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Dynamic assessment of cerebral blood flow and intracranial pressure during inversion table tilt using ultrasonography

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ABSTRACT

Context: Inversion tables are used as treatment for back pain, but there is a lack of agreement on systemic effects of inversion.
Objective: To assess intracranial pressure (ICP) and cerebral blood flow using ultrasonography during inversion table tilt.
Methods: Optic nerve sheath diameter (ONSD), heart rate (HR), blood pressure, internal carotid artery (ICA) and middle cerebral artery (MCA) blood flow of participants were measured in 3 positions: supine before inversion, during inversion with head down, and supine post-inversion. ONSD was evaluated with ocular ultrasonography and blood flow (ICA and MCA) with Doppler ultrasonography.
Results: The ONSD changed significantly between the supine position, at 3 min of inversion, and after returning to supine position (all $P < .001$). The post-inversion HR was less than pre-inversion ($P = .03$) and 3-min inversion HR ($P = .003$). There were significant changes in ICA and MCA flow caused by inversion, which affected blood flow velocity, resistance, and pulsatility index (all $P \le .005$).
Conclusion: Inversion caused significant changes in ICP and blood flow. Thus, increased chance of complications may exist when using inversion as a therapeutic tool or during surgical procedures in patients with previous history of elevated ICP. These results demonstrate that inversion therapy should be used with caution.

1. Introduction

Some medical procedures require placement of the patient in an inverted or Trendelenburg position, such as inversion tables used as a treatment for back pain. These tables are designed to use gravity to create traction in the spine and pelvis, supposedly removing pressure from compressed joints, discs, and nerves [1]. Trendelenburg position is often used during surgical procedures performed laparoscopically [2].

Studies have explored the effects of inversion tables and gravity on cardiovascular and ocular systems [3,4], and results are contradictory. In one study, the inversion table was associated with elevated blood pressure, heart rate, and intraocular pressure [4], but others found no clinically significant changes in cardiovascular hemodynamics in a healthy population [3,5].

Elevated intracranial pressure (ICP), defined as ICP > 20 mmHg, is an important cause of secondary brain injury and may be associated with a poor outcome. Conditions for which ICP monitoring is important include traumatic brain injury, intracerebral hemorrhage, subarachnoid hemorrhage, hydrocephalus, benign intracranial hypertension, meningitis, stroke, acute liver failure, and others [6]. A diagnosis of elevated ICP is critical in neurological and neurosurgical patients because its early recognition prevents possible brain damage or death [7–9]. The gold standard for continuous ICP monitoring is an intraventricular catheter connected to an external pressure transducer; however, the procedure is invasive and has potential complications of infection, hemorrhage, and malfunction [10].

Bedside ocular ultrasonography has been recently identified as an alternative technique for detecting elevated ICP [11–25]. Optic nerve sheath diameter (ONSD) ultrasound may have utility as a noninvasive test of ICP in the intensive care setting or the operating room, where it

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is inconvenient to transport patients for imaging and invasive monitoring may not be possible or convenient [22]. The sensitivity of ultrasonography to identify ICP > 20 mmHg is 74%–95%, and specificity is 74%–100% [12,13,17,26,27]. Increased ICP is passed to the subarachnoid compartment of the optic nerve, causing expansion of the optic nerve sheath and increasing ONSD [28]. When ICP increases, the pressure in the optic nerve sheath increases linearly [29], causing distension [28] as early as 4 h after trauma [30]. Studies have defined normative values for the ONSD in normal adults [31,32] where the mean normal sonographic measurement of ONSD is 3.68 mm to 5.1 mm at 3 mm behind the globe.

Transcranial Doppler (TCD) ultrasound is a noninvasive technique that assesses blood flow in the circle of Willis and in the vertebrobasilar system [33]. It is used in intensive care units [34] to monitor patients with various neurosurgical and vascular disorders [35,36]. It also has practical applications in neurocritical care, such as for diagnosis and monitoring of vasospasm in patients with subarachnoid hemorrhage [37] and critical elevations of ICP [38].

