**Association of Increased Pulsatility Index of the Basilar Artery with Neurological Deterioration after Stroke**

**Short title: PI of BA Correlates with Stroke Progression**

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Keywords: Neurological deterioration, Basilar artery, Stroke, Transcranial Doppler Sonography

Word count: 3924

**Abstract**

**Background and Purpose:** Higher pulsatility of the middle cerebral artery (MCA) is known to be associated with stroke progression. We investigated whether the pulsatility index (PI) of the basilar artery (BA) can predict neurological deterioration (ND) after acute cerebral infarction.

**Methods:** A total of 708 consecutive patients with acute ischemic stroke who had undergone transcranial Doppler (TCD) ultrasonography were included. ND was defined as an increase in the National Institutes of Health Stroke Scale scores by two or more points after admission. The patients were categorized into quartiles according to BA PI. Multivariable logistic regression analysis was performed to examine whether BA PI is independently associated with ND.

**Results:** Mean age, hemoglobin A1c, homocysteine, cerebral atherosclerosis burden, and the proportion of patients with hypertension, diabetes mellitus, presence of old lacunes, and ND as well as those of female sex also increased with increasing BA PI. Multivariable logistic regression analysis for variables including age, sex, vascular risk factors, homocysteine, and cerebral atherosclerosis burden showed that the highest BA PI quartile group was independently associated with ND (odds ratio = 2.06; confidence interval = 1.04–4.09; *p* = 0.039). BA PI was well correlated with the right MCA PI (r = 0.757; *p* < 0.001 by Pearson’s correlation analysis), although MCA could not be measured by TCD ultrasonography for 234 patients (33.1%) owing to a poor temporal window.

**Conclusions:** BA PI could predict ND among acute stroke patients, which is not influenced by a temporal window.

**Introduction**

Neurological deterioration (ND) occurs in 10%–58% stroke patients and results in poor prognosis and mortality.[1-5] Several factors are known to be associated with ND, such as old age, diabetes mellitus (DM), hypertension (HTN), smoking habit, coronary heart disease, the size of low density lesions as observed on initial computed tomography (CT), change in the flow velocity of middle cerebral artery (MCA), impaired cerebral hemodynamic reserve, blood glucose level, proinflammatory cytokine level, and blood pressure (BP).[5-10] From a mechanistic perspective, failed intracranial collateral blood flow or elevated intracranial pressure may lead to decreased cerebral perfusion, thereby causing ND.[2]

Because the stiffness of large arteries is linked with various cerebral small vessel disease phenotypes including cerebral microbleeds, white matter hyperintensities, and lacunar cerebral infarction, it may be plausible that increased cerebral arterial stiffness is associated with ND after stroke.[11-17] The pulsatility index (PI) of intracranial cerebral arteries, as measured by transcranial Doppler (TCD) ultrasonography, is known to reflect the resistance of downstream arteries and compliance of large cerebral arteries.[18-21] Recent study reported that elevated MCA PI is independently associated with ND among lacunar stroke patients.[18]However, MCA PI is often unobtainable in elderly stroke patients owing to poor acoustical temporal bone window. Basilar artery (BA) measured from transforaminal window can be an alternative to obtain intracranial PI, but its clinical significance among stroke patients has not been appreciated yet. We investigated whether BA PI can predict ND after acute stroke.

**Materials and Methods**

1. Patients and evaluation

From January 2014 to December 2015, consecutive patients with acute cerebral infarction or transient ischemic attack (TIA) who had undergone TCD ultrasonography were retrospectively reviewed. This study was reviewed and approved by the institutional review board of Chung-Ang University Hospital (C2013110) and was conducted in accordance with the 1964 Helsinki declaration and its later amendments. Their medical history, clinical manifestations, and vascular risk factors were reviewed from a stroke registry at the Chung-Ang University Hospital. ND was defined as per previous studies, i.e., an increase in the National Institutes of Health Stroke Scale (NIHSS) score by two or more points.[22, 23]

