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Cerebrovascular blood pressure autoregulation monitoring and postoperative transient ischemic attack in pediatric moyamoya vasculopathy

Jennifer K. Lee¹, Monica Williams¹, Michael Reyes¹, and Edward S. Ahn²

¹Department of Anesthesiology and Critical Care Medicine, Johns Hopkins University, Baltimore, MD, USA

²Department of Neurosurgery, Johns Hopkins University, Baltimore, MD, USA

Summary

Background—Children with moyamoya vasculopathy are at high risk of perioperative cerebral ischemia or hyperperfusion. Maintaining blood pressure within the range of functional cerebrovascular blood pressure autoregulation might reduce the risk of perioperative neurologic injury.

Aims—We tested whether blood pressure autoregulation is associated with postoperative transient ischemic attack in a study of patients with pediatric moyamoya vasculopathy.

Methods—We conducted an observational study of 15 pediatric patients undergoing surgical revascularization with pial synangiosis. Nine patients had bilateral moyamoya and 6 had unilateral moyamoya. We measured autoregulatory vasoreactivity intraoperatively and during the first postoperative night with the hemoglobin volume index, a value derived from near-infrared spectroscopy. We also identified the optimal mean arterial blood pressure at which autoregulation was most robust in each patient.

Results—Of the 15 children monitored, 3 with bilateral moyamoya and one with unilateral moyamoya experienced a transient ischemic attack. Poorer autoregulation during surgery was associated with postoperative transient ischemic attack among those with bilateral vasculopathy ($P = .048$, difference in hemoglobin volume index medians: 0.023, 95% confidence interval: 0.003–0.071). This relationship was not observed with postoperative autoregulation. The optimal mean arterial blood pressure was identifiable during surgery in all monitored patients, varied among patients, and often differed between the intraoperative and postoperative periods.

Conclusion—Dysfunctional intraoperative autoregulation may increase the risk of TIA in patients with pediatric moyamoya vasculopathy. The blood pressure range that supports

Correspondence: Jennifer K. Lee, Department of Anesthesiology and Critical Care Medicine, Johns Hopkins University, Baltimore, MD, USA. jklee@jhmi.edu.

ORCID

Jennifer K. Lee <http://orcid.org/0000-0001-9578-4482>

CONFLICT OF INTEREST

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autoregulation appears to vary among patients. Using autoregulation monitoring to guide individualized blood pressure goals should be studied as a potential method to reduce perioperative neurologic morbidity in pediatric patients with moyamoya.

Keywords

blood pressure; cerebral blood flow; cerebrovascular circulation; moyamoya disease; pediatrics; transient ischemic attack

1 | INTRODUCTION

Moyamoya is a rare vasculopathy that can cause stroke or other neurologic injuries in children. It is characterized by progressive steno-occlusive changes in the internal carotid arteries and their main branches with compensatory formation of a fine vascular network.¹ The risk of ischemic² or hyperperfusion³ injury during or after surgical revascularization is high with perioperative ischemic complications ranging from 5% to 20%.^{2,4} Alterations in cerebral blood flow regulation^{2,3,5} may contribute to this perioperative morbidity.

Cerebrovascular blood pressure autoregulation maintains cerebral blood flow across changes in perfusion pressure. The progressive vasculopathy and vessel occlusion seen in moyamoya cause impairments in autoregulation.⁶ The anesthesiologist's goal is to maintain the patient's blood pressure within the range that supports autoregulation to prevent cerebral hypo- or hyperperfusion. However, the blood pressure limits within which autoregulation functions are unknown in pediatric moyamoya. Most clinical techniques that keep intraoperative blood pressure close to baseline do not include cerebral blood flow monitoring. Moreover, preoperative baseline blood pressure measurements can vary with anxiety or different blood pressure cuff sizes. Thus, techniques that continuously monitor autoregulation and identify blood pressures that optimize it would advance clinical care. The ideal autoregulation monitor would be available both in the operating room and postoperatively.