In adults, TCD ultrasound studies require the use of a lower-frequency, 2–3 MHz transducer with spectral Doppler capability [33]. After fontanelle closure, the only 2 available acoustic windows in the skull are the temporal bone and the foramen magnum [39]. The transtemporal window is located at the thinnest portion of the temporal bone cephalad to the zygomatic arch and anterior to the ear. Using this window, the intracranial carotid artery (ICA) bifurcation can be identified at depths of 55 mm to 65 mm based on the direction of the blood flow. The ICA bifurcates into the anterior (flows away from the probe) and middle (flows toward the probe) cerebral arteries (MCA). The ICA terminus is a convenient anatomic landmark to locate the vessels of anterior circulation. The MCA, viewed at depths of 35 mm to 55 mm, runs laterally and slightly anterior after its origin from the ICA [40,41].

When using TCD to measure cerebral blood flow velocity, the MCA is commonly evaluated because of its insonated compliance and accessibility through the temporal window. Changes in cerebral perfusion can be evaluated using pulsatile waveform monitoring with close attention to flow velocity [42]. Although TCD is not suitable for continuous monitoring of cerebral blood flow or ICP, it is beneficial for repeated bedside evaluation, real-time measurements, and long-term patient evaluation [43].

Monitoring cerebral blood flow and peripheral cerebral resistance in the MCA after endarterectomy surgery can be used as indicators of patient outcomes [44]. Further, the MCA pulsatility index (PI), mean flow velocity (MFV), and their difference (PI – MFV) have been shown to be independent prognostic factors for recurrent vascular events, such as stroke, myocardial infarction, or vascular death in patients with a history of transient ischemic attack or non-disabling ischemic strokes [45]. TCD monitoring of ICP has acceptable accuracy for differentiating patients with an ICP > 20 mmHg and can be used to assess longitudinal changes in ICP [46].

In addition to the use of inversion for therapeutic purposes, many procedures, specifically those performed laparoscopically, require the patient to be in the Trendelenburg position [47]. In patients with known vascular disease, such as carotid artery stenosis or history of transient ischemic attack, this position could increase the risk of elevated ICP and intracranial hypertension, resulting in post-operative complications. Therefore, the current study evaluated the effects of inversion on ICP and cerebral blood flow using ultrasonography. We hypothesized that inversion therapy would be associated with an increase in ICP as indicated by ONSD measured using ultrasonography. Such information may provide important insight about the use of the Trendelenburg position or inversion table in patients with significant risk factors for cerebral and cardiovascular complications.

2. Materials and methods

Students from an osteopathic medical school participated in the current study. Participation was voluntary and was not compensated. The study protocol was approved by the local institutional review board, and participants provided written informed consent.

Participants completed an initial patient history questionnaire that asked for information about previous health history, age, and sex. Height and weight were measured at enrollment and used to calculate body mass index (BMI). Participants were excluded if they had a history of any of the following: spinal injury, herniated disk, concussion, brain injury, ocular trauma, vision disturbance, glaucoma, heart disease, or arterial hypertension.

ONSD, heart rate (HR), and blood flow in the ICA and MCA were assessed using ultrasonography. Blood pressure (BP) was measured using an automatic upper arm blood pressure monitor (Omron Healthcare, Inc., Model Hem-711). An inversion table (Ironman, Paradigm Health & Wellness, Inc., Registry No. VA25302 [CN]) was used for inversion tilt. To maintain full inversion, participants were instructed to lower their arms below their head to keep them in full inversion. The ONSD, HR, and ICA and MCA blood flow of participants were measured in 3 positions: supine before inversion (pre-inversion), at 3 min of inversion with the head down (3-min inversion), and supine position after inversion (post-inversion). BP was measured only before and after inversion because of the gravitational inaccuracy of an inverted BP reading [48] (a higher arm level decreases BP while a lower arm level increases it). Because we instructed participants to lower their arms below their head during inversion, a measured BP would not have been accurate.