Each patient was examined with brain magnetic resonance imaging (MRI) and computed tomography angiography (CTA), and acute cerebral infarction was determined by hyperintensity on diffusion-weighted images that matched with hypointensity on apparent diffusion coefficient maps of brain MRI. We gathered information about small vessel disease from MRI and cerebral atherosclerosis from brain CTA. Old lacunes were determined by round or ovoid hypointense lesions which were encompassed by an hyperintense rim measuring <1.5 cm in size at one of the perforating artery territories. Cerebral microbleed was defined as round or ovoid hypointense lesions appearing on susceptibility-weighted images, excluding traumatic hemorrhage or calcification lesions. Cerebral atherosclerosis score (CAS) was calculated by the sum of the degrees of stenosis of the intracranial arteries on brain CTA. Stenosis of intracranial arteries was identified at bilateral anterior/middle/posterior cerebral arteries, BA, intracranial portion of internal carotid arteries, and vertebral arteries and scored as follows: 0, no stenosis; 1, <50% stenosis; 2, >50% stenosis but no occlusion; 3, occlusion.

2. Transcranial Doppler ultrasonographic examination

Within 7 days of admission, TCD ultrasonography was performed by an experienced medical technician with a 2-MHz probe and Companion III (Nicolet EME, UK). In all patients, the sonographic parameters, including peak systolic flow velocities (PSVs), peak diastolic velocities (PDVs), and mean flow velocities, were measured with a probe in the bilateral MCAs, BA, and other sites. All sonographic measurements of BA were performed via a transforaminal window with an insonation depth of 80–100 mm in the lying position. PI was measured according to the Gosling formula [{peak systolic velocity (PSV) – peak diastolic velocity (PDV)}/{(PSV+2PDV)/3}], as described in previous studies.[20, 24] All the results from TCD ultrasonography were interpreted by certified neurologists.

3. Statistical analysis

All statistical analyses were performed using SPSS (version 21.0; IBM Corporation, Armonk, NY, USA) and R (version 3.5.1, July 2, 2018). First, the patients were divided into four groups according to BA PI quartiles. The differences among the groups for categorical variables were assessed using the Fisher’s exact or Pearson’s χ2 tests, the NIHSS and CAS was compared using the Mann–Whitney *U*-tests or Kruskal–Wallis tests, and the differences among the groups for continuous variables were assessed using Student’s *t*-tests or one-way analysis of variance tests. Data are expressed as means ± standard deviation for continuous variables and number (%) for categorical variables. The correlation between BA PI and MCA PI was analyzed by Pearson correlation analysis for ascertaining whether there were any corresponding changes in BA PI owing to various conditions that affected MCA PI.

Second, the patients were grouped into two groups: patients with ND and those without ND to derive factors associated with ND. The differences between the groups for categorical variables were assessed using the Pearson’s χ2 tests, NIHSS and CAS were compared using Mann–Whitney *U*-tests, and the differences between the groups for continuous variables were assessed using Student’s *t*-tests. Multivariable logistic regression analyses using a forward stepwise method were performed to find independent factors related to ND with adjustments for confounding factors derived from bivariate analysis. The results were presented as adjusted odds ratios (ORs) with 95% confidence intervals (95% CI). A *p* value of <0.05 was regarded as statistically significant.

**Results**

A total of 779 consecutive patients with acute ischemic stroke or TIA were registered in the Chung-Ang University Hospital Stroke Registry during the study period. Among them, 708 patients (mean age, 68.2 ± 13.0 years; 347 female patients) who had undergone TCD ultrasonography were finally included. The mean BA PI was 0.96 ± 0.23, and the patients were categorized into four subgroups according to their BA PI values with the following cut-off points: 0.80, 0.94, and 1.10 (Table 1). As BA PI increases, mean age, NIHSS at admission, serum homocysteine level, HbA1c level, and the proportion of females, HTN, DM, and the presence of old lacunes also increased (Table 1). The proportion of patients who experienced ND showed an increasing tendency to belong to the BA PI group. BA PI was well correlated with right MCA PI (r = 0.757, *p* < 0.001, Figure 1).

ND occurred in 92 patients (13.0%). Comparison between patients with ND and those without it revealed that ND was associated with older age, higher systolic blood pressure (SBP), higher NIHSS at admission, current smoking state, presence of atrial fibrillation, and higher CAS (Table 2). BA PI was higher in patients with ND (1.02 ± 0.26) than in neurologically stable patients (0.95 ± 0.22). Bivariable analyses showed that old age, female sex, high SBP, CAS, current smoking state, atrial fibrillation, higher NIHSS at admission, and high BA PI were associated with ND (Table 2). Multivariable logistic regression model including age, female sex, HTN, DM, appearance of old lacunes on brain MRI, and CAS derived from brain CTA revealed that the highest BA PI quartile was independently associated with ND (OR = 2.06; 95% CI = 1.04–4.09; *p* = 0.039; Table 3).