Some intraoperative cerebral blood flow monitoring techniques do exist, including micro-Doppler ultrasonography,⁷ laser Doppler flowmetry,⁸ and jugular bulb oxygen saturation measurements.⁹ However, these methods are not routinely available to clinicians. Transcranial Doppler can be used postoperatively,⁶ but continuous Doppler is not feasible for long periods at many institutions. We have developed methods to measure autoregulation using near-infrared spectroscopy (NIRS),¹⁰ which is a standard and continuous monitor frequently used in clinical practice.

Near-infrared spectroscopy measures oxygen saturation in the frontal cortex and provides optical density concentrations of oxygenated and deoxygenated hemoglobin. The sum of these 2 is the relative total tissue hemoglobin (rTHb). The rTHb can be used as a surrogate measure of cerebral blood volume to determine autoregulatory vasoreactivity.¹⁰ The hemoglobin volume index (HVx) is an autoregulation measure that is calculated by correlating rTHb and mean arterial blood pressure (MAP). HVx is a continuous variable that ranges from -1 to +1. When autoregulation is functional, rTHb and MAP have near-zero or negative correlation. Thus, negative or near-zero HVx indicates functional autoregulation. The range of MAP with most robust autoregulation is known as the optimal MAP

(MAP_{OPT}), which is conceptually located in the center of the autoregulatory plateau¹¹ and at the HVx nadir.^{12,13} When blood pressure deviates from MAP_{OPT} and autoregulation becomes dysfunctional, the correlation between rTHb and MAP becomes positive. HVx becomes increasingly more positive as blood pressure deviates farther from MAP_{OPT}. HVx has been validated against intracranial pressure (ICP)-derived measures of vasoreactivity,^{10,14} transcranial Doppler,¹⁵ and laser Doppler flowmetry.^{10,16,17}

We previously published the feasibility of HVx monitoring during surgical revascularization for pediatric moyamoya.¹⁸ Here, we continue our study to test whether pressure autoregulation monitoring is associated with postoperative transient ischemic attack (TIA).

2 | MATERIALS AND METHODS

We conducted an observational study of patients with pediatric moyamoya. All procedures were approved by the Johns Hopkins University Institutional Review Board, which waived the requirement for written consent, and in accordance with the Declaration of Helsinki. We sequentially screened all patients undergoing pial synangiosis revascularization in the pediatric operating rooms of the Johns Hopkins Bloomberg Children's Center for cases of moyamoya between January 2011 and June 2015. Inclusion criteria included 21 years of age or younger and planned pial synangiosis for moyamoya vasculopathy. Patients older than 21 years were excluded.

Clinical protocol at our institution includes providing 1.5× maintenance intravenous fluids during the evening before surgery. All patients receive intraoperative and postoperative invasive arterial blood pressure monitoring. The surgeons positioned the NIRS monitors (bilateral, adhesive forehead stickers; Medtronic, Minneapolis, MN, USA) prior to preparing the surgical field. The anesthetic and blood pressure management were at the discretion of the anesthesia providers.

We synchronously sampled the NIRS and arterial blood pressure signals with a bedside laptop computer and ICM+ software (Cambridge University, Cambridge, UK) as previously reported.^{10,18–20} Briefly, we manually removed artifacts in the data, including arterial catheter flushes, blood gas sampling, transducer movements, and transient gaps in the NIRS data. We also excluded data that comprised <1% of the recording period as an additional method to remove signal artifacts. Ten-second mean values of MAP and rTHb were time integrated as a low pass filter removed pulse and respiratory frequencies. This process leaves slow wave signals from changes in rTHb (a surrogate measure of cerebral blood volume) during blood pressure autoregulation at 0.004–0.05 Hz.¹⁰ HVx was calculated by a continuous, moving Pearson correlation coefficient between MAP and rTHb. Each HVx value was calculated from consecutive and paired 10-second averaged values from 300-second windows. This method incorporates 30 data points for each HVx calculation. Clinicians could view the arterial blood pressure and NIRS' regional cerebral oxygen saturation, but they were unable to see the HVx calculations.

