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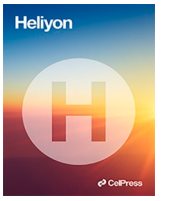

Research article

Hemodynamic predictors of early neurological deterioration and clinical outcome after endovascular treatment in large artery occlusion

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ABSTRACT

Objective: Half of the patients with acute large artery occlusion (LAO) have poor outcomes after endovascular treatment (EVT). Early complications such as cerebral edema and symptomatic intracranial hemorrhage (sICH) can lead to early neurological deterioration (END), which correlates with hemodynamics. This study aimed to identify the hemodynamic predictors of END and outcomes in LAO patients after EVT.

Methods: A total of 76 patients with anterior circulation LAO who underwent EVT and received transcranial Doppler (TCD) monitoring were included. Bilateral middle cerebral artery (MCA) blood flow velocities (BFVs) were measured repeatedly within 1 week. Mean flow velocities (MFV) and MFV index (ipsilateral MFV/contralateral MFV) were calculated. The primary outcome was the incidence of END within 72 h. The secondary outcome was the functional outcome at 90 days—a good outcome was defined as a modified Rankin scale (mRS) score of 0–2, while a poor outcome was defined as an mRS score of 3–6.

Results: A total of 13 patients (17.1 %) experienced END within 72 h, including 5 (38.5 %) with cerebral edema, 5 (38.5 %) with sICH, and 3 (23.0 %) with infarct progression. Multivariable logistic regression analysis showed that a higher 24 h MFV index was independently associated with END (aOR 10.5; 95 % CI 2.28–48.30, $p = 0.003$) and a poor 90-day outcome (aOR 5.10; 95 % CI 1.38–18.78, $p = 0.014$). The area under the receiver operating characteristic (ROC) curve (AUC) of the 24 h MFV index for predicting END was 0.807 (95 % CI 0.700–0.915, $p = 0.0005$), the sensitivity was 84.6 %, and the specificity was 66.7 %. At the 1-week TCD follow-up, patients who had poor 90-day outcomes showed significantly higher 1-week iMFV [73.5 (58.4–99.0) vs. 57.7 (45.3–76.3), $p = 0.004$] and MFV index [1.24 (0.98–1.57) vs.1.0 (0.87–1.15) $p = 0.007$]. A persistent high MFV index (PHMI) was independently associated with a poor outcome (aOR 7.77, 95 % CI 1.81–33.3, $p = 0.006$).

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Conclusion: TCD monitoring within 24 h after EVT in LAO patients can help predict END, while dynamic follow-up within 1 week is valuable in predicting clinical outcomes.

1. Introduction

Large artery occlusion (LAO) accounts for 31.1 % of acute ischemic stroke (AIS) and is an important cause of disability and death [1]. Endovascular treatment (EVT) can significantly improve the prognosis of these patients, but approximately half of them still have a poor prognosis [2–4]. Approximately one-third of patients experience early neurological deterioration (END) after EVT [5–7], including severe cerebral edema, intracranial hemorrhage (ICH), and infarction progression, which are the main causes of poor prognosis [6]. Some studies found that transcranial Doppler (TCD) can predict the occurrence of complications after EVT, and the increased blood flow velocity (BFV) of recanalized vessels is associated with a higher risk of ICH [8] and poor prognosis [9] and can predict the occurrence of early neurological deterioration (END) [10]. However, these studies have different TCD monitoring times and lack dynamic assessment. The association of TCD results with END and clinical outcomes is still unclear. This study investigated the value of TCD in predicting END and long-term prognosis by repeatedly monitoring bilateral middle cerebral artery (MCA) BFV with TCD for 1 week after EVT.

2. Methods

2.1. Patient selection and data collection

This is a retrospective single-center observational study of patients with AIS who had undergone EVT for LAO in the anterior circulation from 2022 March to 2023 March. The inclusion criteria were as follows: age over 18 years, within 24 h of onset, previous functional independence corresponding to a modified Rankin Scale (mRS) $\leq$2, intracranial internal carotid artery (ICA), MCA main stem occlusion demonstrated by digital subtraction angiography (DSA) and achievement of an expanded thrombolysis in cerebral infarction (eTICI) grade $\geq$2b recanalization after EVT. The exclusion criteria were as follows: residual stenosis >50 % of the bilateral cervical segment of the ICA or MCA mainstem and lack of an appropriate transtemporal window.

Data were collected on demographic variables, cardiovascular risk factors, previous treatment, initial National Institutes of Health Stroke Scale (NIHSS) score, blood pressure and blood glucose on admission; initial neuroimaging parameters (occlusion site and hyperdensity of the MCA on CT); intravenous thrombolysis; the status of vascular recanalization, time from onset to recanalization, time to first TCD monitoring after EVT; clinical evolution, incidence of END and 90-day clinical follow-up data. The mRS score served to estimate patient outcomes.