**Discussion and Conclusions**

In this study, which included 708 acute stroke patients who had undergone brain MRI, CTA, and TCD ultrasonographic examination, ND occurred in 13.0% patients and the proportion of patients with ND was the highest in the highest BA PI quartile group. Multivariable logistic regression analysis conducted after adjusting clinical and imaging variables showed that BA PI is an independent factor associated with ND. Although right MCA PI was well correlated with BA PI, its detection was not possible owing to poor temporal windows in 252 (33.05%) patients.

Exaggerated pulsatile cerebral blood flow can result in cerebrovascular endothelial failure, blood–brain barrier disruption, perfusion decrease during diastolic phase, and increase in endothelial shear stress.[12, 16, 17, 18, 25] Several studies have demonstrated that elevated PI is linked with an inverse nonlinear relationship of cerebral perfusion pressure and linear relationship of intracranial pressure as well as with an increased cerebral vascular resistance and cerebral small vessel disease burden.[22, 26, 27] Our study also showed an increasing tendency in the proportion of old lacunes according to the BA PI quartile, suggesting that small vessel disease burden is related to cerebral arterial stiffness.

Elevated MCA PI is reportedly associated with deterioration of lacunar cerebral infarction.[18] Consistent with a previous study, appropriate results could not be obtained from MCA in the present study owing to poor acoustical temporal windows in approximately 5%–20% of patients.[28] Contrary to MCA PI, BA PI can be measured irrespective of temporal bone windows. A previous study reported that BA PI increased earlier than MCA PI in patients with microangiopathy complicated with DM because vessels in the posterior cerebral circulation have fewer adrenergic neurons which regulate vascular tone in response to stimulations other than those in the anterior cerebral circulation.[21]

The study has several limitations. First, the cross-sectional design of our analyses limits our ability to determine a causal relationship between BA PI and ND. Second, BA PI was only measured at admission, which yielded no data regarding the temporal change during acute cerebral infarction. Third, this study was performed in a single hospital in Seoul, Korea; therefore, more studies are required to generalize our findings. The strength of this study is that we constructed a multivariable logistic model including clinical, laboratory, and imaging variables of brain MRI and CTA and confirmed the independent association between BA PI and ND.

**Summary**

Increased BA PI was independently associated with ND after acute stroke and suggested that cerebral arterial stiffness is linked to further neuronal injury after cerebral infarction. Future studies are warranted to develop therapeutic strategy to prevent secondary neuronal injury by modulating cerebral arterial stiffness.

**Statement of Ethics**

Each participant or their guardian signed written informed consent. This study was approved by the institutional review board of Chung-Ang University Hospital (C2013110) and was conducted in accordance with the 1964 Helsinki declaration and its later amendments.

**Conflict of Interest Statement**

The authors have no conflict of interest to disclose.

**Funding**

The work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A1B03029909, NRF-2019R1F1A1059455). The funding has no role in design, collection, analysis, or interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication.

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Figure legend

Figure 1. Correlation analysis of the relationship between basilar artery and right middle cerebral artery pulsatility indices. The pulsatility index of basilar artery was well correlated with that of right middle cerebral artery (n = 456, r = 0.757, p < 0.001).

Table 1. Clinical characteristics of the study population according to basilar artery pulsatility index

