Effects of High Atmospheric Pressure and Oxygen on Middle Cerebral Blood Flow Velocity in Humans Measured by Transcranial Doppler

Tsuyoshi Omae, MD; Setsuro Ibayashi, MD; Kenji Kusuda, MD; Hidefumi Nakamura, BS; Hiroshi Yagi, MD; Masatoshi Fujishima, MD

**Background and Purpose**—There are several reports that have studied the effects of hyperbaric oxygen (HBO) on cerebral blood flow (CBF). However, most of the reports have been of animal experiments, and human studies are few so far. The aim of this study is to clarify the relationship between HBO and CBF in humans.

**Methods**—Middle cerebral arterial blood flow velocity (MCV) was measured using transcranial Doppler (TCD) technique in a multiplace hyperbaric chamber. The Doppler probe was fixed on the temporal region by a head belt, and the transcutaneous gas measurement apparatus (tcPO2 and tcPCO2) was fixed on the chest wall. MCV and transcutaneous gas were measured continuously in eight healthy volunteers under four various conditions: 1 atmosphere absolute (ATA) air, 1 ATA oxygen (O2), 2 ATA air, and 2 ATA O2. On the next step, the effect of environmental pressure was studied in another eight healthy volunteers, in whom the tcPO2 was kept at almost the same level under conditions of both 1 ATA and 4 ATA by inhaling oxygen at 1 ATA.

**Results**—MCV of 1 ATA O2, 2 ATA air, and 2 ATA O2 decreased, and tcPO2 increased significantly in comparison with that of 1 ATA air. A significant difference in MCV was observed between the O2 group and the air group under the same pressure circumstance. On the other hand, there were no differences in MCV or tcPO2 between 4 ATA air and 1 ATA plus O2, and the influence for the MCV of the environmental pressure was not observed.

**Conclusions**—We conclude that hyperoxemia caused by HBO reduces the CBF, but the high atmospheric pressure per se does not influence the CBF in humans. *(Stroke. 1998;29:94-97.)*

**Key Words:** cerebral blood flow • hyperbaric oxygenation • oxygen • ultrasonics

There are only a few papers reported on CBF under HBO circumstances.1–4 However, most of the reports are of animal experiments, and human studies are few,5,6 because it is quite difficult to measure CBF in humans under such a special condition.

A recent development of ultrasonic instruments has enabled us to evaluate noninvasively the cerebral circulation in humans.7 There are some reports about the cerebral hemodynamic changes using these techniques in healthy volunteers,8,9 in stroke patients,10 in patients with hemodialysis,11 or in patients with syncope.12 Therefore, we decided to use this technique to examine the relationship between HBO and CBF in the present study.

The aim of our study was to clarify the effects of HBO in different atmospheric pressures on CBF in healthy adults.

**Subjects and Methods**

Our study consisted of two series. In the first series, the effect of HBO on CBF was observed in eight healthy volunteers; and in the second series, the influence of high atmospheric pressure on CBF was examined in another eight young normal volunteer subjects. All of them received an explanation of this study, and informed consent was taken; the study was approved by the hospital ethics committee. The sex breakdown of each group was almost the same, and age was 28.1 ± 4.7 (mean ± SD) years in the former series and 26.6 ± 5.5 years in the latter.

Right MCV was measured by TCD (TransScan, EME) in a multiplace hyperbaric chamber (KHO-301, Kawasaki Engineering Co). With the use of a 2-MHz pulse Doppler probe, the sampling position and measurement depth (range, 52 to 56 mm) were determined on the temporal region at which maximal value with minimal noise was obtained, and the Doppler probe was fixed at the place with a head belt. Moreover, tcPO2 and tcPCO2 (OKV-7301, Nihon Koden Co, Japan) were continuously recorded on the chest wall of the examinees during the experimental periods. The electrode temperature was kept at 44°C before the calibration at least for 20 minutes and during the study to produce the optimum arterialization. All data were recorded after the tcPO2 and tcPCO2 became stable and had remained stable for more than 5 minutes. Blood pressure was measured by mercury sphygmomanometer.