2.2. Treatment protocol

Patients with suspected large artery occlusion underwent computed tomography (CT), CT angiography (CTA) and CT perfusion (CTP) scanning (Aquilion/ONE TSX-301A, Toshiba, Tokyo, Japan). The decision to perform EVT was made according to the latest guidelines, and the procedure was performed after the patient's relatives signed the informed consent form. At our center, EVT was performed within 24 h of symptom onset by 3 interventional neuroradiologists (W.P., S.Z.J., and W.H.D.) with more than 5 years of experience in stroke treatment. The methods of thrombectomy include mechanical thrombectomy with a stent retriever, direct aspiration, balloon dilatation, and angioplasty/stenting. The procedures were performed under general anesthesia in all patients. Recanalization status was evaluated according to the eTICI grading scale, and eTICI grades $\geq$2b were defined as successful recanalization. All patients were subsequently transferred to our stroke unit or neurological intensive care unit with their arterial blood pressure controlled below 140/90 mmHg.

2.3. TCD ultrasonography

All patients underwent bedside TCD (Delica EMS-9 PB, Shenzhen Delica Medical Equipment Co., China) by experienced sonographers in our stroke unit or neurointensive care unit within 24 h after EVT and had follow-up at 48 h, 72 h, and 1 week. We used a 2 MHz pulsed wave Doppler probe to monitor the BFV of the bilateral MCA through the temporal window (depth 50–60 mm) and obtained the peak systolic velocity (PSV), end diastolic velocity (EDV), and mean flow velocities (MFV) (MFV = [PSV-EDV]/3 + EDV) and calculated the MFV index (ipsilateral MFV/contralateral MFV, iMFV/cMFV). Meanwhile, the patient's blood pressure at that time was recorded.

2.4. Follow-up

All patients underwent a dual-energy CT (DECT) scan immediately after EVT and a head CT or magnetic resonance imaging (MRI) within 24–72 h. If necessary, continuous follow-up of neurological imaging was performed. END was defined as an NIHSS score increase of $\geq$1 point in category 1a (level of consciousness) or $\geq$4 points in total within 72 h [11]. END included symptomatic

intracranial hemorrhage (sICH), cerebral edema, and infarction progression confirmed by imaging examinations. All neuroimaging assessments were performed by two experienced neurologists.

2.5. Statistical analysis

Statistical analyses were performed using the IBM Statistical Package of Social Sciences (SPSS), V.26. The normally distributed data between the groups were analyzed using Student's *t*-test, with the results expressed as the mean ± standard deviation. Nonnormally distributed data were analyzed using the Mann−Whitney *U* test, with the results expressed as the median with interquartile range (IQR). Frequencies and categorical data were tested with the $\chi 2$ or Fisher's exact test. To identify early predictors of END, multiple logistic regression analyses were performed, and corresponding odds ratios (ORs) and 95 % confidence intervals (CIs) were calculated. The receiver operating characteristic (ROC) curve was configured, and the Youden index was used to find the cutoff value for balancing the sensitivity and specificity. A p value < 0.05 was considered statistically significant.

3. Results

During the study period, a total of 76 LAO patients had complete recanalization (eTICI grade≥2b) and underwent TCD monitoring after EVT. Fifty patients (65.8 %) were male, with a mean age of 69 ± 14 years. Fifty-two patients (68.4 %) had MCA occlusion. Twenty-five patients (32.9 %) received intravenous thrombolysis before EVT. The median time from onset to recanalization was 446 (269–763) minutes. Fifty-two patients (68.4 %) achieved eTICI grade 2c or 3 recanalization, and 24 patients (31.6 %) achieved 2b recanalization. Further information on medical history, clinical, and treatment characteristics is presented in Table 1.

The median time to first TCD monitoring was 7.3 (2.6–14.7) hours. Of the 76 patients, 13 (17.1 %) had END, including 5 (38.5 %) with sICH, 5 (38.5 %) with cerebral edema, and 3 (23 %) with infarction progression. At 90 days poststroke, 37 patients (48.7 %) had a good functional outcome (mRS 0–2), and 39 patients (51.3 %) had a poor outcome (mRS 3–6), including 6 patients (7.9 %) who died. Fig. 1 shows the description of the patient selection process and grouping.

3.1. END vs. Non-END

Among the 13 END patients, 8 experienced END within 24 h, and 5 deteriorated within 72 h. END patients had higher baseline NIHSS scores, and there were no differences between END and non-END patients in terms of history, clinical, and treatment characteristics (Table 1). END patients had significantly higher baseline NIHSS scores [20 (16–22) vs. 13 (8–16), p = 0.001] and 24 h MFV index [1.55 (1.15–1.75) vs. 0.95 (0.79–1.21), p = 0.001] than non-END patients. There was a worse 90-day functional outcome (mRS

Table 1
Clinical characteristics and *trans*-cranial Doppler findings in END and non-END patients.