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Group 1  N = 178 | Group 2  N = 192 | Group 3  N = 219 | Group 4  N = 119 | *p* value |
| Age (years) | 59.7 ± 14.0 | 66.5 ± 12.0 | 72.0 ± 10.4 | 76.3 ± 8.7 | <0.001‡ |
| Sex, female, n (%) | 73 (41.0) | 90 (46.9) | 119 (54.3) | 65 (54.6) | 0.03**\*** |
| Vascular risk factors |  |  |  |  |  |
| Hypertension, n (%) | 96 (53.9) | 121 (63.0) | 147 (67.1) | 96 (80.7) | <0.001‡ |
| Diabetes mellitus, n (%) | 39 (21.9) | 64 (33.3) | 87 (39.7) | 49 (41.2) | <0.001‡ |
| Smoking, n (%) | 53 (29.8) | 50 (26.0) | 62 (28.3) | 28 (23.5) | 0.64 |
| Atrial fibrillation, n (%) | 29 (16.3) | 40 (20.8) | 42 (19.2) | 31 (26.1) | 0.22 |
| Previous stroke, n (%) | 16 (9.0%) | 22 (11.5%) | 25 (11.4%) | 18 (15.1%) | 0.45 |
| SBP (mmHg) | 145 ± 25.8 | 145 ± 26.6 | 150 ± 28.1 | 149 ± 26.9 | 0.07 |
| Laboratory variables |  |  |  |  |  |
| Hematocrit (%) | 41.0 ± 6.33 | 40.8 ± 5.64 | 39.6 ± 5.52 | 40.0 ± 5.48 | 0.07 |
| Leukocytes (109/L) | 7.80 ± 2.83 | 8.62 ± 6.46 | 8.41 ± 3.24 | 8.04 ± 3.67 | 0.27 |
| Fasting blood glucose (mmol/L) | 3.40 ± 1.51 | 3.70 ± 1.45 | 3.70 ± 1.57 | 3.86 ± 1.67 | 0.059 |
| HbA1c (%) | 5.99 ± 1.35 | 6.07 ± 1.32 | 6.37 ± 1.43 | 6.31 ± 1.34 | 0.024**\*** |
| Total cholesterol (mmol/L) | 4.82 ± 1.26 | 4.66 ± 1.31 | 4.74 ± 1.25 | 4.66 ± 1.30 | 0.68 |
| LDL cholesterol (mmol/L) | 2.80 ± 0.89 | 2.77 ± 0.95 | 2.80 ± 0.89 | 2.75 ± 0.90 | 0.94 |
| hsCRP (mmol/L) | 0.16 ± 0.56 | 0.19 ± 0.56 | 0.21 ± 0.63 | 0.37 ± 1.05 | 0.07 |
| Homocysteine (μmol/L) | 14.9 ± 7.53 | 14.6 ± 6.28 | 15.2 ± 6.20 | 16.8 ± 6.89 | 0.045**\*** |
| Basilar artery PI | 0.70 ± 0.08 | 0.87 ± 0.04 | 1.04 ± 0.05 | 1.32 ± 0.18 | <0.001‡ |
| Cerebral microbleeds, n (%) | 70 (39.3) | 86 (44.8) | 101 (46.1) | 55 (46.2) | 0.52 |
| Old lacunes, n (%) | 104 (58.4) | 121 (63.0) | 162 (74.0) | 90 (75.6) | 0.001† |
| CAS, median (IQR) | 2 (0–5) | 3 (0–6) | 4 (1–7) | 4 (2–6) | 0.007† |
| Neurological progression, n (%) | 19 (10) | 20 (10) | 28 (10) | 25 (20) | 0.03**\*** |

All numerical values are expressed as means ± SD.

MI, Myocardial infarction; SBP, Systolic blood pressure; DBP, Diastolic blood pressure; HbA1c, Hemoglobin A1c; LDL, Low density lipoprotein; HDL, High density lipoprotein; AST, Aspartate aminotransferase; BUN, Blood urea nitrogen; hsCRP, high sensitivity C-reactive protein; PSV, Peak systolic velocity; DV, Diastolic velocity; PI, Pulsatility index; Rt MCA, Right middle cerebral artery; Lt MCA, Left middle cerebral artery.; CAS, Cerebral atherosclerosis score.

Differences between groups using the analysis of chi-square test and the one-way analysis of variance test, Kruskal–Wallis tests for comparing the cerebral atherosclerosis score (CAS).

