cdot \nabla^2 V \quad (4)$$

where ρ is the fluid density (1.0007 g/cm^3), μ is the fluid viscosity (1.1 cP), and V is the velocity vector. To correct for the loss of pressure derived from the difference in cross-sectional flow area, *PG* was normalized by multiplying by the CSF flow area. The peak-to-peak *PG* (PG_{p-p}) was calculated from Eq. (5):

$$PG_{p-p} = PG_{max} - PG_{min} \quad (5)$$

where the PG_{max} and PG_{min} are the maximum and minimum *PG* during the cardiac cycle, respectively.

Finally, the *ICCI* was calculated from Eq. (6):

$$ICCI = ICVC_{p-p}/PG_{p-p} \quad (6)$$

In addition to these parameters, we also evaluated the CSA and blood flow velocity of the aforementioned vessels.

All statistical analyses were performed using SPSS for Windows, v. 23.0 (Chicago, IL). The Wilcoxon signed-rank test was used for statistical comparisons in the sHDT study. In the mHDT study, the intracranial physiological and blood flow parameters were assessed using a paired *t*-test. A *P*-value < 0.05 was defined as statistically significant.

Data Analysis of Voxel-Based Morphometry

We used SPM12 software for voxel based morphometry (VBM) analysis.[18] First, a bias correction was computed for the 3D-FSPGR images. The corrected images were segmented into gray matter (GM), white matter (WM), and CSF. A study-specific template was created using the Diffeomorphic Anatomical Registration using Exponentiated Lie Algebra algorithm.[19] The images were transformed to the Montreal Neurological Institute space, and smoothing was performed using an 8 mm full-width at half-maximum (FWHM) Gaussian kernel. The spatially normalized images were modulated by multiplying the relative volumes derived from the Jacobian determinant. After modulation, the GM, WM, and CSF volumes were computed. We calculated the total intracranial volume (TIV) by summing each brain compartment volume. Whole-tissue volumes of each brain compartment were compared by the Wilcoxon signed-rank test. Region-wise volumetric comparisons between the groups were statistically performed using a paired *t*-test. $P < 0.05$ was considered statistically significant.

Results

None of the intracranial physiological and blood flow parameters showed significant differences between the sHDT and the HS ($n = 7$; Table 1). All nonsignificant *P*-values were as follows: $P = 0.611$ for tCBF; $P = 0.866$ for venous outflow of IJVs; $P = 0.866$ for CSF stroke volume; $P = 0.866$ for systolic CSF velocity; $P = 0.176$ for PG_{p-p}; $P = 0.112$ for $ICVC_{p-p}$; $P = 0.866$ for *ICCI*; $P = 0.499$, $= 0.063$, $= 0.176$ for maximum blood flow velocity of the ICAs, VAs, and IJVs, respectively; $P = 0.735$, $= 0.735$, $= 0.091$ for minimum blood flow velocity of the ICAs, VAs, and IJVs, respectively; $P = 1.000$, $= 0.612$, $= 0.176$ for mean blood flow velocity of the ICAs, VAs, and IJVs, respectively; and $P = 0.612$, $= 0.176$, $= 0.128$ for the CSA of the ICAs, VAs, and IJVs, respectively.

In contrast, the PG_{p-p} in the mHDT ($7.9 \pm 2.5 \times 10^{-2}$ mmHg·cm) was significantly higher when compared to the HS ($6.4 \pm 2.3 \times 10^{-2}$ mmHg·cm; $P < 0.001$). The venous outflow of the IJVs was significantly increased in the mHDT (543 ± 92 mL/min) compared with the HS (459 ± 174 mL/min; $P = 0.025$). The mean blood flow velocity of the ICAs in the mHDT (11.1 ± 1.3 cm/s) was significantly decreased when compared to the HS (11.9 ± 1.6 cm/s; $P = 0.023$). The maximum, minimum, and mean blood flow velocity of the IJVs were significantly decreased in the mHDT ($P = 0.003$, < 0.001, $= 0.001$, respectively), whereas the CSA of the IJVs was significantly larger in the mHDT (0.54 ± 0.21 cm^2) compared to the HS (0.36 ± 0.20 cm^2; $P < 0.001$). None of the other parameters significantly varied between the mHDT and the HS ($n = 15$; Table 1). All nonsignificant *P*-values were as follows: $P = 0.566$ for tCBF; $P = 0.138$ for CSF stroke volume; $P = 0.260$ for systolic CSF velocity; $P = 0.289$ for $ICVC_{p-p}$; $P = 0.673$ for *ICCI*; $P = 0.096$, $= 0.585$ for maximum blood flow velocity of the ICAs and VAs, respectively; $P = 0.143$, $= 0.263$ for minimum blood flow velocity of the ICAs and VAs, respectively; $P = 0.188$ for mean blood flow velocity of the VAs; $P = 0.135$, $= 0.653$ for the CSA of the ICAs and VAs, respectively.

