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Case report

A case report of the treatment of carotid artery stenosis by staged angioplasty based on intraoperative TCD monitoring

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ABSTRACT

Objective: Cerebral hyperperfusion syndrome (CHS) is the most severe complication of carotid artery stenting (CAS) or endarterectomy (CEA). Staging treatment can effectively reduce the risk of CHS without increasing the risk of ischemic stroke. The first stage of balloon dilatation is critical for staged treatment. However, the successful criterion of the first stage balloon dilatation is still inconsistent.
Method: In the current study presents a case of a 61-year-old male with bilateral internal carotid subtotal occlusion, transcranial doppler (TCD) was used to measure middle cerebral artery (MCA) flow rate on the narrow side of surgery and the results are promising.
Result: Intraoperative TCD monitoring is expected to be an evaluation criterion for staged angioplasty for carotid artery stenosis.
Conclusion: The approach of blood flow velocity in the brain based on intraoperative measurement of TCD during the treatment of this patient is a new idea for staging treatment in the future.

1. Introduction

Cerebral hyperperfusion syndrome (CHS) is one of the most severe complications associated with carotid artery stenting (CAS) and endarterectomy (CEA), once it causes intracranial hemorrhage, the death rate can reach to 50 % [1,2]. Significantly, CHS is not as rare as previously thought, for high-risk patients, the incidence rate can reach to 14.1%–18.9 %, which like a devil's curse haunted surgeons. For the prevention of CHS, it's necessary to control blood pressure and enhance monitoring. Unfortunately, for some patients, these measures have failed to prevent the tragedy. It's a good idea that Yoshimura et al. proposed staged angioplasty (SAP) might prevent CHS, which is composed of balloon angioplasty at stage 1 and CAS at stage 2 [3]. Some later studies further confirmed the effectiveness of SAP for CHS prevention and the safety of the surgery [4–11]. However, there is a critical problem for SAP, that is, the successful criterion of the first stage of balloon dilation is not clear. So far, the recent researches about the goal setting for the first stage of balloon angioplasty is inconsistent. Some took the improvement of forward blood flow after balloon angioplasty as the target without re-constriction of the lesion after 30 minutes (mins) observation on angiogram [7]; others took the residual stenosis after balloon/angioplasty less than 70 % as the target of stage 1 [11]; others took the minimum luminal diameter (MLD) exceeded 2mm on intravascular ultrasonography as target [3]. While, some studies suggested that the optimal MLD may be slightly less than 2mm [9].

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The idea of the above criterias is to find a uniform quantitative measurement of improvement in proximal stenosis in order to provide an effective but not excessive improvement in blood supply for the distal end of the stenosis lesion.

For the first time, we attempted to evaluate the success of the first stage of balloon angioplasty for carotid stenosis in patients with bilateral internal carotid subtotal occlusion, transcranial doppler (TCD) was used to measure MCA flow rate on the narrow side of surgery, rather than overemphasizing residual stenosis after balloon dilation. The results are promising and provide a new approach for staging treatment in the future. It's worth noting that if we had adhered to the goal of the previous balloon angioplasty treatment at the first stage, the dilatation outcome in this patient would have been considered significantly below standard.