ICM+ software provided the maximum HVx for a recording period. The maximum HVx represents the patient's worst autoregulation measurement. To examine overall

autoregulatory vasoreactivity across a range of blood pressure, ICM+ software divided the blood pressure into 5-mm Hg bins of MAP and determined the mean HVx value from each MAP bin. This mean HVx value represents the patient's overall autoregulatory function at that level of blood pressure. We then generated bar graphs to examine mean HVx across the patient's entire range of MAP. An investigator (JKL) experienced with pediatric HVx monitoring^{13,18–20} identified MAP_{OPT} as the MAP bin with HVx nadir. If an HVx nadir was not apparent, then the patient was coded as having an unidentifiable MAP_{OPT} (Figure 1). MAP_{OPT} also could not be identified if the NIRS monitor did not detect consistent signals. We then measured blood pressure deviation from MAP_{OPT} by determining the percentage of the monitoring period spent with blood pressure below or above MAP_{OPT} and the maximal blood pressure deviation below or above MAP_{OPT}. We also measured the change in MAP_{OPT} from the intraoperative to postoperative periods. The lower limit of autoregulation (LLA) was identified as the MAP bin with mean HVx = 0.3.¹⁰ The investigator who identified MAP_{OPT} and the LLA was blinded to disease laterality, age, and incidence of TIA.

All patients were extubated in the operating room and recovered in the pediatric intensive care unit (PICU), where intravenous fluids were administered at 1.5× maintenance per clinical protocol. HVx monitoring was continued overnight until the first postoperative morning. The clinicians determined all care in the PICU. They could view the blood pressure and NIRS' regional cerebral oxygen saturation, but they were unable to view HVx.

A neurosurgeon (ESA), who remained blinded to HVx and MAP_{OPT}, conducted postoperative follow-up during the hospitalization and through 1 month after surgery. A postoperative TIA was defined as a new transient neurologic deficit. Clinical and anesthesia data were obtained from the electronic medical records.

2.1 | Statistical methods

Data are displayed as means with standard deviation (SD) or medians with interquartile range (IQR) and confidence intervals (CI) as appropriate. The range of blood pressure data is presented from 95% to 99% of the intraoperative and postoperative HVx recording periods to show the full blood pressure variability of each patient. In a 6-hour intraoperative monitoring session, for example, blood pressure data from 95% of this period comprises 342 minutes and 99% comprises 356 minutes. Graphs were generated with GraphPad Prism (GraphPad Software, Inc., La Jolla, CA, USA), and statistical testing was conducted with R version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria).²¹ The associations between TIA and maximum HVx; the duration spent with blood pressure below or above MAP_{OPT}; maximal blood pressure deviation below or above MAP_{OPT}; and change in MAP_{OPT} (PICU MAP_{OPT} – intraoperative MAP_{OPT}) were tested with Mann-Whitney rank-sum tests. Children with bilateral and unilateral disease were analyzed separately, and the maximum HVx from the right or left side was used for analysis. Intraoperative and postoperative MAP_{OPT} in patients with unilateral moyamoya were compared with Wilcoxon signed rank tests. Without prior knowledge of the relationship between autoregulation during pial synangiosis and TIA in pediatric moyamoya, we were unable to estimate an a priori sample size for this study.

3 | RESULTS

We sequentially screened 22 cases scheduled for moyamoya revascularization with pial synangiosis. We were unable to monitor 2 eligible patients because of inadequate resources. Of the 20 surgeries in which HVx was monitored, NIRS signals could not be detected in 1 patient. Additionally, 2 patients underwent 2 surgeries each (for a total of 4 surgeries) and were excluded from the analysis. Thus, the final sample size was 15 cases (8 girls and 7 boys)—9 (60%) with bilateral vasculopathy and 6 (40%) with unilateral vasculopathy. The median age was 9 years (IQR: 5, 14; range: 2–21 years). The patients' clinical summaries are presented in Table 1.

Eight patients received preoperative oral midazolam. Fourteen received volatile agents (isoflurane, sevoflurane, or desflurane), 3 received nitrous oxide, and 1 received only a propofol infusion. Fentanyl was the most common opiate, followed by hydromorphone and remifentanyl. All patients received neuromuscular blockade with vecuronium or rocuronium. During the postoperative period of HVx monitoring, all patients received morphine or hydromorphone, and none received benzodiazepines. No patient received a vasoactive medication or blood product transfusion during the intraoperative or postoperative periods. Vital sign and laboratory values are listed in Tables 2 and 3.