Portable ultrasound machines Mindray M7 with the linear transducer L4–12s and Mindray M5 with the linear transducer 10L4s were used in the current study. ONSD was measured using ocular ultrasonography with a linear transducer to provide optimal optic nerve visualization for adult ONSD measurements [13,27,31]. Ultrasound gel was applied onto the closed eyelid, and optic nerve diameter was measured 3 mm posterior to the globe [28] (Fig. 1). Gain and depth were adjusted individually. Ultrasound imaging was performed by medical students under the supervision of a physician certified by the American Registry for Diagnostic Medical Sonography with 19 years of ultrasound and teaching experience.

Doppler ultrasonography was used to assess blood flow in the ICA [49] and MCA [33]. Specifically, assessment of blood flow included the following parameters: peak systolic velocity (PSV), end diastolic velocity (EDV), resistance index (RI), and pulsatility index (PI). The RI was calculated by the following: (PSV - EDV)/EDV. The PI was calculated by the following: (PSV - EDV)/MFV where MFV was calculated from (PSV + [EDV × 2])/3.

Frequency and percentage or mean and standard deviation were reported for demographic variables. Mixed-effects models were used to test for changes in body position (pre-inversion, 3-min inversion, post-inversion) in ONSD, HR, BP and ICA and MCA blood flow, ICA PI and RI, and MCA PI and RI. These models were repeated to test for interactions with each of the demographic variables of sex, age, and BMI. Results from a final model were reported that controlled for all significant demographic variables. A first-order autoregressive or unstructured covariance was used according to Schwarz's Bayesian information criterion for individual participants to allow for correlations among the repeated measurements collected on an individual over time and on outcomes with both a diastolic and systolic component. Means and standard error (SE) were reported. The coefficient associated with age was reported for a 10-year increase. SAS version 9.4 software (SAS Institute, Inc.) was used to conduct the analyses. A $P < .05$ was considered statistically significant.

3. Results

Thirty-two osteopathic medical students participated in the study: 21 males (66%) and 11 females (34%) with mean (SD) age of 25.3 (3.3) years and mean (SD) BMI of 25 (SD 3.8).

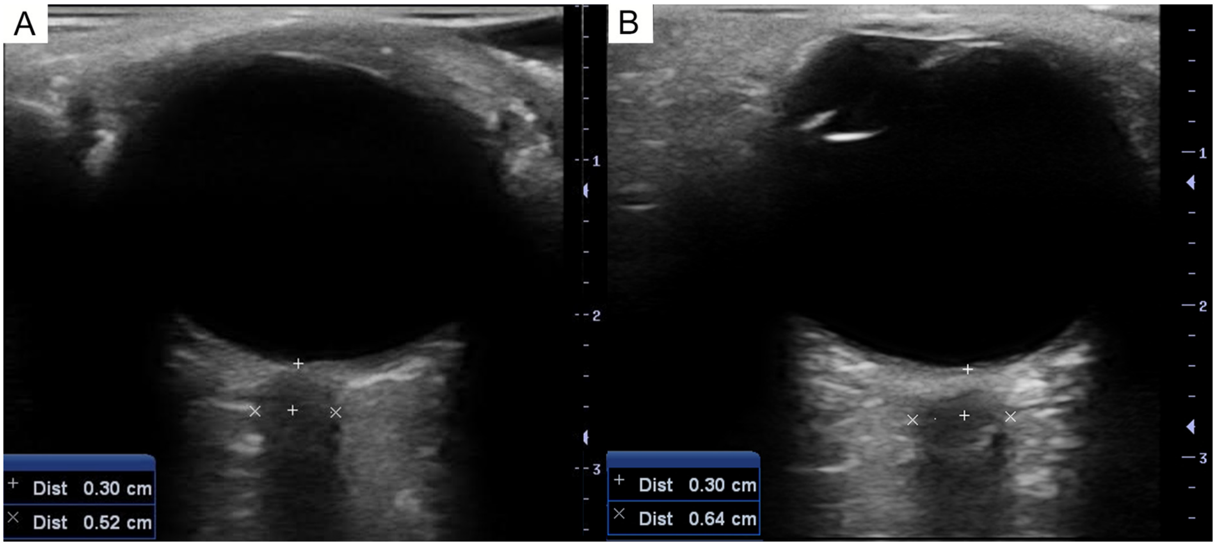

Fig. 1. Ultrasound images of the optic nerve pre-inversion (A) and post-inversion (B).