Variable	Total (n = 76)	Non-END (n = 63)	END (n = 13)	*p*-Value	OR (95 % CI), *P* -Value (multivariate analysis)
Age, mean ± SD	69 ± 14	68 ± 13	74 ± 14	0.143	–
male sex, n(%)	50 (65.8)	42 (66.7)	8 (61.5)	0.973	–
Diabetes Mellitus, n(%)	19 (25)	15 (23.8)	4 (30.8)	0.860	–
Hypertension, n(%)	50 (65.8)	39 (61.9)	11 (84.6)	0.211	–
Smoking, n(%)	35 (46.1)	32 (50.8)	3 (23.1)	0.068	–
Atrial fibrillation, n(%)	33 (43.4)	27 (42.9)	6 (46.2)	0.827	–
Blood glucose levels (mg/dl), median (IQR)	7.34 (6.34–9.44)	7.23 (6.29–9.29)	7.62 (6.71–12.20)	0.783	–
MBP before EVT (mmHg), mean ± SD	108 ± 20	109 ± 21	105 ± 14	0.534	–
Baseline NIHSS, median (IQR)	15 (9–18)	13 (8–16)	20 (16–22)	**0.001**	**1.2 (1.05–1.37), 0.007**
Antithrombotic therapy, n(%)	22 (28.9)	18 (28.6)	4 (30.8)	1.00	–
MCA occlusion, n(%)	52 (68.4)	44 (69.8)	8 (61.5)	0.796	–
Bridging thrombolysis, n(%)	25 (32.9)	19 (30.2)	6 (46.2)	0.428	–
Time to recanalization (min), median (IQR)	446 (269–763)	451 (267–766)	334 (267–802)	0.435	–
Time to first TCD (h), median (IQR)	7.3 (2.6–14.7)	6 (2.5–13)	12 (2.75–15.8)	0.183	–
eTICI 3/2c, n(%)	52 (68.4)	44 (69.8)	8 (61.5)	0.796	–
Hyperdense of MCA on CT, n(%)	24 (31.6)	19 (30.2)	5 (38.5)	0.796	–
LAA, n(%)	29 (38.2)	25 (39.7)	4 (30.8)	0.773	
CE, n(%)	40 (52.6)	33 (52.4)	7 (53.8)	0.923	
24h MFV index, median (IQR)	1.05 (0.83–1.30)	0.95 (0.79–1.21)	1.55 (1.15–1.75)	**0.001**	**10.5 (2.28–48.30); 0.003**
MBP within 24h, (mmHg), mean ± SD	88 ± 11	88 ± 12	88 ± 11	0.890	–
mRS 3–6 at 90 days, n(%)	39 (51.3)	26 (41.3)	13 (100)	**0.000**	**-**

END, early neurologic deterioration; *SD,* standard deviation; *IQR*, interquartile range; *MBP*, mean arterial blood pressure; *EVT*, endovascular treatment; *NIHSS*, National Institutes of Health Stroke Scale; *MCA*, middle cerebral artery; *TCD,* transcranial Doppler; *eTICI*, expanded Thrombolysis in Cerebral Infarction; *CT,* computed tomography; *LAA*,large artery atherosclerosis; *CE*,cardioembolism; *MFV*, mean flow velocities; *mRS*, modified Rankin Scale.

3–6) in END patients (100 % vs. 41.3 %, $p < 0.001$). In logistic multivariate regression analysis, a higher baseline NIHSS score (aOR 1.2; 95 % CI 1.05–1.37, $p = 0.007$) and 24 h MFV index (aOR 10.5; 95 % CI 2.28–48.30, $p = 0.003$) were independently associated with END. We included these two factors in a variance inflation factor (VIF) analysis, which showed a tolerance of 0.978 (>0.1) and a VIF of 1.022 (<5), which demonstrated noncollinearity between the baseline NIHSS and 24h MFV index. The receiver operating characteristic (ROC) curve showed the diagnostic performance of the 24 h MFV index for detecting END (Fig. 2). The area of the curve (AUC) based on the ROC analysis was 0.807 (95 % CI 0.700–0.915, $p = 0.0005$), the sensitivity was 84.6 %, the specificity was 66.7 %, and the cutoff value was 1.12. Fig. 3 (A-E) shows a representative image of an END patient with an increased MCA MFV index after recanalization.

3.2. MFV index and 90-day outcome

Among the 76 patients, there were no significant differences between the good outcome group and the poor outcome group in age, sex, or other clinical data, but the 24 h MFV index in patients with poor outcomes was higher than in the good outcome group [1.16 (0.92–1.54) vs. 0.93 (0.77–1.17), $p = 0.011$] (Table 2). An ROC analysis was performed. The optimal cutoff value of the 24 h MFV index for predicting 90-day functional outcomes was 1.19, which had a sensitivity of 48.7 %, a specificity of 81.9 %, and an AUC of 0.669 (95 % CI 0.547–0.792; $p = 0.011$). A persistent high MFV index (PHMI) was defined as a result showing an MFV index >1.19 on at least three of the four monitoring sessions, but one of them was at 1 week. The persistent normal MFV index (PNMI) was defined as an MFV index >1.19 detected on at most one occasion only. In the multivariate logistic regression, the 24 h MFV index (aOR 5.10; 95 % CI 1.38–18.78, $p = 0.014$) and PHMI (aOR 7.77, 95 % CI 1.81–33.3, $p = 0.006$) were independently associated with poor 90-day outcomes after adjustment for blood glucose levels and a hyperdense MCA on CT. In addition, PNMI was independently associated with a good outcome (aOR 0.14, 95 % CI 0.038–0.478, $p = 0.002$). Fig. 4 shows the 90-day mRS distribution in patients with PHMI and PNMI.