In the first series, we examined the effect of HBO on CBF. The TCD probe and the transcutaneous gas measurement apparatus were fixed after the examinees were kept in supine position inside the
The MCV was measured under four various conditions: 1 ATA air, 1 ATA oxygen (O₂), 2 ATA air, and 2 ATA O₂, after the examinees were stable under each condition. In both groups of 1 ATA O₂ and 2 ATA O₂, 20 L/min of oxygen was given to the examinees with a facial mask.

In the second series, we investigated the effect of high ambient atmospheric pressure on CBF. The MCV under 4 ATA air was compared with that measured under 1 ATA, which showed almost the same tcPO₂ level as that under 4 ATA by inhaling various volumes of oxygen with a facial mask at 1 ATA circumstance (1 ATA plus O₂).

Compression and decompression speeds in the chamber were 0.1 kg/cm² per minute or less, and decompression time was slightly longer than compression time. These evaluations were monitored using a diving computer (ProAladin), and we followed its instructions during decompression.

The MCV was measured under four various conditions: 1 ATA O₂, 2 ATA air, and 2 ATA O₂. Left, systolic blood flow velocity; center, diastolic blood flow velocity; and right, mean blood flow velocity. All values are mean±SD. *P<.05.

### Results

The mean MCV values under the conditions of 1 ATA air, 1 ATA O₂, 2 ATA air, and 2 ATA O₂ were 65±15, 52±16, 61±13, and 50±13 cm/s, respectively. The mean MCVs of 1 ATA O₂, 2 ATA air, and 2 ATA O₂ decreased significantly in comparison with that of 1 ATA air (the control group), and at the same time, a significant difference was observed between the O₂ group and the air group under the same pressure circumstance. The mean MCV values of 1 ATA O₂ and 2 ATA O₂ were essentially the same (Table 1, Fig 1).

On the other hand, the tcPO₂ increased significantly under conditions of 1 ATA O₂, 2 ATA air, and 2 ATA O₂ in comparison with that in the control group, and those in the groups with O₂ inhalation were significantly higher than those breathing air at the same pressure. On the contrary, although the values of tcPCO₂ were not different among conditions of 1 ATA air (38±4 mm Hg), 1 ATA O₂ (37±4 mm Hg), and 2 ATA air (37±4 mm Hg), tcPCO₂ under 2 ATA O₂ (33±5 mm Hg) decreased significantly (P<.05). Blood pressure and pulse rate showed no change during the experimental periods in all groups (Table 1).

As the next step, we compared the pressure effect of 4 ATA with that of 1 ATA (control). As the environmental pressure rose from 1 ATA to 4 ATA, tcPO₂ increased, from 75.8±12.0 to 416.4±46.2 mm Hg. In order to get the same tcPO₂ level in 1 ATA as in 4 ATA air, the examinees inhaled various volumes of oxygen with a facial mask at 1 ATA. As a result, tcPO₂ of the examinees increased from 75.8±12.0 to 416.4±46.2 mm Hg at 1 ATA with oxygen (1 ATA plus O₂). The tcPCO₂ values

### Selected Abbreviations and Acronyms

- **ATA**: atmosphere absolute
- **CBF**: cerebral blood flow
- **HBO**: hyperbaric oxygen
- **MCV**: middle cerebral arterial blood flow velocity
- **TCD**: transcranial Doppler
- **tcPO₂**: transcutaneous oxygen tension
- **tcPCO₂**: transcutaneous carbon dioxide tension