Table 1
Optic nerve sheath diameter (ONSD), heart rate (HR), and blood pressure (BP) measured in the current study.

Blood flow parameter	Inversion position	Mean change[a] (SE)	*P*
ONSD	3-min inversion	10.2 (0.7)	< 0.001
	Post-inversion	13.4 (0.7)	< 0.001
HR	3-min inversion	0.4 (1.4)	0.79
	Post-inversion	−4.0 (1.8)	0.03
Systolic BP	Post-inversion	−2.3 (2.2)	0.31
Diastolic BP	Post-inversion	1.5 (1.2)	0.22

Abbreviations: ONSD, optic nerve sheath diameter; HR, heart rate; BP, blood pressure.
[a] Mean change is relative to the participant in supine position pre-inversion.

The pre-inversion mean (SE) ONSD was 5.02 (0.05) mm, 3-min inversion mean 6.04 (0.08) mm, and post-inversion mean 6.36 (0.08) mm. The ONSD changed during the 3 positions (all $P < .001$) (Table 1; Figs. 1, 2A). Demographic variables had no effect on changes in ONSD (all $P \geq .52$).

The pre-inversion mean (SE) HR was 66.7 (2.0) bpm, 3-min inversion mean 67.1 (2.0) bpm, and post-inversion mean 62.7 (2.0) bpm. The post-inversion HR was less than pre-inversion ($P = .03$) and 3-min inversion HRs ($P = .003$) (Table 1; Fig. 2B). Demographic variables had no effect on changes in HR (all $P \geq .10$). Males had slightly less change in HR than females post-inversion (2.4 [1.7] bpm vs 8.0 [2.3] bpm), but the difference was not significant ($P = .10$).

Inversion caused no changes in systolic or diastolic BP (both $P \geq .22$) (Table 1; Figs. 2C, D). The mean (SE) estimate for systolic BP was 136.7 mmHg (1.9) for pre-inversion and 134.4 mmHg (2.9) for post-inversion; diastolic was 83.7 mmHg (1.4) and 85.2 mmHg (1.6), respectively. Changes in BP did not depend on sex ($P = .41$), but males had slightly higher systolic BP than females (13.7 mmHg, $P < .001$) and no difference in diastolic BP (2.3 mmHg, $P = .44$). Older participants had a larger increase in BP during inversion ($P = .04$); a 10-year increase in age was predicted to have a mean (SE) increase of 8.2 (3.8) mm Hg in overall BP. BMI had no effect on changes in BP ($P \geq .31$).

Blood flow velocity in the ICA during systole and diastole was lower at 3-min inversion ($P < .001$) (Table 2; Fig. 3), and changes were more pronounced during systole than diastole ($P = .002$). RI of the blood flow in the ICA did not change with inversion ($P = .32$). Changes in RI were not dependent on sex ($P = .23$) but were dependent on age ($P = .03$) and BMI ($P = .04$); older participants and those with higher