For both datasets, there were no significant differences in any of the whole-tissue volumes of each brain compartment or TIV (Table 2). *P*-values for the sHDT study ($n = 7$) were as follows: $P = 0.735$ for GM volume, $P = 0.612$ for WM volume, $P = 0.499$ for CSF volume, and $P = 0.499$ for TIV. The results of the statistical tests for the mHDT ($n = 8$) study were as follows: $P = 0.889$ for GM volume, $P = 0.889$ for WM volume, $P = 0.674$ for CSF volume, and $P = 0.674$ for TIV.

There were no statistical differences between the region-wise measured tissue volumes for both datasets.

Discussion

None of the intracranial physiological or blood flow parameters were significantly changed in the sHDT condition. We assessed the intracranial physiological parameters immediately after a position change. The loading induced by lowering the head did not exceed the intracranial compensatory faculties, due to the low tilt angle and extremely short

TABLE 1. Intracranial Physiological and Blood Flow Parameters Obtained in the Horizontal Supine Position (HS) and the Head-Down Tilt (HDT) Positions

	HS		HDT	P-value
tCBF (mL/min)	HS = 750 ± 145	v.s.	sHDT = 716 ± 128	0.611
	HS = 722 ± 103	v.s.	mHDT = 712 ± 82	0.566
Venous outflow of IJVs (mL/min)	HS = 514 ± 259	v.s.	sHDT = 508 ± 178	0.866
	HS = 459 ± 174	v.s.	mHDT = 543 ± 92	0.025
CSF stroke volume (mL/cc)	HS = 0.53 ± 0.27	v.s.	sHDT = 0.66 ± 0.48	0.866
	HS = 0.61 ± 0.17	v.s.	mHDT = 0.56 ± 0.12	0.138
Systolic CSF velocity (cm/s)	HS = 2.35 ± 0.88	v.s.	sHDT = 2.38 ± 0.79	0.866
	HS = 2.29 ± 0.68	v.s.	mHDT = 2.47 ± 0.90	0.260
$PG_{P\text{-}P}$ (mmHg·cm)	HS = 0.077 ± 0.034	v.s.	sHDT = 0.069 ± 0.026	0.176
	HS = 0.064 ± 0.023	v.s.	mHDT = 0.079 ± 0.025	< 0.001
$ICVC_{P\text{-}P}$ (mL)	HS = 0.67 ± 0.35	v.s.	sHDT = 0.62 ± 0.36	0.112
	HS = 0.54 ± 0.15	v.s.	mHDT = 0.61 ± 0.24	0.289
ICCI (mL/mmHg·cm)	HS = 10.0 ± 6.9	v.s.	sHDT = 10.1 ± 7.7	0.866
	HS = 9.2 ± 3.7	v.s.	mHDT = 8.7 ± 4.5	0.673
Maximum blood flow velocity (cm/s)				
ICAs	HS = 21.3 ± 4.5	v.s.	sHDT = 20.4 ± 3.3	0.499
	HS = 20.1 ± 2.8	v.s.	mHDT = 19.5 ± 2.2	0.096
VAs	HS = 13.0 ± 1.3	v.s.	sHDT = 12.0 ± 1.4	0.063
	HS = 12.8 ± 1.9	v.s.	mHDT = 12.6 ± 1.5	0.585
IJVs	HS = 29.4 ± 10.5	v.s.	sHDT = 25.9 ± 11.5	0.176
	HS = 32.0 ± 10.9	v.s.	mHDT = 26.5 ± 8.9	0.003
Minimum blood flow velocity (cm/s)				
ICAs	HS = 8.3 ± 1.6	v.s.	sHDT = 8.3 ± 1.2	0.735
	HS = 8.0 ± 1.3	v.s.	mHDT = 7.5 ± 1.1	0.143
VAs	HS = 4.4 ± 0.7	v.s.	sHDT = 4.5 ± 0.8	0.735
	HS = 4.3 ± 1.0	v.s.	mHDT = 4.1 ± 0.9	0.263
IJVs	HS = 18.3 ± 8.8	v.s.	sHDT = 15.3 ± 9.3	0.091
	HS = 17.6 ± 7.5	v.s.	mHDT = 11.7 ± 5.8	< 0.001
Mean blood flow velocity (cm/s)				
ICAs	HS = 12.1 ± 2.4	v.s.	sHDT = 11.9 ± 2.4	1.000
	HS = 11.9 ± 1.6	v.s.	mHDT = 11.1 ± 1.3	0.023
VAs	HS = 7.0 ± 0.9	v.s.	sHDT = 6.9 ± 1.0	0.612
	HS = 4.3 ± 1.0	v.s.	mHDT = 4.1 ± 0.9	0.188
IJVs	HS = 24.0 ± 8.8	v.s.	sHDT = 20.8 ± 10.2	0.176
	HS = 25.2 ± 10.9	v.s.	mHDT = 19.1 ± 7.2	0.001
CSA (cm^2)				
ICAs	HS = 0.38 ± 0.04	v.s.	sHDT = 0.37 ± 0.05	0.612
	HS = 0.38 ± 0.06	v.s.	mHDT = 0.40 ± 0.06	0.135