2. Case presentation

A 61 years old male was admitted to the Department of pain in the Zhejiang Provincial People's Hospital with complaint of pain in the right shoulder joint for 9 months at Oct 20, 2020. He had a history of hypertension and hospitalized in the local hospital for "left side cerebral infarction" 10 months ago and discharged from the hospital with a vague speech and immobility of the right limb. After leaving the hospital, he adhered to take aspirin 100mg once a day and atorvastatin 20mg once a night, amlodipine 5mg once a day. When he was admitted to the pain department, on physical examination he was vague speech, right nasolabial groove slightly shallow, slight weakness in the right limb. The National Institute of Health stroke scale (NIHSS) score was 2. After admission 3 days, the patient's speech disturbance was worse than before suddenly. On physical examination, the patients with mixed aphasia. The rest of the physical examination was the same as before and the NIHSS score was 5. She was transferred to the Department of Neurology immediately. Cranial one-stop multi-mode computed tomography (CT) was performed, non-contrast CT showed no signs of bleeding or massive infarction (Fig. 1A), and cerebral computer tomography angiography (CTA) indicated proximal occlusion of the left internal carotid artery (ICA) (Fig. 1B). It was suggested that the patient had a minor ischemic stroke with large artery occlusion and intravenous Alteplase (0.9mg/kg) was given 146 minutes after onset. Considering he was a disabling stroke, we suggested emergency cerebrovascular angiography and emergency endovascular treatment as appropriate, but the patient's family insisted on refusing. After intravenous Alteplase 24 hours, cranial CT reminded no bleeding transformation, we gave aspirin 100mg, clopidogrel 75mg, and atorvastatin 40mg once a day. There was no significant improvement or progression in the patient's condition. The combined CTA of the head and neck, and CT perfusion (CTP) examination found that the left ICA recanalization with extremely severe initial stenosis of the patient (Fig. 2A), the right ICA had extremely severe initial length stenosis (Fig. 2B), the right vertebral artery was dominant with moderate or severe initial stenosis and the left vertebral artery was thin with multiple severe stenosis (Fig. 2C). In CTP original image, increased pial arteries are seen (Fig. 2D). CTP suggested bilateral anterior mass hypoperfusion (Fig. 2E). The patient received the digital subtraction angiography (DSA), subtotal occlusion (extremely severe stenosis) of the initial segment of bilateral ICA (Fig. 3A and B), dominance of the right vertebral artery (RVA), severe stenosis at the initial segment (Fig. 3C), compensatory blood supply to the bilateral anterior circulation through the pial branch and the slender posterior communication artery (Fig. 3D and E), the left vertebral artery (LVA) was thin and multiple severe stenosis (Fig. 3F). Regrettably, the patient was not cooperative during the operation, and some images were not clear. In addition, high-resolution magnetic resonance (MR) imaging showed that T1 images of bilateral ICA were dominated by equal signals, T2 images of left ICA plaque were dominated by low signals and mixed with slightly higher or equal signals, while the right ICA plaque was characterized by high and low mixed signals, especially high signals in the distal lumen of the lesion. T1 enhanced carotid plaque on both sides was slightly enhanced, while the right side slightly more than the left side. High-resolution MR suggested that the right ICA plaque is relatively unstable, especially with the possibility of intra-plaque bleeding or thrombosis in the distal segment (Fig. 3G). The TCD also showed that severe stenosis before the onset of bilateral ICA ophthalmologic artery, posterior communication artery and anterior communication artery are open on both sides, and at the left side, the external carotid arterio-ICA circulation is open. (Fig. 4E–G, Table 1). Meanwhile, blood flow signals of both anterior cerebral arteries (ACA) were reversed, and bilateral posterior cerebral artery (PCA) blood flow velocity were increased.

The patient changed his initial idea and requested active intervention treatment, after in-depth communication with the patient. The interventional treatment plan is left ICA balloon dilation at the first stage, left ICA stent implantation at the second stage, and right

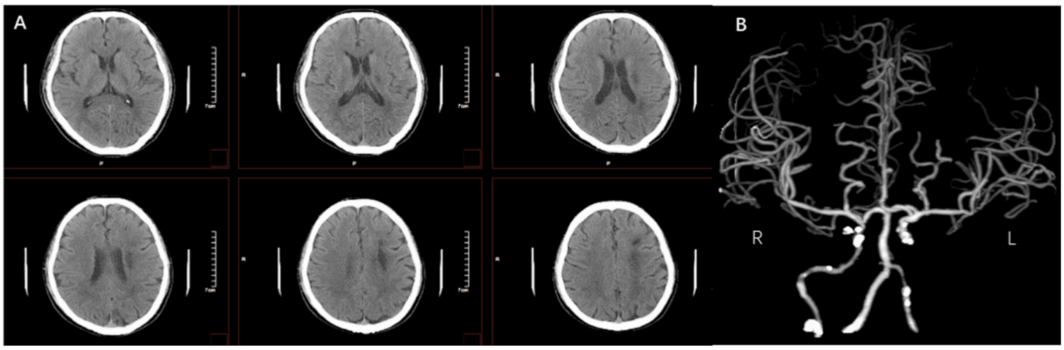

Fig. 1. The computed tomography (CT) and cerebral computer tomography angiography (CTA) of the patient. (A) Non-contrast CT showed no signs of bleeding or massive cerebral infarction; (B) Cerebral CTA showed occlusion of the left internal carotid artery.