Within 1 week after EVT, 3 patients underwent bone flap removal within 72 h, 2 patients were discharged automatically, 1 patient died within 48 h, and 4 patients were lost to follow-up. Thus, a total of 67 patients completed the TCD monitoring at 48 h, 72 h, and 1 week. Of these, 35 (52.2 %) patients had good outcomes, and 32 (47.8 %) patients had poor outcomes. Table 3 and Fig. 5 (A, B) show the changes in the ipsilateral MCA flow velocities. IMFV in all patients showed a general trend of increasing and then decreasing over 1 week (Fig. 5A), while iMFV [73.5 (58.4–99.0) vs. 57.7 (45.3–76.3), $p = 0.004$] and the MFV index [1.24 (0.98–1.57) vs. 1.0 (0.87–1.15), $p = 0.007$] in the poor outcome group were still significantly higher than those in the good outcome group at 1 week (Fig. 5B). It can be seen that having a higher iMFV and MFV index at 1 week is more suggestive of a poor outcome, while the recovery of MFV at 1 week is suggestive of a better outcome.

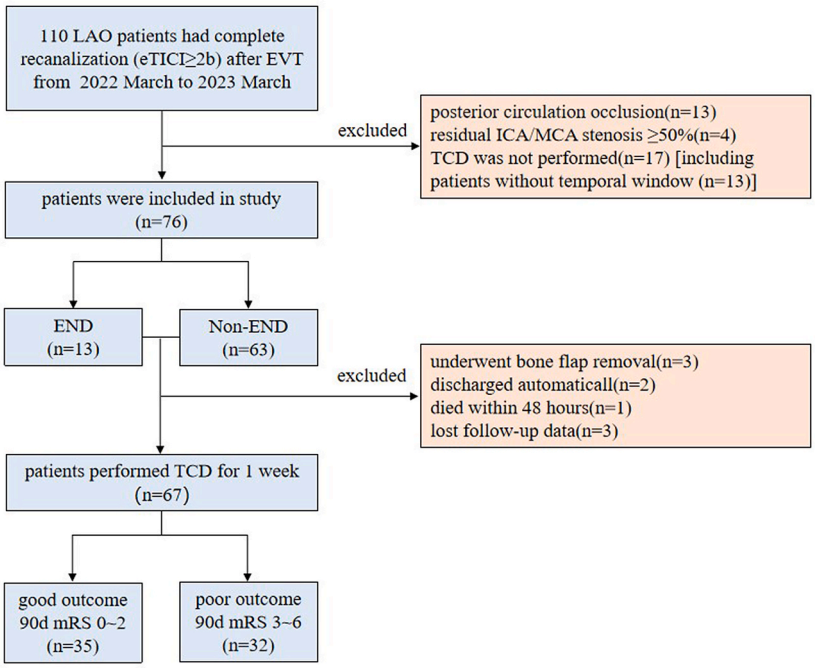

Fig. 1. Description of the patient selection process and grouping.

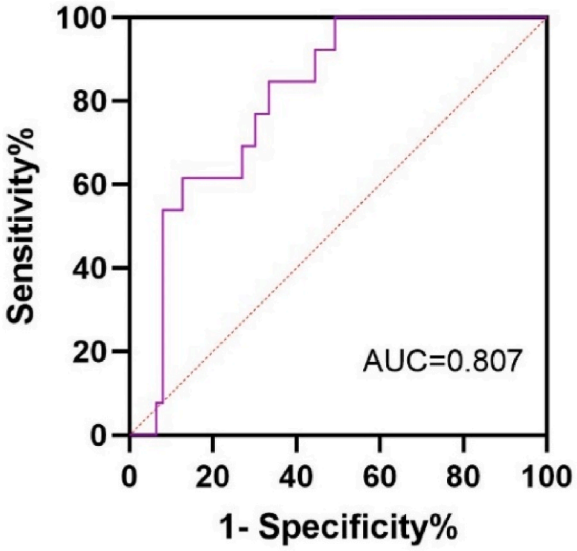

Fig. 2. Receiver operating characteristic (ROC) curve showing the diagnostic performance of the 24h MFV index for detecting END. The area of the curve (AUC) based on ROC analysis was 0.807 (95 % CI 0.700–0.915, p = 0.0005).