### Table 1. Physiological Variables and Middle Cerebral Arterial Blood Flow Velocities

<table>
<thead>
<tr>
<th></th>
<th>1 ATA Air</th>
<th>1 ATA O₂</th>
<th>2 ATA Air</th>
<th>2 ATA O₂</th>
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<tbody>
<tr>
<td>SBP, mm Hg</td>
<td>115±11</td>
<td>112±11</td>
<td>115±11</td>
<td>117±13</td>
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<tr>
<td>DBP, mm Hg</td>
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<td>73±9</td>
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<td>75±9</td>
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<td>MBP, mm Hg</td>
<td>86±7</td>
<td>84±10</td>
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<td>PR, beats/min</td>
<td>65±6</td>
<td>63±5</td>
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<td>62±5</td>
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<td>tcPO₂, mm Hg</td>
<td>77±15</td>
<td>413±124*</td>
<td>184±29†</td>
<td>93±47†‡</td>
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<tr>
<td>tcPCO₂, mm Hg</td>
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<td>37±4</td>
<td>37±4</td>
<td>33±5*‡</td>
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<tr>
<td>MCVs, cm/s</td>
<td>90±21</td>
<td>79±23*</td>
<td>87±17†</td>
<td>74±22*‡</td>
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<tr>
<td>MCVd, cm/s</td>
<td>47±11</td>
<td>35±11*</td>
<td>42±9†</td>
<td>33±10*‡</td>
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<tr>
<td>MCVm, cm/s</td>
<td>65±15</td>
<td>52±16*</td>
<td>61±13†</td>
<td>50±13*‡</td>
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<td>PI</td>
<td>0.67±0.08</td>
<td>0.84±0.03*</td>
<td>0.74±0.11†</td>
<td>0.82±0.08*‡</td>
</tr>
</tbody>
</table>

*SBP indicates systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PR, pulse rate; MCVs, systolic middle cerebral artery flow velocity; MCVd, diastolic middle cerebral artery flow velocity; MCVm, mean middle cerebral artery flow velocity; PI, pulsatility index. MCVs=MCVd/MCVm. Values are means±SD.

*P<.05 vs 1 ATA air; †P<.05 vs 1 ATA O₂; ‡P<.05 vs 2 ATA air, by ANOVA and Fisher's protected least significant difference test.
were not different among 1 ATA air (38±3 mm Hg), 4 ATA air (37±4 mm Hg), and 1 ATA plus O₂ (37±5 mm Hg). We compared the MCV of 4 ATA air with that of 1 ATA plus O₂ (Table 2). MCVs of 4 ATA air and the 1 ATA plus O₂ group were 64±14 and 62±13 cm/s, respectively, and there was no significant difference between the two groups (Table 2, Fig 2).

**Discussion**

Kety and Schmidt⁵ first described a method to measure CBF in humans using nitrous oxide in a low concentration, although it was an invasive technique. As the next methods to measure CBF, techniques using radioisotopes, eg,¹³³Xe,¹²⁵I,⁹⁹ᵐTc, or computed tomography with cold Xe, have been devised. These methods are noninvasive, but at the same time inadequate for detection of the CBF under a high pressure circumstance.

So far, there are several reports that have measured CBF under the HBO circumstance. However, almost all of those reports are on animal experiments,⁴⁻⁶ and human studies are few.⁷⁻⁹ The results of the animal experiments have shown that HBO decreases CBF. Conditions such as hyperoxemia⁵⁻⁷ and hypocapnia due to hyperventilation⁹⁻¹⁰ have been considered as reasons for such a phenomenon, but a clear view is not yet estimated. Nowadays, it has been considered that the increase of arterial oxygen tension causes constriction of the superficial cortical arterioles,¹⁵⁻¹⁸ which leads to the decrease in the CBF.

The development of an ultrasonic technique has enabled us to measure CBF changes noninvasively without any hazard in humans. The TCD expresses the flow velocity of the middle cerebral artery, although it does not show real quantitative cerebral blood flow velocity.¹⁹ However, it has been reported that the changes in MCV obtained by TCD have an excellent correlation with the changes in CBF as measured with other techniques.²⁰⁻²¹ Therefore, we accepted the TCD technique for evaluating cerebral hemodynamics under the HBO circumstance in humans.

In the present human study, CBF of 1 ATA O₂, 2 ATA air, and 2 ATA O₂ decreased significantly in comparison with that of 1 ATA air. The decrease of CBF was remarkable, especially under conditions of 1 ATA O₂ and 2 ATA O₂, although no significant difference was observed between the groups. Our results coincided with the results by Lamberts et al⁵ who found a 25% reduction of CBF at 3.5 ATA in humans using the nitrous oxide method. Kanai et al²² reported the effect of HBO on blood flows in the common, internal, and external carotid arteries and the vertebral artery in humans by transcutaneous ultrasonic blood rheography. They demonstrated the reduction of blood flow by HBO in the arteries except the vertebral artery.