Four patients had postoperative TIAs. Symptoms included transient aphasia and unilateral weakness (Table 1). All neurologic changes resolved with the primary treatment of intravenous fluid boluses, and no patient suffered a stroke or other permanent neurologic deficit.

3.1 | Dysfunctional autoregulation was associated with postoperative TIA in bilateral moyamoya

Patients with bilateral vasculopathy received intraoperative HVx monitoring for a median of 6 hours (IQR: 5.8, 7.0; $n = 9$). Seven were monitored postoperatively for 14.4 hours (IQR: 12.1, 14.7). HVx monitoring was discontinued in 2 patients in the PICU because one pulled out the arterial catheter and the other pulled off the NIRS stickers. Patients with unilateral vasculopathy were monitored with HVx intraoperatively for 3 hours (IQR: 2.6, 3.7; $n = 6$) and postoperatively for 17.4 hours (IQR: 16.0, 18.0; $n = 6$).

One patient with unilateral vasculopathy had a TIA, and 3 with bilateral vasculopathy had TIAs (Table 1). Therefore, the relationship between autoregulation and postoperative TIA could be analyzed only among those with bilateral disease. When analyzing maximal HVx, higher intraoperative HVx (indicating worse autoregulation) was associated with occurrence of postoperative TIA ($P = .048$; difference in medians: 0.023; 95% CI: 0.003–0.071; $n = 9$; Figure 2A). Postoperative HVx and TIA were not associated ($P = .4$; difference in medians: 0.049; 95% CI: −0.100–0.156; $n = 7$; Figure 2B).

3.2 | Intraoperative and postoperative MAP_{OPT} differed in patients with unilateral moyamoya

We identified intraoperative MAP_{OPT} on at least one side in all 15 patients. We identified postoperative MAP_{OPT} on at least one side in 5 patients (83%) with unilateral vasculopathy

and all monitored patients with bilateral vasculopathy. MAP_{OPT} varied among patients (Table 4). In patients with unilateral vasculopathy who had MAP_{OPT} identified in both intraoperative and postoperative periods, the postoperative MAP_{OPT} exceeded that of the intraoperative MAP_{OPT} on both affected and unaffected sides (Figure 3A,B). These differences were not statistically significant (affected side: $P = .063$, difference in medians: 30 mm Hg, 90% CI: 10.0–35.0, $n = 5$; unaffected side: $P = .125$, difference in medians: 25 mm Hg, 60% CI: 25.0–35.0, $n = 4$). MAP_{OPT} during the intraoperative and postoperative periods showed less variability in patients with bilateral disease (Figure 3C,D).

Among patients with bilateral moyamoya, the incidence of TIA was not associated with the duration of blood pressure below MAP_{OPT} (intraoperative: $P = 1.0$, difference in medians: 9.6% of recording period, 95% CI: –34.7–80.7%; PICU: $P = .4$, difference in medians: 27%, 95% CI: –40.2–69.9) or above MAP_{OPT} (intraoperative: $P = 1.0$, difference in medians: 14%, 95% CI: –21.5–58.2; PICU: $P = 1.0$, difference in medians: 32.3, 95% CI: –54.7–86.5; data not shown). Having a TIA was also unrelated to the maximal blood pressure deviation below MAP_{OPT} (intraoperative: $P = .4$, difference in medians: 10 mm Hg, 95% CI: –30–30; PICU: $P = .6$, difference in medians: 7.5 mm Hg, 95% CI: –12.5–17.5) or above MAP_{OPT} (intra-operative: $P = 1.00$, difference in medians: 0.0 mm Hg, 95% CI: –30.0–30; PICU: $P = .9$, difference in medians: 2.0 mm Hg, 95% CI: –10.0–15.0; data not shown). Finally, the difference in MAP_{OPT} between intraoperative and postoperative periods was not associated with TIA ($P = .629$, difference in medians: 5 mm Hg, 95% CI: –27.5–27.5).