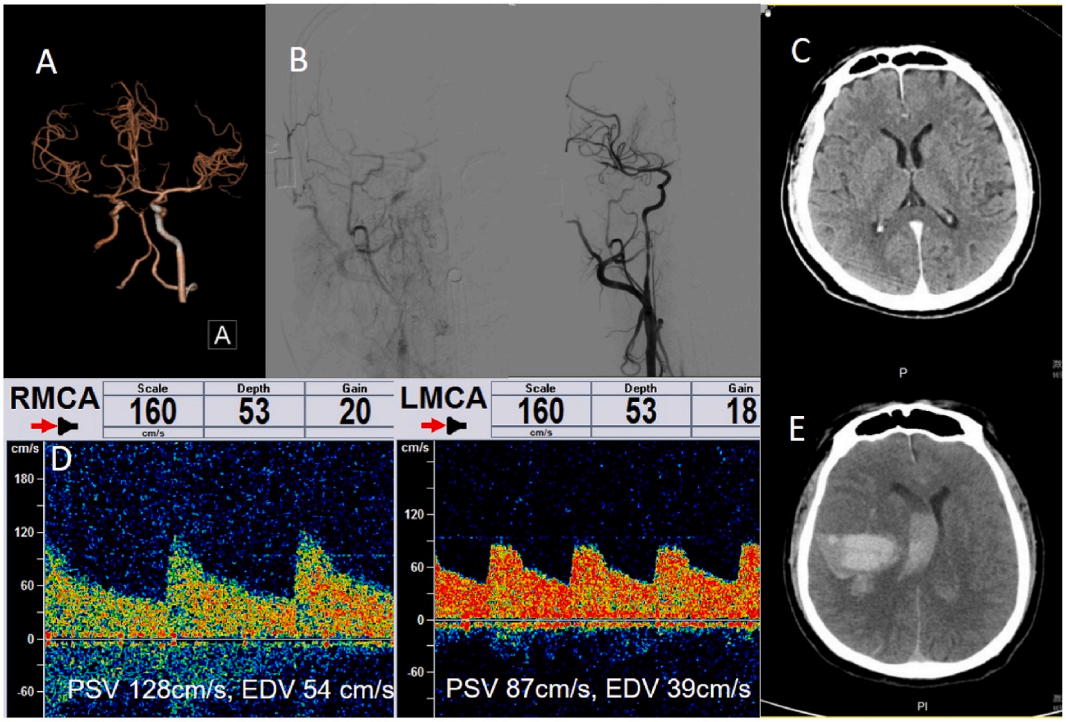

Fig. 3. A 64-year-old man was admitted to the hospital with sudden onset of left-sided limb weakness and slurred speech for 2 h and received endovascular treatment. (A) CTA showed right ICA occlusion; (B) Preoperative DSA showed right ICA occlusion, and postoperative DSA showed recanalization (eTICI grade 3); (C) Postoperative DECT showed no ICH; (D) First TCD monitoring immediately after EVT showed a right MCA PSV of 128 cm/s and EDV of 54 cm/s, a left MCA PSV of 87 cm/s and EDV of 39 cm/s, and an MFV index of 1.43. (E) The patient had sudden projectile vomiting 5 h after EVT with a bilateral pupil diameter of approximately 2 mm. Head CT showed ICH in the right cerebral hemisphere, breaking into the ventricle. The 90-day mRS score was 5.

Table 2
Clinical characteristics and *trans*-cranial Doppler findings in patients with different outcomes.

Variable	Total (n = 76)	Good outcome (n = 37)	Poor outcome (n = 39)	p Value	OR(95%CI), *p*-Value; (multivariate analysis)
Age, mean ± SD	69 ± 14	67 ± 12	70 ± 15	0.423	–
male sex, n(%)	50 (65.8)	26 (70.3)	24 (61.5)	0.423	–
Diabetes Mellitus, n(%)	19 (25)	7 (18.9)	12 (30.8)	0.233	–
Hypertension, n(%)	50 (65.8)	22 (59.5)	28 (71.8)	0.257	–
Smoking, n(%)	35 (46.1)	19 (51.4)	16 (41)	0.367	–
Atrial fibrillation, n(%)	33 (43.4)	15 (40.5)	18 (46.2)	0.622	–
Blood glucose levels (mg/dl), median (IQR)	7.34 (6.34–9.44)	7.23 (5.9–8.2)	7.62 (6.7–10.22)	0.082	–
MBP before EVT (mmHg), mean ± SD	108 ± 20	108 ± 21	108 ± 20	0.974	–
Baseline NIHSS, median (IQR)	15 (9–18)	11 (7.5–15.5)	16 (13–20)	**0.000**	–
Antithrombotic Therapy, n(%)	22 (28.9)	9 (24.3)	13 (33.3)	0.387	–
MCA occlusion, n(%)	52 (68.4)	27 (73)	25 (64.1)	0.406	–
Bridging thrombolysis, n(%)	25 (32.9)	11 (29.7)	14 (35.9)	0.630	–
Time to recanalization (min), median (IQR)	446 (269–763)	451 (295–737)	385 (264–850)	0.901	–
Time to first TCD (h), median (IQR)	7.3 (2.6–14.7)	6 (2.9–11.5)	10 (2.5–15.5)	0.454	–
eTICI 3/2c, n(%)	52 (68.4)	24 (64.9)	28 (71.8)	0.516	–
Hyperdense of MCA on CT, n(%)	24 (31.6)	8 (21.6)	16 (41)	0.069	–
LAA, n(%)	29 (38.2)	15 (40.5)	14 (35.9)	0.677	–
CE, n(%)	40 (52.6)	19 (51.4)	21 (53.8)	0.828	–
24h MFV index, median (IQR)	1.05(0.83–1.30)	0.93 (0.77–1.17)	1.16 (0.92–1.54)	**0.011**	**5.10 (1.38–18.78), 0.014**
24h MBP(mmHg), mean ± SD	88 ± 11	87 ± 12	88 ± 10	0.847	–
PHMI, n%	15/67(22.4)	3(8.1)	12(30.8)	**0.005**	**7.77(1.81–33.3),0.006**
PNMI, n%	45/67(67.2)	29(78.4)	16(41.2)	**0.004**	**0.14 (0.038–0.478),0.002**