TABLE 1: Continued

	HS		HDT	P-value
VAs	HS = 0.24 ± 0.05	v.s.	sHDT = 0.23 ± 0.05	0.176
	HS = 0.23 ± 0.05	v.s.	mHDT = 0.23 ± 0.04	0.653
IJVs	HS = 0.39 ± 0.18	v.s.	sHDT = 0.48 ± 0.23	0.128
	HS = 0.36 ± 0.20	v.s.	mHDT = 0.54 ± 0.21	< 0.001

Mean ± standard deviation are shown for each value, tCBF = total cerebral blood flow, IJV = internal jugular vein, CSF = cerebrospinal fluid, PG = pressure gradient, ICVC = intracranial volume change, ICCI = intracranial compliance index, ICAs = internal carotid arteries, VAs = vertebral arteries, IJVs = internal jugular veins, CSA = cross-sectional area.

duration exposure. In contrast to our results, a recent report documented that the CBF and the venous outflow of the IJVs were decreased after 4.5 hours in a –6° HDT.[14] According to these results, the duration of the posture may be a profound factor when investigating the effects of a low-angle HDT on the intracranial condition.

The $PG_{p\text{-}p}$ in the mHDT was significantly larger than that in the HS, as lowering the head altered the gravitational hydrostatic pressure gradient. We deduced that the increase in *PG* in the mHDT indicated an elevation of intracranial pressure in accordance with the law of fluid mechanics and not derived from a cephalad fluid shift.[20,21] The *PG* is the most sensitive to postural changes of the intracranial physiological parameters. Therefore, the CSF dynamics associated with posture is the most important factor to evaluate the acute effects of a HDT. Our brain volume measurement of each tissue compartment results also support this inference, since the whole-tissue volumes of each brain compartment and the TIV were not significantly different between the positions. Due to the stiffness and lack of distensibility of dura mater and the fixation to the skull, the intradural volume was unchangeable.[21] However, a temporal change (in a unit of a second or millisecond) of the intracranial volume was observed due to the pulsatile arterial flow into the cranium during the cardiac cycle.[22] The intracranial volume was transiently altered during the cardiac cycle, indicating some possibility that a cephalad fluid shift is caused by the larger tilt angles and/or long-term exposure to the HDT. Further investigations should explore these effects on intracranial conditions.

Venous outflow of the IJVs was significantly increased in the HDT. The IJVs are the main pathway for venous outflow in the supine position[23]; however, the IJVs also play a predominant role in cerebrovenous drainage immediately after a change in posture to the mHDT. The total venous outflow may have remained unchanged, since the tCBF, CSF stroke volume, and *ICVC* were not significantly different. Therefore, a significant increase in the venous outflow of the IJVs represents a shift of the venous pathway in response to a postural change. Furthermore, a significant increase in the CSA in the IJVs demonstrated the compliant nature of the venous system. The increase in *PG* in the HDT was regulated by dilation of the IJVs, which are more compliant than secondary venous pathways (eg, vertebral, epidural, and deep cervical veins). This vasodilation induced a decrease in venous velocity via the Venturi effect. Thus,

TABLE 2. Tissue Volume of Each Brain Compartment and the Total Intracranial Volume (TIV) in the Horizontal Supine Position (HS) and the Head-Down Tilt (HDT) Positions

	HS		HDT	*P-value*
GM (mL)	HS = 802 ± 55	v.s.	sHDT = 803 ± 58	0.735
	HS = 792 ± 38	v.s.	mHDT = 792 ± 40	0.889
WM (mL)	HS = 488 ± 46	v.s.	sHDT = 487 ± 43	0.612
	HS = 484 ± 34	v.s.	mHDT = 485 ± 36	0.889
CSF (mL)	HS = 319 ± 54	v.s.	sHDT = 321 ± 58	0.499
	HS = 311 ± 40	v.s.	mHDT = 310 ± 40	0.674
TIV (mL)	HS = 1609 ± 130	v.s.	sHDT = 1611 ± 130	0.499
	HS = 1588 ± 71	v.s.	mHDT = 1588 ± 72	0.674