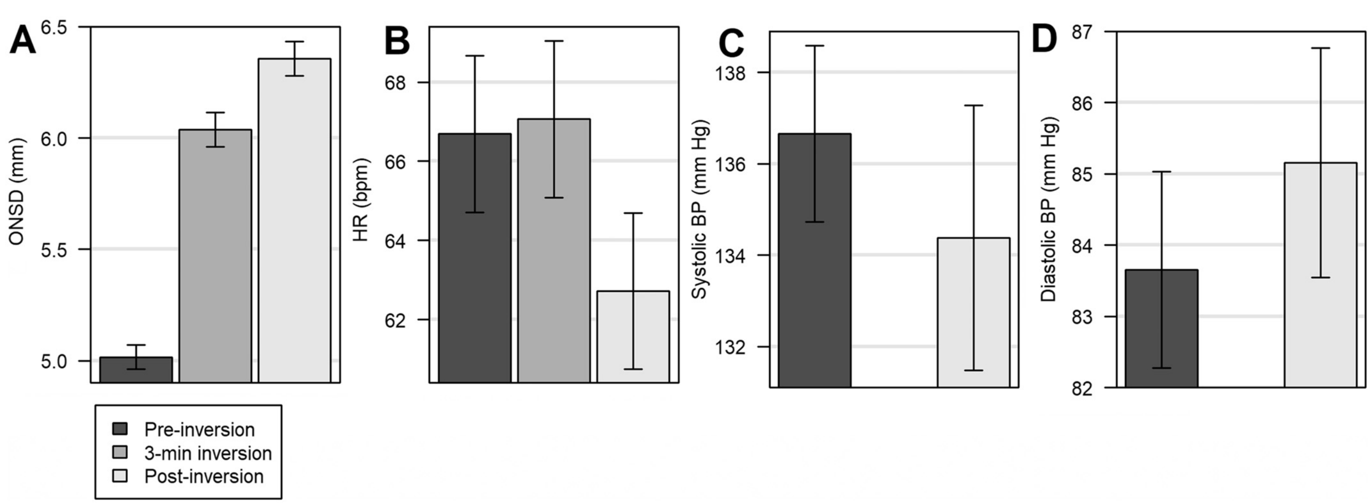

Fig. 2. A, Optic nerve sheath diameter at pre-inversion, 3-min inversion, and post-inversion; B, Heart rate at pre-inversion, 3-min inversion, and post-inversion; C, Systolic blood pressure at pre-inversion and post-inversion; D, Diastolic blood pressure at pre-inversion and post-inversion.
Error bars represent the standard error.

Table 2
Internal carotid artery (ICA) and middle cerebral artery (MCA) blood flow parameters measured in the current study.

Blood flow parameter	Inversion position	ICA		MCA	
		Mean Change[a] (SE)	*P*	Mean Change[a] (SE)	*P*
PSV	3-min inversion	−9.7 (2.3)	< 0.001	−7.0 (4.3)	0.12
	Post-inversion	−2.4 (2.8)	0.40	−8.0 (3.4)	0.02
EDV	3-min inversion	−2.8 (0.9)	0.005	−0.3 (1.8)	0.87
	Post-inversion	−0.7 (0.9)	0.42	−0.7 (1.5)	0.64
RI[b]	3-min inversion	−0.013 (0.011)	0.24	−0.038 (0.013)	0.005
	Post-inversion	0.004 (0.012)	0.76	−0.040 (0.010)	< 0.001
PI[c]	3-min inversion	−0.036 (0.030)	0.24	−0.101 (0.033)	0.005
	Post-inversion	0.006 (0.033)	0.85	−0.106 (0.027)	< 0.001

Abbreviations: EDV, end diastolic velocity; PI, pulsatility index; PSV, peak systolic velocity; RI, resistance index.
[a] Mean change is relative to the participant in supine position pre-inversion.
[b] RI was calculated as (PSV - EDV)/EDV.
[c] PI was calculated as (PSV - EDV)/MFV, where MFV was the mean flow velocity calculated by (PSV + [EDV × 2])/3.

BMIs had a larger increase in vascular resistance between 3-min inversion and post-inversion and between pre-inversion and post-inversion, respectively. Holding BMI constant, a 10-year increase in age (25 vs 35 years) was predicted to have a larger mean (SE) increase in RI of 0.082 (0.032) units between 3-min inversion and post-inversion ($P = .02$). Holding age constant, a 5-unit increase in BMI (22 vs 27) was predicted to have a larger mean (SE) increase in RI of 0.033 (0.015) units between pre-inversion and post-inversion ($P = .03$). Changes in PI from inversion were not significant ($P = .36$), were not dependent on sex ($P = .33$) or BMI ($P = .07$), but were dependent on age ($P = .03$). Similar to RI, PI for older participants had a larger increase between 3-min inversion and post-inversion and between pre-inversion and post-inversion, respectively. A 10-year increase in age (25 vs 35 years) was predicted to have a larger mean (SE) increase in PI of 0.22 (0.09) units between 3-min inversion and post-inversion ($P = .02$).