SD, standard deviation; *IQR*, interquartile range; *MBP*, mean arterial blood pressure; *EVT*, endovascular treatment; *NIHSS*, National Institutes of Health Stroke Scale; *MCA*, middle cerebral artery; *eTICI*, expanded Thrombolysis in Cerebral Infarction; *CT,* computed tomography; *LAA*,large artery atherosclerosis; *CE*,cardioembolism; *MFV*, mean flow velocities; *PHMI*, persistent high MFV index; *PNMI*, persistent normal MFV index.

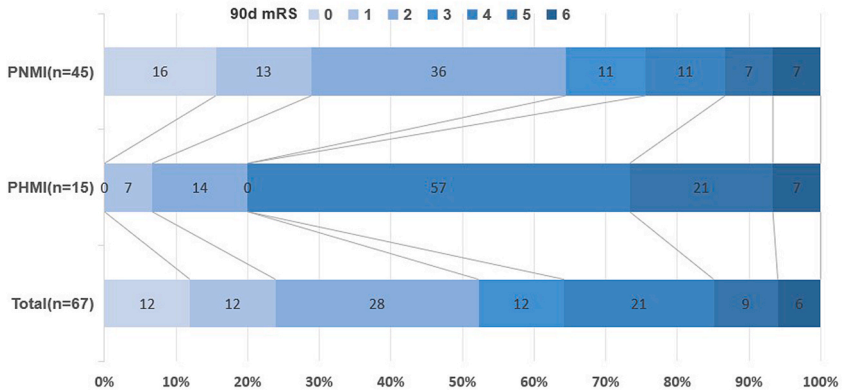

Fig. 4. Distribution of 90-day mRS outcomes in PHMI patients and PNMI patients. *PNMI* , persistent normal MFV index; *PHMI* , persistent high MFV index.

Table 3
Hemodynamic characteristics in patients with different outcomes during 1 week after EVT.

	Time	Total (n = 67)	Good outcome (n = 35)	Poor outcome (n = 32)	p Value
iMFV(cm/s), median (IQR)	24h	52 (42.3–73.3)	52 (42.3–73.3)	55.3 (42.3–74.1)	0.711
	48h	59.7 (44.3–83.7)[b]	57.3 (42.3–77.7)[b]	59.8 (46.3–92.6)[b]	0.393
	72h	67 (48.7–89.2)[a]	64.7 (48–77.7)[b]	72.7 (49.5–98.8)[a]	0.089
	7d	62 (52–85)[a]	57.7 (45.3–76.3)[b]	73.5 (58.4–99.0)[a]	**0.004**
MFV index, median (IQR)	24h	1.0 (0.82–1.26)	0.94 (0.77–1.18)	1.09 (0.89–1.52)	0.098
	48h	1.0 (0.89–1.20)[b]	1.0 (0.86–1.14)[b]	1.02 (0.93–1.48)[b]	0.205
	72h	1.05 (0.86–1.29)[b]	0.98 (0.78–1.12)[b]	1.08 (0.93–1.44)[b]	**0.020**
	7d	1.04 (0.93–1.45)[b]	1.0 (0.87–1.15)[b]	1.24 (0.98–1.57)[b]	**0.007**

[a] Compared with 24h iMFV (index), $p < 0.05$. [b] Compared with 24h iMFV (index), $p > 0.05$.
iMFV, Ipsilateral mean flow velocities; *MFV index,* ipsilateral MFV/contralateral MFV; *IQR*, interquartile rang.