3.3 | Lower limit of autoregulation

The LLA was identified in 2 patients with bilateral moyamoya. The LLA was 50 mm Hg on the right side of a 5-year-old child who did not have a TIA. A 12-year-old child with a TIA had LLAs at 65 and 60 mm Hg in the right and left sides, respectively. We identified the LLA in 2 patients with unilateral moyamoya. A 21-year-old patient without TIA had an LLA at 60 mm Hg on the unaffected side, and a 16-year-old with a TIA had an LLA of 45 mm Hg on the unaffected side.

4 | DISCUSSION

We found that dysfunctional autoregulation during surgery was associated with a higher likelihood of postoperative TIA in pediatric patients with bilateral moyamoya in a small study. MAP_{OPT} varied among patients, illustrating that generalized blood pressure goals will not support autoregulation in all children with moyamoya. Moreover, MAP_{OPT} shifted to a higher blood pressure between the intraoperative and postoperative periods in those with unilateral moyamoya on sides both with and without vasculopathy. HVx can be calculated in real-time at the bedside. Thus, HVx monitoring during the perioperative period may enable clinicians to identify the MAP_{OPT} that supports autoregulation in individual patients and possibly reduce the risk of TIA.

The blood pressure limits of autoregulation are unknown in pediatric moyamoya. Anesthesia guidelines generally recommend maintaining the cerebral perfusion pressure at or above the patient's baseline and increasing the blood pressure to a high-normal range during revascularization.²² However, cerebral perfusion pressure cannot be calculated without ICP,

and ICP is not usually monitored during revascularization for moyamoya. Additionally, anxiety in children can make it difficult to obtain a reliable baseline blood pressure. We propose that identifying MAP_{OPT} with HVx could provide a more reliable method of determining neuroprotective hemodynamic goals than existing practice.

The association between intraoperative autoregulation measured by HVx and postoperative TIA in bilateral moyamoya suggests that children with dysfunctional autoregulation during surgery are at greater risk of TIA. Though the sample size was small in our study of a rare disease, this finding warrants further investigation. Aberrant cerebral blood flow with hypoperfusion or hyperperfusion after revascularization surgery is known to increase the risk of postoperative neurologic injury in adult moyamoya.^{23,24} Hypotension can cause graft thrombosis, and hypertension increases the risk of postoperative bleeding.²²

One method to support autoregulation is to identify the MAP_{OPT} at which autoregulation is most functional. Conceptually, MAP_{OPT} is located in the center of the blood pressure–cerebral blood flow curve, where autoregulatory vasoreactivity is most robust. We showed that HVx can identify MAP_{OPT} during and after pial synangiosis. However, MAP_{OPT} varied among individuals, and age-dependent or generalized blood pressure goals may not support autoregulation in all children with moyamoya. We did not identify MAP_{OPT} bilaterally in all patients. Because this was an observational study, we did not manipulate the blood pressure to determine whether a different blood pressure range would optimize autoregulation.

Optimal mean arterial blood pressure moved to a higher postoperative blood pressure in children with unilateral but not bilateral moyamoya. Although the difference was not statistically significant, this observation is clinically important. The rationale for a shift in MAP_{OPT} is unclear, and we are unaware of prior reports with similar findings. The higher MAP_{OPT} values suggest limited postoperative cerebral vasodilatory capacity at lower blood pressures. We were unable to determine preoperative HVx measurements because invasive arterial blood pressure monitoring would have been required. The possibility that MAP_{OPT} might change between the intraoperative and postoperative periods deserves further study as such changes could have critical implications for the perioperative care of patients.

Overall, our patients had higher postoperative than intraoperative blood pressures. These blood pressures were often higher than would be expected for their age. Patients received 1.5× maintenance intravenous fluids after surgery per clinical protocol and no patient received vasoactive medications. Pain was treated with opiates. Clinicians did not have specific postoperative blood pressure goals other than to maintain blood pressure above the preoperative “baseline.” Because MAP_{OPT} was apparent in these relatively high blood pressure ranges, it appears that these higher blood pressures included those with functional autoregulation.