Significant changes in MCA blood flow velocity were found during systole between pre-inversion and post-inversion ($P = .02$) (Table 2; Figs. 3, 4). Changes were not dependent on demographic variables (all $P \geq .26$). RI of the blood flow in MCA changed during inversion ($P = .002$); there was a mean (SE) decrease of 0.038 (0.013) at 3-min inversion and of 0.040 (0.010) post-inversion (both $P \leq .005$). These changes were not dependent on sex or age ($P \geq .64$) but had a weak association with BMI ($P = .07$); a 5-unit increase in BMI (22 vs 27) was predicted to have a larger mean (SE) decrease in resistance of 0.035 (0.016) units between pre-inversion and 3-min inversion and a larger increase of 0.025 (0.012) units between 3-min inversion and post-inversion (both $P < .05$). PI of the blood flow in the MCA changed because of inversion ($P = .002$). The PI in pre-inversion was higher than at 3-min inversion and post-inversion by 0.101 and 0.106, respectively (both $P < .005$) (Table). These changes were not dependent on demographic variables (all $P \geq .10$).

4. Discussion

The current study evaluated the effects of inversion on ICP and cerebral blood flow using ultrasonography. The ICP was assessed through evaluation of the ONSD using ultrasonography. Cerebral blood flow was assessed by evaluation of blood flow parameters in the ICA and MCA, namely, PSV, EDV, RI, and PI, using Doppler ultrasonography.

One of our study goals was to determine whether ICP, and thus ONSD, changed during inversion. We also wanted to know whether demographic variables had an effect on these changes. The optic nerve sheath is continuous with the dura mater of the brain, and the subarachnoid compartment around the optic nerve contains cerebrospinal fluid, which communicates with the subarachnoid space of the brain [50]. Our results showed that mean ONSD grew progressively larger during and after inversion. Several studies have directly correlated ONSD measurements obtained using ultrasound with ICP measured invasively [12,13,17,21,26,27,51,52]. The cut-off value for normal ONSD, measured 3 mm posterior to the globe, ranges from 5.2 mm to 5.9 mm [31,32]. In our study, the ONSD ranged from 5.02 mm at pre-inversion to 6.04 mm at 3-min inversion and 6.36 mm post-inversion. Both the 3-min inversion and post-inversion ONSD measurements were