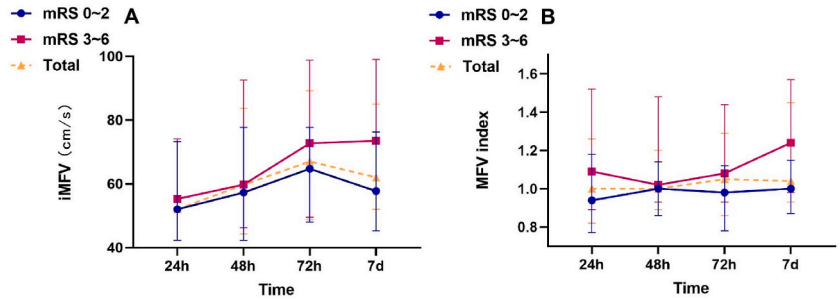

Fig. 5. Hemodynamic follow-up for 1 week after successful recanalization in patients with different outcomes. **A** iMFV over 1 week; **B** MFV index over 1 week. *iMFV*, Ipsilateral side mean flow velocities; *MFV index*, ipsilateral MFV/contralateral MFV.

4. Discussion

Our study showed that hemodynamic changes within 1 week after EVT in LAO patients were valuable in predicting complications and neurological prognosis and that an increased MCA MFV index within 24 h after surgery was an independent risk factor for the development of END. Patients with a persistent high MFV index within 1 week had a poor prognosis, whereas a normal MFV index with a stable trend within 1 week suggested a good prognosis.

Endovascular treatment can significantly reduce disability and mortality rates in patients with LAO, but half of patients still have a poor prognosis [2–4]. Vascular occlusion leads to decreased cerebral blood flow (CBF), followed by rapid neuronal ischemia, hypoxia, dysfunction, and cytotoxic edema and is accompanied by blood–brain barrier disruption and cerebral autoregulation impairment. The sudden restoration of cerebral blood flow after hematologic reconstitution may result in a pathological increase in capillary hydrostatic pressure, exacerbating blood–brain barrier leakage and predisposing to complications such as ICH and cerebral edema and causing END [12,13]. In our study, END occurred in 13 patients, and the median time of TCD monitoring for these patients was 6 (2.5–13) h. Since END mostly occurs within 24 h and patients are unlikely to show END symptoms when they are under anesthesia or sedation after EVT, TCD monitoring immediately after EVT within a few hours is more predictive of END.

Aaslid et al. used TCD in 1982 to monitor the MFV of major intracranial arteries such as the MCA to estimate CBF [14], and TCD assessment of cerebral perfusion is currently used in several fields [15–18]. In carotid endarterectomy, a significant increase in flow velocity in the affected vessel postoperatively compared to preoperatively suggests the occurrence of hyperperfusion [19]. Previous studies have shown that the risk factors for END include age, female sex, large artery atherosclerosis, previous use of antiplatelet drugs, baseline NIHSS score, and admission systolic blood pressure et al. [5,6,20]. Our study also showed that the baseline NIHSS score was a risk factor for END. A higher baseline NIHSS score can indicate that patients have larger ischemic tissue and worse collateral circulation, so they are more likely to have postoperative complications and often have a poor prognosis.

At present , there is still a lack of research on the predictive efficacy of hemodynamic factors for END. Our study showed that an increase in the MFV index within 24 h was an independent risk factor for END in LAO patients who achieved successful recanalization after EVT, which is similar to the results of previous studies. Several studies have shown that an increase in ipsilateral flow velocity compared to the contralateral side (MFV index) postoperatively is associated with the risk of ICH [8,21,22]. He et al. found that iMFV/cMFV $\geq$1.12 increased the risk of ICH and cerebral edema [10]. Castro et al. found an abnormal decrease in the cerebrovascular resistance index and an increase in mean cerebrovascular flow velocity before the onset of cerebral edema [23]. In our study, patients with residual stenosis $\geq$50 % were excluded, and the flow velocity difference due to stenosis was avoided to some extent. Several factors may have contributed to the increased BFV. Hyperperfusion and reperfusion injury may play a synergistic role in the development of END [13,24]. Cerebral ischemia disrupts the cerebral autoregulation that keeps CBF stable, making it more susceptible to changes in blood pressure, which can lead to perfusion abnormalities. The regulatory mechanism of cerebral autoregulation is still unclear. According to metabolic theory, cerebral ischemia results in a decrease in CBF, local O2 levels, and an accumulation of CO2 and other metabolites, which causes distal cerebral vasodilation [25], and for every 1 mmHg increase in partial pressure of CO2 (1 mmHg = 0.133 kPa), CBF increases by approximately 4 % [26]. Approximately 48 % of LAO patients experience hyperperfusion after EVT [27]. Focal hyperperfusion is associated with hemorrhagic transformation [28,29], and certain patients may have severe hyperperfusion syndrome [24,30]. Notably, certain studies have shown that a rise in CBF on the afflicted side is a trustworthy sign of reperfusion and a predictor of a good outcome [31,32]. Therefore, more research into the relationship between BFV and CBF is necessary. In our study, 3 patients experienced infarct-progressive END, which probably caused by a reperfusion injury. It was shown that there was still a large increase in the infarct volume in LAO patients after revascularization [33]; Gomez-Escalonilla et al. found that an increase of more than 50 % in MFV on the affected side compared to the contralateral side 6 h after EVT was an independent predictor of large infarct volume [34]. Larger infarct volumes are associated with more severe cerebral autoregulatory dysfunction [35], leading to poorer vasoconstriction performance and greater susceptibility to abnormal increases in BFV. Similar to previous study [8], our study did not find a significant correlation between the baseline NIHSS score and the 24 h MFV index. However, the correlation between them remains unclear and requires further study.