Mean ± standard deviation are shown for each value, GM = gray matter, WM = white matter, CSF = cerebrospinal fluid, TIV = total intracranial volume.

the venous system played a major role in the compensation for the increase in *PG* immediately after a change in posture to the HDT, ie, the sudden change in intracranial condition. In contrast to our results, a previous study showed that venous outflow of the IJVs was decreased after 4.5 hours in the –12° HDT.[14] This discrepancy indicates the importance of a time-dependency effect of the HDT.

In agreement with the previous study,[14] the mean blood flow velocity in the mHDT was significantly decreased when compared to the HS. There are many reports on the CBF and blood flow velocity in the HDT; however, the results of posture-related blood flow analyses are inconsistent. It is difficult to interpret these previous reports due to diverse bias factors, eg, measured vessel location, procedure, tilt angle, and duration in the HDT.[13,24–26] On the basis of our results, we speculate that the ICAs have a higher reactivity to posture changes than the VAs. Despite the significant increase in mean blood flow velocity of the ICAs, the tCBF was not significantly affected.

Our brain morphological analyses using SPM12 showed no differences between the positions. The VBM analyses revealed that brain morphology was not significantly affected by the postural changes. A previous study reported that brain morphology was altered after 3 hours in parabolic flight,[27] indicating that larger loading may affect brain morphology. However, the increase in *PG* associated with a brief exposure to the HDT was not enough to alter brain morphology.

Our study has several limitations. First, the study population was small, and all participants were adult males in a narrow age range. A larger study population would enable us to demonstrate more rigorous statistical analyses. Intracranial physiology shows sexual specificity and age dependence[28]; therefore, further evaluations are needed with a larger sample size, female subjects, and a wider age range. Second, the subjects in each study group were not exactly the same, biasing the observation of the present study. However, we believe that this problem in the study design had a small effect on the measurements, since the majority of each group was similar. Future studies should be performed on a single group of participants. We only evaluated the intracranial condition after a brief exposure to the HDT, ie, an acute effect. Hence, time-dependency and long-term exposure to the HDT, ie, a chronic effect, should be assessed. Furthermore, separation of the acute and chronic effects associated with the HDT is indispensable to obtain more detailed information on the intracranial physiology related to body posture. We used two tilt angles for the HDT. Although none of the measurements were significantly changed in the sHDT, several parameters were statistically significant in the mHDT. This indicates that the intracranial physiology associated with the HDT is dependent on the tilt angle. It is necessary to identify a threshold tilt angle for physiological effects.

In this study we evaluated the intracranial physiological parameters, blood flow, brain tissue volume, and brain morphology in the HDT using two tilt angles. In conclusion, as an acute effect of the HDT, the PG and the venous outflow were increased in accordance with the elevation of intracranial pressure. However, the CSF was not constantly shifted from the spinal canal to the cranium.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number JP16K09013.