It is important to note that supporting blood pressure autoregulation alone will not prevent ischemic or hyperemic insults in patients with moyamoya. Maintaining normocapnia, for example, is essential to preventing perioperative TIAs.² Given the small sample size of this study, we could not adjust for carbon dioxide level in the analysis. We also did not account for anesthetic depth. Although volatile agents affect autoregulation, shifts in the lower and

upper limits of blood pressure autoregulation will still permit some degree of pressure reactivity along the autoregulatory plateau. Therefore, MAP_{OPT} can be identified during anesthesia with isoflurane.¹⁵ Moreover, patients with severe vasculopathy may be at risk of TIA independent of blood pressure management. We were unable to adjust for disease severity in this small study.

We identified the LLA in 2 patients with bilateral moyamoya and 2 patients with unilateral moyamoya. The mean HVx threshold of 0.3 to distinguish MAP with pressure-passive autoregulatory vasore-activity (and therefore MAP below the LLA) is based on a piglet model of hypotension with laser Doppler flux measurements of cortical cerebral blood flow and ICP measurements of vasoreactivity.¹⁰ Because we did not manipulate blood pressure in our observational study, MAP did not decrease low enough to identify a LLA in the majority of patients. The 11 patients without an identified LLA had overall functional autoregulation indicated by mean HVx < 0.3 at all MAP levels throughout the intraoperative and postoperative courses. We were unable to analyze relationships between blood pressure below the LLA and TIA due to small sample size.

The advantages of NIRS-based autoregulation metrics include familiarity of NIRS to many clinicians, the ability to conduct continuous monitoring for long periods of time, and relative ease of application. Because the NIRS monitors were placed bilaterally on the forehead, HVx was measured only in the frontal cortex. Autoregulation was not assessed in other regions, and NIRS cannot be routinely monitored directly in the surgical field. We used frontal cortex monitoring as the best surrogate determination of pressure autoregulation in distal brain regions. We cannot comment on whether MAP_{OPT} in frontal cortex approximates that of other brain regions. It is possible, though, that deviation in blood pressure from MAP_{OPT} of frontal cortex might also worsen cerebral blood flow regulation in other brain regions.

It must be acknowledged that the translation of NIRS autoregulation monitoring into clinical use has been limited. This may be due, in part, to the multitude of algorithms that are used in clinical research. For example, the NIRS tissue oxygen saturation, difference between oxygenated and deoxygenated hemoglobin, and sum of oxygenated and deoxygenated hemoglobin have all been used as surrogate measures of cerebral blood flow or blood volume. Analysis methods include coherence, gain, wavelet coherence, and correlation. We do not know whether one method is superior to another in pediatric patients. These methods assess spontaneous blood pressure fluctuations without intentionally changing the blood pressure. While this increases the safety profile of autoregulation monitoring in critically ill infants and children, the blood pressure range at which autoregulation can be measured becomes limited. Additional critiques of autoregulation monitoring include overly simplistic mathematical averaging and time averaging that may fail to fully represent physiologic cerebrovascular pressure oscillations.²⁵ Future research is needed to improve autoregulation monitoring in pediatric populations.²⁶

There were several limitations to this study, including small sample size in this single institution study. Given the rare nature of this disease and low incidence of postoperative TIAs,⁴ future research should include multicenter studies that provide a sample size large

enough to permit analyses adjusted for disease severity, partial pressure of arterial carbon dioxide, and other factors that affect neurologic risk. Causal relationships between autoregulation and TIA cannot be determined in this observational study. Although we did not validate HVx against transcranial Doppler in pediatric moyamoya, HVx has proven to be a reliable autoregulation measure when compared with ICP,^{10,14} transcranial Doppler,¹⁵ and laser Doppler flowmetry.^{10,16,17} Future studies to test HVx against transcranial Doppler, micro-Doppler ultrasonography,⁷ or laser Doppler flowmetry⁸ in moyamoya are needed to further justify its use. We also did not distinguish specific portions of the surgery, such as removing and replacing the bone. Changes in the local environment could impact autoregulatory vasoreactivity and blood flow. Because MAP_{OPT} could not be identified in all patients, additional biomarkers may be needed to guide blood pressure management in moyamoya such as serum biomarkers or combining HVx with cerebral blood flow measures.