Among the 76 patients, the 24 h MFV index was significantly higher in poor-outcome patients than in good-outcome patients. After excluding 9 patients who were lost to follow-up, the 24 h MFV index in the poor-outcome group was still higher than that in the good-

outcome group, but there was no significant difference because 6 of these 9 patients had END, all of whom had a high 24 h MFV index and a poor prognosis. Subsequent flow monitoring in the remaining 67 patients showed an overall trend of increasing and then decreasing iMFV within 1 week after EVT (Fig. 5), which differs from another study [9]. We observed that a peak in iMFV increased not in the immediate postoperative period but at 48–72 h. This is related to the fact that most patients were sedated or anesthetized after EVT, and all patients were under strict blood pressure control, which has an impact on the BFV. IMFV then gradually increased as sedative drugs were discontinued. Patients became conscious, and their cerebral autoregulation recovered. Cerebral autoregulation on the affected side was persistently impaired within 1 week after AIS onset and gradually returned to normal by the second week [36]. Persistent impairment of cerebral autoregulation was associated with ICH and malignant cerebral edema [37]. EVT can help prevent further deterioration of cerebral autoregulation [38], and therefore, the time to cerebral autoregulation recovery after successful recanalization may be earlier than in patients without recanalization. We considered that the decrease in iMFV from 72 h to 1 week was associated with the recovery of cerebral autoregulation, and it can be assumed that iMFV will remain relatively stable after 1 week. In addition, the poor-outcome group had a significantly higher MFV index at 1 week. The good-outcome patients had a milder degree of cerebral autoregulation damage with less effect on hemodynamic velocity, whereas poor-outcome patients had a larger infarct volume with severe cerebral autoregulation damage and took longer to return to normal cerebral hemodynamics. Baracchini et al. showed that early BFV normalization after EVT was a predictor of good prognosis [9], which is similar to our findings. Patients with a better prognosis had an earlier decrease in iMFV to normal levels and a stable normal MFV index for 1 week, whereas a persistently higher iMFV suggested a poorer prognosis. We emphasize the importance of 1-week TCD monitoring in LAO patients after EVT, as the MFV index within 24 h is of greater value in predicting END, while the trend of the iMFV and MFV index at 1 week after EVT is of greater value in suggesting outcomes.

There are still some limitations in this study. First, as an ultrasound technique, the results of TCD monitoring are highly dependent on the operator's experience, and TCD can only monitor flow velocity changes and cannot assess vessel diameter size, which lacks spatial specificity. Our elderly patients with poor temporal window translucency could not be monitored accurately because no ultrasound contrast was available. Second, only 1 week of BFV monitoring was performed in this study, and flow velocity after 1 week of EVT was not followed up. Third, our study was a single-center study, so the sample size was small and may not be representative of the population; therefore, a large, multicenter study is needed to validate it. Our study highlights the value of TCD for early hemodynamic assessment after EVT in patients with LAO, which can provide predictive information for the emergence of complications and prognosis so that clinicians can take early measures, such as strict blood pressure control, early dehydration to lower cranial pressure or timely decompression by debridement, to prevent further deterioration and improve the clinical outcomes of patients.

5. Conclusions

Our study shows that an increased MFV index in LAO within 24 h after EVT increases the risk of END and that a persistently high MFV index within 1 week predicts poor clinical outcomes. Therefore, hemodynamics should be closely monitored by TCD in LAO patients within 1 week after EVT.

Ethical approval

This study involved human participants and was approved by the Human Ethics Committee of Zhejiang Provincial People's Hospital (ID: No. 2017KY021). Participants gave informed consent before participating in the study. The study was conducted in accordance with the 1964 Declaration of Helsinki.

Data availability statement

Data relevant to this study are not stored in publicly available repositories. Data will be made available on request.

CRediT authorship contribution statement

Jie Xu: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Xin-Yi Chen:** Methodology, Formal analysis. **Hui-Yuan Wang:** Investigation, Data curation. **Ya-Fei Shang:** Investigation, Data curation. **Pan-Pan Shen:** Writing – original draft, Formal analysis. **Sheng Zhang:** Supervision, Formal analysis. **Shun-Yuan Guo:** Writing – review & editing. **Ming-Ming Tan:** Funding acquisition. **Yu Geng:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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