References

1. Marmarou A, Shulman K, LaMorgese J. Compartmental analysis of compliance and outflow resistance of the cerebrospinal fluid system. J Neurosurg 1975;43:523–534.
2. Sklar FH, Elashvili I. The pressure-volume function of brain elasticity. Physiological considerations and clinical applications. J Neurosurg 1977;47:670–679.
3. Alsop DC, Detre JA, Golay X, et al. Recommended implementation of arterial spin-labeled perfusion MRI for clinical applications: A consensus of the ISMRM perfusion study group and the European consortium for ASL in dementia. Magn Reson Med 2015;73:102–116.
4. Miyati T, Mase M, Banno T, et al. Frequency analyses of CSF flow on cine MRI in normal pressure hydrocephalus. Eur Radiol 2003;13:1019–1024.
5. Miyati T, Mase M, Kasai H, et al. Noninvasive MRI assessment of intracranial compliance in idiopathic normal pressure hydrocephalus. J Magn Reson Imaging 2007;26:274–278.
6. Ohno N, Miyati T, Mase M, et al. Idiopathic normal-pressure hydrocephalus: temporal changes in ADC during cardiac cycle. Radiology 2011;261:560–565.
7. Alperin N, Sivaramakrishnan A, Lichtor T. Magnetic resonance imaging-based measurements of cerebrospinal fluid and blood flow as indicators of intracranial compliance in patients with Chiari malformation. J Neurosurg 2005;103:46–52.
8. Tain RW, Bagci AM, Lam BL, Sklar EM, Ertl-Wagner B, Alperin N. Determination of cranio-spinal canal compliance distribution by MRI: Methodology and early application in idiopathic intracranial hypertension. J Magn Reson Imaging 2011;34:1397–1404.
9. Alperin N, Lee SH, Sivaramakrishnan A, Hushek SG. Quantifying the effect of posture on intracranial physiology in humans by MRI flow studies. J Magn Reson Imaging 2005;22:591–596.
10. Alperin N, Lee SH, Bagci AM. MRI measurements of intracranial pressure in the upright posture: The effect of the hydrostatic pressure gradient. J Magn Reson Imaging 2015;42:1158–1163.
11. Nelson ES, Mulugeta L, Myers JG. Microgravity-induced fluid shift and ophthalmic changes. Life (Basel) 2014;4:621–665.
12. Schreiber SJ, Lambert UK, Doepp F, Valdueza JM. Effects of prolonged head-down tilt on internal jugular vein cross-sectional area. Br J Anaesth 2002;89:769–771.
13. Sun XQ, Yao YJ, Yang CB, Jiang SZ, Jiang CL, Liang WB. Effect of lower-body negative pressure on cerebral blood flow velocity during 21 days head-down tilt bed rest. Med Sci Monit 2005;11:CR1–5.
14. Marshall-Goebel K, Ambarki K, Eklund A, et al. Effects of short-term exposure to head-down tilt on cerebral hemodynamics: A prospective evaluation of a spaceflight analog using phase-contrast MRI. J Appl Physiol (1985) 2016;120:1466–1473.

15. Ohno N, Miyati T, Chigusa T, et al. Technical note: Development of a cranial phantom for assessing perfusion, diffusion, and biomechanics. Med Phys 2017;44:1646–1654.

16. Alperin N, Lee SH. PUBS: pulsatility-based segmentation of lumens conducting non-steady flow. Magn Reaon Med 2003;49:934–944.

17. Urchuk SN, Plewes DB. MR measurements of pulsatile pressure gradients. J Magn Reson Imaging 1994;4:829–836.

18. Ashburner J, Friston KJ, Voxel-based morphometry—the methods. Neuroimage 2000;11:805–821.

19. Ashburner J. A fast diffeomorphic image registration algorithm. Neuroimage 2007;38:95–113.

20. Petersen LG, Petersen JC, Andresen M, Secher NH, Juhler M. Postural influence on intracranial and cerebral perfusion pressure in ambulatory neurosurgical patients. Am J Physiol Regul Integr Comp Physiol 2016; 310:R100–R104.

21. Klarica M, Rodoš M, Erceg G, Petošić A, Jurjević I, Orešković D. The influence of body position on cerebrospinal fluid pressure gradient and movement in cats with normal and impaired craniospinal communication. PLoS One 2014;9:e95229.

22. Alperin NJ, Lee SH, Loth F, Raksin PB, Lichtor T. MR-Intracranial pressure (ICP): a method to measure intracranial elastance and pressure noninvasively by means of MR imaging: baboon and human study. Radiology 2000;217:877–885.

23. Valdueza JM, von Münster T, Hoffman O, Schreiber S, Einhäupl KM. Postural dependency of the cerebral venous outflow. Lancet 2000;355:200–201.

24. Kawai Y, Murthy G, Watenpaugh DE, Breit GA, Deroshia CW, Hargens AR. Cerebral blood flow velocity in humans exposed to 24 h of head-down tilt. J Appl Physiol (1985) 1993;74:3046–3051.

25. Stolz E, Fox BC, Hoffmann O, et al. Cranial venous outflow under lower body positive and negative pressure conditions and head-up and -down tilts. J Neuroimaging 2009;19:31–36.

26. Pavilla A, Arrigo A, Colombani S, Mejdoubi M. Absolute and regional cerebral perfusion assessment feasibility in head-down position with arterial spin-labeling magnetic resonance. A preliminary report on healthy subjects. J Neuroradiol 2016;43:392–397.

27. Van Ombergen A, Jeurissen B, Vanhevel F, et al. A first insight in regional brain changes after parabolic flight: a voxel-based morphometry study. In: Proc 23rd Annual Meeting ISMRM, Toronto; 2015 (abstract 1258).

28. Schmid Daners M, Knobloch V, Soellinger M, et al. Age-specific characteristics and coupling of cerebral arterial inflow and cerebrospinal fluid dynamics. PLoS One 2012;7:e37502.