In conclusion, we identified an association between dysfunctional intraoperative autoregulation and postoperative TIA in a small study of pial synangiosis for pediatric moyamoya vasculopathy. The blood pressure range that optimizes autoregulation can be identified intra-operatively and postoperatively with HVx. MAP_{OPT} varied among patients and differed between the intraoperative and postoperative periods in some. The utility of HVx to identify neuroprotective hemodynamic goals in children with moyamoya deserves further study.

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What is already known

- Children with moyamoya vasculopathy are at risk of transient ischemic attack in the perioperative period.

What this article adds

- Our study suggests that poor autoregulation during pial synangiosis revascularization is associated with postoperative transient ischemic attack in children with bilateral moyamoya.

FIGURE 1.

Example hemoglobin volume index (HVx) curves and identification of the optimal mean arterial blood pressure (MAP_{OPT}) during intraoperative monitoring. A–D, MAP_{OPT} was identified as the 5-mm Hg bin of MAP with a nadir in HVx and most functional autoregulatory vasoreactivity. As blood pressure deviates from MAP_{OPT}, autoregulatory dysfunction increases and the HVx index overall becomes more positive. E, F, If a clear HVx nadir could not be identified, the patients were coded as having an unidentifiable MAP_{OPT}.

FIGURE 2.

Correlation between autoregulatory vasoreactivity measured by the hemoglobin volume index (HVx) and postoperative transient ischemic attack (TIA) among patients with bilateral moyamoya vasculopathy. A, Higher intraoperative HVx (and thus poorer autoregulation) was associated with postoperative TIA ($P = .048$; difference in medians: 0.023; 95% CI: 0.003–0.071; $n = 9$). B, Postoperative HVx was not associated with TIA ($P = .4$; difference in medians: 0.049; 95% CI: –0.100–0.156; $n = 7$). Data were analyzed by Mann-Whitney rank-sum tests. Each circle represents 1 patient. Box plots are shown, and whiskers are the 5th and 95th percentiles

FIGURE 3.

Comparison of optimal mean arterial blood pressure (MAP_{OPT}) with most robust autoregulation in frontal cortex during the intraoperative and postoperative periods. A, B, In patients with unilateral moyamoya, MAP_{OPT} was lower intraoperatively than postoperatively on the side with vasculopathy (affected side) and on the side without vasculopathy (unaffected side). C, D, Patients with bilateral moyamoya did not have apparent differences in MAP_{OPT} between the intraoperative and postoperative periods. Each circle represents 1 patient. Paired comparisons are shown

TABLE 1

Clinical descriptions

Patient	Age (y)	Presentation	Comorbidities	Vasculopathy location	Suzuki grade	Postoperative ischemia
1	2	Stroke, seizures	Neurofibromatosis type 1	Bilateral	4	
2	3	Tremors	Keutel syndrome	Bilateral	4	
3	5	Stroke	Down's syndrome	Bilateral	3	
4	5	Headaches	Neurofibromatosis type 1	Left	3	
6	7	Stroke	HbSS	Right	4	
7	9	TIA's, seizures		Bilateral	3	
8	10	Stroke	Type I diabetes mellitus	Left	— ^a	
10	13	Stroke	HbSS	Bilateral	4	
12	15	Strokes	HbSS	Bilateral	4	
14	18	TIA's		Left	— ^a	
15	21	Stroke	Down's syndrome	Left	3	
5	6	Stroke		Bilateral	4	TIA (facial weakness)
9	12	Stroke	Type I diabetes mellitus	Bilateral	4	TIA (aphasia)
11	14	Stroke		Bilateral	4	TIA (facial weakness)
13	16	TIA's		Left	3	TIA (aphasia and weakness)

TIA, transient ischemic attack; HbSS, homozygous sickle cell disease.

^aPreoperative angiogram not available.

TABLE 2

Clinical parameters

Parameter	Intraoperative		Postoperative	
	N	Mean (SD)	N	Mean (SD)
End-tidal CO ₂	15	38 (3)	0	—
PaCO ₂ , mm Hg	12	38 (3)	5	46 (1.5)
Hemoglobin, g/dL	12	10.6 (1)	15	10.9 (1)
Temperature, °C	15	36.8 (0.5)	15	36.8 (0.3)
SaO ₂ , %	15	99.6 (0.4)	15	98.3 (0.8)
Right regional cerebral oxygen saturation, %	14	84 (9)	13	77 (16)
Left regional cerebral oxygen saturation, %	14	87 (7)	13	79 (11)

SD, standard deviation; CO₂, carbon dioxide; PaCO₂, partial pressure of arterial carbon dioxide; SaO₂, oxyhemoglobin saturation; HVx, hemoglobin volume index.