In this series, although the tcPO₂ in 2 ATA O₂ was significantly higher than that in 1 ATA O₂, the values of MCV were not different between 1 ATA O₂ and 2 ATA O₂. Ohta⁵ demonstrated a tendency toward an increase in CBF at the level of 2.5 ATA O₂, following gradual decreases in CBF to the level of 2 ATA O₂. These results suggested that the relation between tcPO₂ and CBF is not linear. Further examination is needed to clarify the relation. Although low Pco₂ conditions were sometimes encountered under the condition of HBO, our results suggested the reason for the MCV decrease under HBO conditions was mainly due to hyperoxemia. Although the tcPCO₂ level may influence the MCV at 2 ATA O₂ in the first series, the decrease of tcPCO₂ level seems unlikely to be the only cause of the decrease in MCV because of the CO₂ vasomotor reactivity level.¹⁴⁻²⁴

Although hyperoxemia due to inhalation of high doses of O₂ reduced MCV under 1 ATA and 2 ATA in the first series, it remained unclear about the effect of the atmospheric pressure on CBF.

In our second series, we compared MCV of 4 ATA air with that of 1 ATA plus O₂ and also found that ambient atmospheric pressure did not produce any influences on CBF in humans. In the animal study, Hordnes and Tyssebotn¹³ examined the relationship between partial arterial oxygen tension and CBF in rats, and reported that the ambient atmospheric pressure did not show any changes in CBF.

Although these results suggest that the changes in Po₂ affect the CBF, the effect is much smaller than that in Paco₂. The changes in Po₂ may not influence the assessment of Paco₂ reactivity in hyperventilation or CO₂ inhalation tests except the O₂ inhalation test.

In summary, oxygen inhalation reduced MCV under 1 ATA and 2 ATA, and there was no MCV difference between 4 ATA and 1 ATA when tcPO₂ was kept at the same level by inhaling.

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**Table 2. Physiological Variables and Middle Cerebral Arterial Blood Flow Velocities**

<table>
<thead>
<tr>
<th></th>
<th>1 ATA Air</th>
<th>4 ATA Air</th>
<th>1 ATA + O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP, mm Hg</td>
<td>108±13</td>
<td>109±16</td>
<td>108±13</td>
</tr>
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<td>DBP, mm Hg</td>
<td>62±9</td>
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<td>MBP, mm Hg</td>
<td>77±9</td>
<td>80±10</td>
<td>81±8</td>
</tr>
<tr>
<td>PR, beats/min</td>
<td>68±8</td>
<td>61±6*</td>
<td>62±6*</td>
</tr>
<tr>
<td>tcPO₂, mm Hg</td>
<td>76±12</td>
<td>419±47*</td>
<td>416±46*</td>
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<tr>
<td>tcPCO₂, mm Hg</td>
<td>38±3*</td>
<td>37±4</td>
<td>37±5</td>
</tr>
<tr>
<td>MCVs, cm/s</td>
<td>105±17</td>
<td>91±18*</td>
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<td>MCVd, cm/s</td>
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<td>45±12*</td>
<td>44±11*</td>
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<td>MCMc, cm/s</td>
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</tr>
<tr>
<td>PI</td>
<td>0.66±0.09</td>
<td>0.74±0.07*</td>
<td>0.73±0.09*</td>
</tr>
</tbody>
</table>

Abbreviations as in Table 1. Values are mean±SD.

*P<.01 vs 1 ATA air by ANOVA and Fisher’s protected least significant difference test.

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**Figure 2.** Bar graphs show MCV under the conditions of 1 ATA air, 4 ATA air, and 1 ATA + O₂. Left, systolic blood flow velocity; center, diastolic blood flow velocity; right, mean blood flow velocity. All values are mean±SD. **P<.01.**
O₂ at 1 ATA. We conclude that the hyperoxemia causes CBF reduction under HBO conditions and that the ambient atmospheric pressure does not influence the CBF.

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