**\****p* < 0.05, † *p* < 0.01, ‡*p* < 0.001

**Table 2. Comparison among patients with and without neurological deterioration\***

|  |  |  |  |
| --- | --- | --- | --- |
|  | Neurological deterioration (−)  (n = 616) | Neurological deterioration (+)  (n = 92) | *p* value |
| Age (years) | 67.7 ± 13.2 | 71.2 ± 11.2 | 0.016 ‡ |
| Sex, female, n (%) | 293 (47.6) | 54 (58.7) | 0.06† |
| Hypertension, n (%) | 396 (64.3) | 64 (69.6) | 0.383 |
| Diabetes mellitus, n (%) | 206 (33.4) | 33 (35.9) | 0.733 |
| Smoking, n (%) | 177 (28.7) | 16 (17.4) | 0.031 ‡ |
| Atrial fibrillation, n (%) | 113 (18.3) | 29 (31.5) | 0.005 ‡ |
| Previous stroke, n (%) | 68 (11.0) | 13 (14.1) | 0.488 |
| SBP (mmHg) | 146.3 ± 27.1 | 153.2 ± 25.7 | 0.023 ‡ |
| Hematocrit (%) | 40.4 (5.9) | 40.4 (5.0) | 0.954 |
| Leukocytes (109/L) | 8.21 ± 4.43 | 8.51 ± 3.75 | 0.485 |
| Fasting blood glucose (mmol/L) | 3.65 ± 1.59 | 3.70 ± 1.19 | 0.704 |
| HbA1c (%) | 6.20 ± 1.42 | 6.07 ± 1.04 | 0.278 |
| Total cholesterol (mmol/L) | 4.74 ± 1.30 | 4.67 ± 1.07 | 0.565 |
| LDL cholesterol (mmol/L) | 2.78 ± 0.92 | 2.77 ± 0.84 | 0.898 |
| hsCRP (mmol/L) | 0.22 ± 0.66 | 0.25 ± 0.84 | 0.725 |
| Homocysteine (μmol/L) | 15.40 ± 6.92 | 14.16 ± 5.09 | 0.043 ‡ |
| Basilar artery PI | 0.95 ± 0.22 | 1.02 ± 0.26 | 0.01 ‡ |
| Rt MCA PI (n = 474) | 0.92 ± 0.21  (n = 422) | 0.97 ± 0.27  (n = 52) | 0.208 |
| Cerebral microbleeds, n (%) | 267 (43.3) | 45 (48.9) | 0.37 |
| Old lacunes, n (%) | 416 (67.5) | 61 (66.3) | 0.91 |
| CAS, median (IQR) | 3 (0–6) | 5 (2–8) | <0.001 § |
| NIHSS score at admission, median (IQR) | 2 (0–5) | 6 (3–9) | <0.001§ |

All numerical values are expressed as means ± SD.

MI, Myocardial infarction; SBP, Systolic blood pressure; DBP, Diastolic blood pressure; HbA1c, Hemoglobin A1c; LDL, Low density lipoprotein; HDL, High density lipoprotein; AST, Aspartate aminotransferase; BUN, Blood urea nitrogen; hsCRP, high sensitivity C-reactive protein; PSV, Peak systolic velocity; DV, Diastolic velocity; PI, Pulsatility index; Rt MCA, Right middle cerebral artery; Lt MCA, Left middle cerebral artery; CAS, Cerebral atherosclerosis score; NIHSS, National Institutes of Health Stroke Scale

Differences between groups using chi-square test and one-way analysis of variance test, Mann–Whitney *U*-tests for comparing NIHSS and CAS.

\*Univariably significant with a p value of ≤0.10 and considered in a multivariable model.

†*p* < 0.1, ‡*p* < 0.05, §*p* < 0.001

**Table 3. Logistic regression analysis for the determinants of early neurological deterioration**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Bivariable analyses | | Multivariable analyses | |
| OR (95% CI) | *p* | Adjusted OR (95% CI) | *p* |
| BA PI | 3.59 (1.46–8.79) | 0.005† | 2.29 (0.85–6.15) | 0.101 |
| BA PI, quartiles | | | | |
| Q1 (0.42–0.80) | 1 |  | 1 |  |
| Q2 (0.80–0.94) | 0.97 (0.50–1.89) | 0.936 | 0.97 (0.49–1.92) | 0.929 |
| Q3 (0.94–1.10) | 1.23 (0.66–2.28) | 0.518 | 1.02 (0.53–1.94) | 0.963 |
| Q4 (1.10–2.50) | 2.23 (1.16–4.26) | 0.016\* | 2.06 (1.04–4.09) | 0.039\* |

OR, Odds ratio; CI, Confidence interval; *p*, *p* value; BA PI, Basilar artery pulsatility index measured by transcranial Doppler ultrasonography

Group was divided into quartiles based on BA PI

Adjusted by Age, Sex, National Institutes of Health Stroke Scale at admission, Systolic blood pressure, Serum homocysteine level, Cerebral atherosclerosis score

**\****p* < 0.05