Near-infrared spectroscopy (NIRS) did not detect a signal on the right side in one patient or on the left in a second patient during surgery. HVx monitoring was stopped in the pediatric intensive care unit after one patient removed the arterial blood pressure catheter and a second removed the NIRS monitors.

TABLE 3

Range of mean arterial blood pressure for each patient

Patient	Age (y)	Vasculopathy	Intraoperative period			Postoperative period		
			MAP during 95% of period (range, mm Hg)	MAP during 99% of period (range, mm Hg)	Duration (min)	MAP during 95% of period (range, mm Hg)	MAP during 99% of period (range, mm Hg)	Duration (min)
1	2	Bilateral	55–85	50–95	354	— ^a	— ^a	— ^a
2	3	Bilateral	50–70	50–75	420	75–85	75–95	870
3	5	Bilateral	50–64	45–75	150	— ^b	— ^b	— ^b
4	5	Unilateral	40–55	40–65	165	60–80	55–85	1005
5	6	Bilateral	60–85	55–90	345	90–120	85–120	888
6	7	Unilateral	60–80	55–85	150	70–85	70–90	1110
7	9	Bilateral	75–95	70–105	306	75–95	70–100	1152
8	10	Unilateral	65–95	60–110	195	60–100	55–105	1080
9	12	Bilateral	60–100	55–110	360	85–100	80–105	240
10	13	Bilateral	70–85	65–90	408	85–100	80–110	630
11	14	Bilateral	75–95	70–100	450	70–85	70–90	825
12	15	Bilateral	70–100	70–110	450	85–110	85–110	864
13	16	Unilateral	50–75	45–90	132	75–100	70–105	1080
14	18	Unilateral	65–90	55–100	228	65–90	85–120	948
15	21	Unilateral	65–80	60–90	250	80–95	80–100	60 ^b

MAP, mean arterial blood pressure; HVx, hemoglobin volume index. Duration refers to the duration of HVx monitoring.

^a HVx monitoring was stopped in the pediatric intensive care unit because the patient removed the arterial blood pressure catheter.^b HVx monitoring was stopped in the pediatric intensive care unit because the patient removed the near-infrared spectroscopy monitor.

TABLE 4

Optimal mean arterial blood pressure values

Patient	Unilateral moyamoya	Age (y)	Intraoperative MAP _{Opt}			Postoperative MAP _{Opt}		
			Affected side	Unaffected side	Unidentifiable	Affected side	Unaffected side	Unaffected side
	4	5	40		Unidentifiable	65	65	65
	6	7	65		65	90	85	85
	8	10	60		60	70	85	85
	13	16	55		50	85	85	85
	14	18	55		55	90	90	90
	15	21	No NIRS signal		65	No NIRS signal	Unidentifiable	Unidentifiable
Bilateral moyamoya								
			Right side	Left side		Right side	Left side	
	1	2	60	60	60	— ^a	— ^a	— ^a
	2	3	Unidentifiable	75	75	80	75	75
	3	5	70	Unidentifiable	Unidentifiable	— ^b	— ^b	— ^b
	5	6	85	85	85	105	105	105
	7	9	70	80	80	85	70	70
	9	12	95	85	85	80	85	85
	10	13	80	65	65	80	80	80
	11	14	95	85	85	70	70	70
	12	15	No NIRS signal	105	105	110	85	85

MAP_{Opt}, optimal mean arterial blood pressure; NIRS, near-infrared spectroscopy.

Unidentifiable: no apparent nadir in the hemoglobin volume index (HVx) despite NIRS monitoring.

No NIRS signal: HVx could not be calculated owing to inconsistent NIRS readings.

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q_p Patient pulled out arterial catheter and HVx could not be calculated.
q_p Patient pulled off NIRS monitors and HVx could not be calculated.