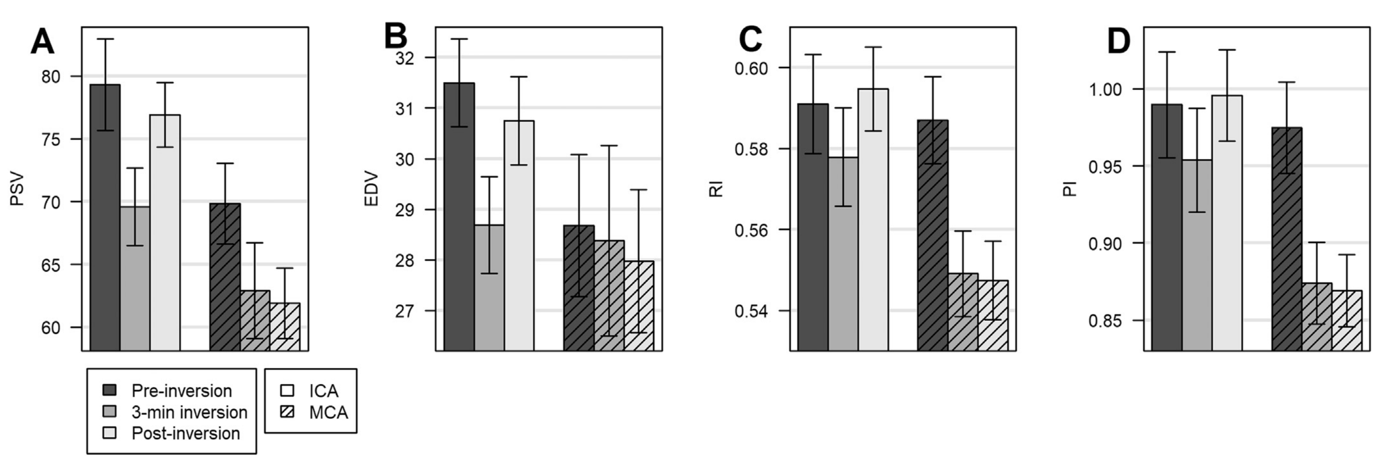

Fig. 3. Internal carotid artery (ICA) and middle cerebral artery (MCA) blood flow parameters: A, Peak systolic velocity (PSV) at pre-inversion, 3-min inversion, and post-inversion; B, End diastolic velocity (EDV) at pre-inversion, 3-min inversion, and post-inversion; C, Resistance index (RI) at pre-inversion, 3-min inversion, and post-inversion; D, Pulsatility index (PI) at pre-inversion, 3-min inversion, and post-inversion.
Error bars represent the standard error.

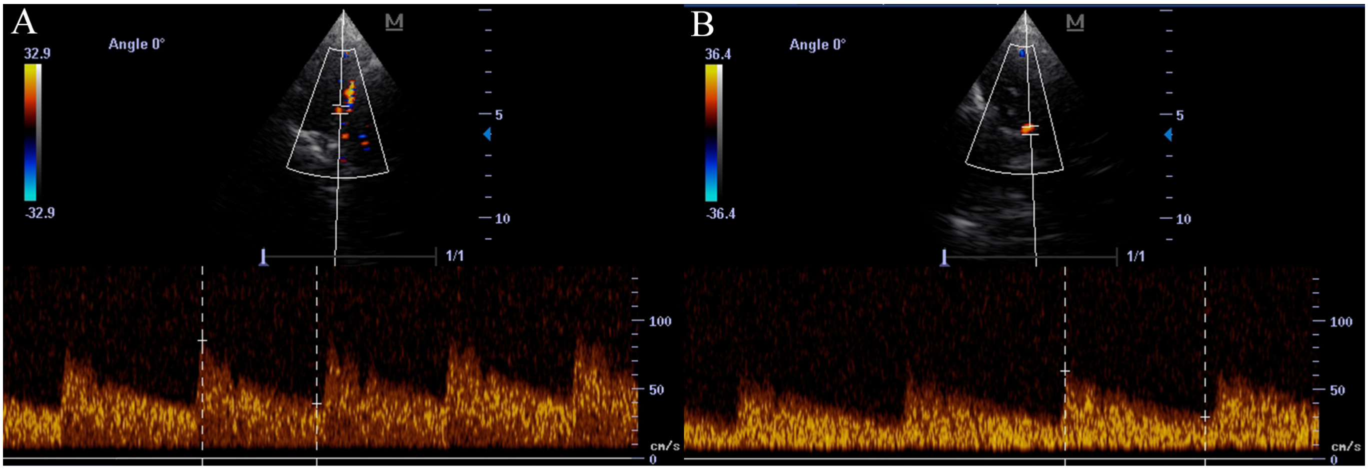

Fig. 4. Transcranial Doppler images of the middle cerebral artery (MCA) pre-inversion (A) and post-inversion (B).

higher than the cut-off values for normal optic nerve diameter [12,13,17,21,26,27,51,52], indicating the ICP was above normal. Further, it is important to note that the increased ICP did not immediately return to normal after inversion. Our results found no relationships between demographic variables and changes in ONSD.

In the current study, we also wanted to determine whether there were changes in HR and BP during inversion. Previous studies have contradictory results [3–5]. Klatz et al. [4] found use of an inversion table was associated with cardiovascular risks because inversion resulted in elevated BP, HR, and intraocular pressure [4]. As such, clinicians should use caution when using inversion with patients who have a history of cardiovascular conditions, such as hypertension or stroke [4]. The authors also suggested risk factors should be considered for patients with possible spinal fusion stability issues, weak spinal ligaments, and reflux esophagitis and for patients on aspirin or platelet inhibitors [4]. Conversely, others [3,5] reported no clinically significant changes in cardiovascular hemodynamics in a healthy population. Those studies concluded that inversion appeared to be safe for patient use [3,5]. In the current study, post-inversion HR was significantly lower than pre-inversion and 3-min inversion. The decreased HR suggests decreased cardiac output during inversion. Cardiac output is the volume of blood pumped by the heart per unit time and is the product of HR and stroke volume (volume of blood pumped from the ventricle per beat) [53]. Because cardiac output is related to the quantity of blood delivered to various parts of the body, it indicates that participants had decreased blood volume to different body regions, including the cerebral circulation, during and after inversion. Such a decrease could result in hypoxia. None of the demographic variables we examined (sex, age, or BMI) had any effect on changes in HR, which contradicts published research. In one study, a significant relationship between cardiac output and age was found; there was about 1% reduction of cardiac output (both stroke volume and HR) per year of age for participants [54]. These findings suggest that inversion would have an even greater negative effect on perfusion of the brain in the ageing population. Overall, inversion in the current study did not cause significant changes in diastolic or systolic BP, which is consistent with previous studies [5].

To evaluate changes in cerebral blood flow during inversion in the current study, we evaluated blood flow in the ICA and MCA in the 3 positions. Blood flow in the ICA was significantly decreased for systolic and diastolic velocity at 3-min inversion. The systolic velocity decreased more than diastolic velocity, which suggested changes in resistance are the result of an increase in the vessel diameter caused by pooling of blood in the ICA. Even a slight increase in diameter can cause a significant decrease in resistance since resistance is inversely proportional to the radius of the blood vessel raised to the fourth power ($R = 1/r^4$) [55]. Although there is relatively little pressure change as blood flows from the aorta to the large arteries, the small arteries and arterioles have about 70% pressure drop and are the main regulators of vascular resistance [55].

During postural changes, arteriole constriction or dilation can result in large increases or decreases in vascular resistance [55]. In the current study, the MCA also had decreased velocity measurements during inversion. RI in the MCA significantly decreased at 3-min inversion and decreased even more at post-inversion. These results suggest significant decreases in flow velocity and vascular resistance during inversion are caused by pooling of blood in the vessels of the brain and vasodilation.

Compared with pre-inversion, PI of the blood flow in the MCA decreased significantly at 3-min inversion and post-inversion. Contrary to our findings, increased ICP in neurosurgical patients with intracranial pathology corresponded with an increase in PI [47]. These findings indicate that the mechanism for an increase in ICP caused by inversion (likely pooling of blood in the venous system) is different from the mechanism involved in the increased ICP of patients with head injury, subarachnoid hemorrhage, or hydrocephalus (likely extrinsic compression of the brain).

Ultimately, we believe the current study provided a necessary foundation for future research on cardiovascular and cerebrovascular hemodynamics during inversion. A possible direction for future research is the assessment of patients with known vascular disease, such as carotid artery stenosis or history of transient ischemic attack, in the Trendelenburg position. Results from such a study could improve patient care since the Trendelenburg position is used for therapeutic purposes and during surgical procedures, such as those performed laparoscopically, that require the patient in the Trendelenburg position during the procedure [2]. Our study suggests that an inverted position in those patients could increase the risk of elevated ICP and intracranial hypertension, increasing the risk of post-operative complications.

The current study had several limitations, including its small size. Another limitation was that there was no control group, and all participants were healthy young adults. In addition, noninvasive methods of assessing ICP, such as that used in the current study, are less accurate than direct methods. Future studies should include the use of additional methods of ICP assessment such as a fundoscopic exam before, during, and after inversion to evaluate for signs of possible papilledema.

5. Conclusions

Our results suggested a close correlation between inversion and ONSD, which indicated elevated ICP, as measured using ocular ultrasound. The increased ICP did not immediately return to normal after inversion, and it stayed elevated for at least a minute. Therefore, there might be a higher chance of complications in patients with previous history of elevated ICP when using inversion as a therapeutic tool or during certain surgical procedures. Our results also suggested inversion therapy caused a significant decrease in blood flow through the ICA and MCA, which was still evident in the MCA after inversion and indicated changes in cerebral circulation. Taken together, results of the current study demonstrate that inversion therapy should be used with caution in individuals at risk for cerebrovascular accidents.

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Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jns.2019.07.033.

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