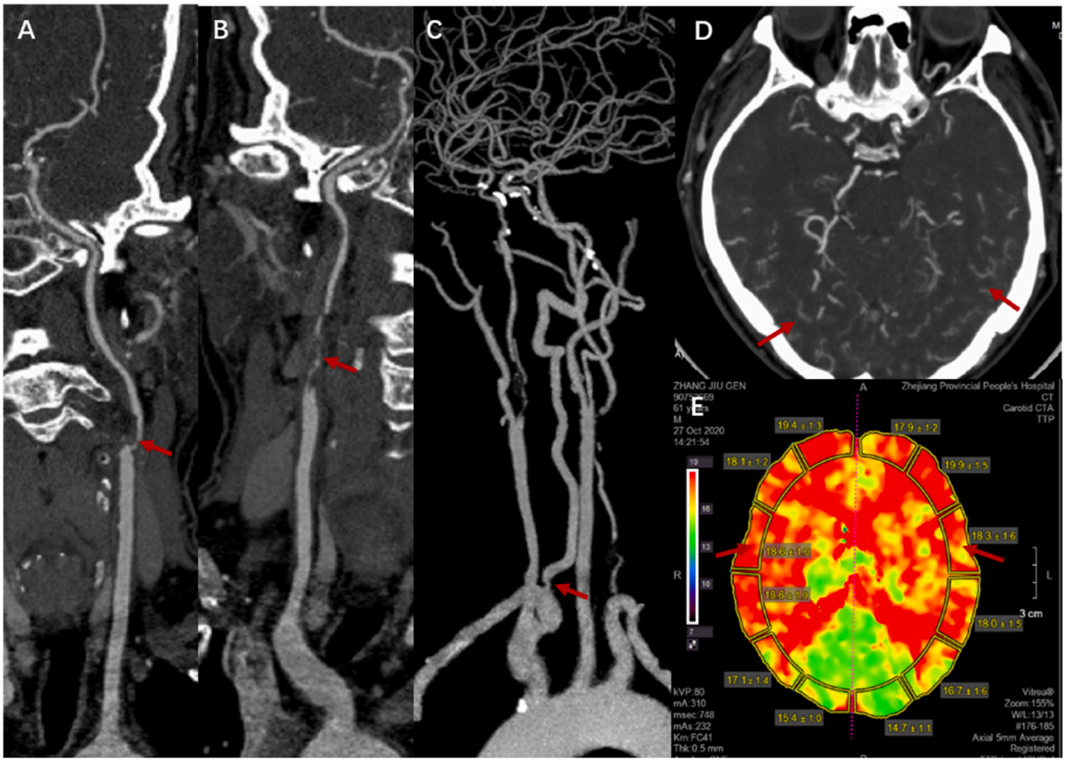

Fig. 2. The combined computer tomography angiography (CTA) and Computer tomography perfusion (CTP) of the head and neck after the patient received intravenous Alteplase. (A) The left internal carotid artery recanalization with extremely severe initial stenosis; (B) The right internal carotid artery had extremely severe initial stenosis; (C) The right vertebral artery was dominant with severe initial stenosis (red arrow), the left vertebral artery was tenuous with multiple severe stenosis; (D) The pial arteries were significantly increase; E: CTP showed bilateral anterior circulation transit time to the peak (TTP) significant extension. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

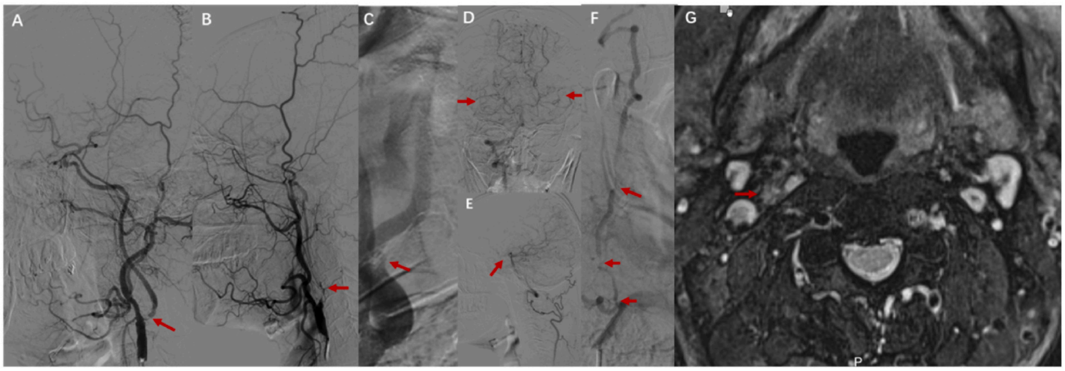

Fig. 3. A: The digital subtraction angiography (DSA) and High-resolution magnetic resonance (HRMR) of the patient before treatment. (A) The initial segment of left internal carotid artery (ICA) was subtotal occlusion; (B) The initial segment of right ICA was subtotal occlusion; (C) The right vertebral artery (RVA) was dominant and its origin was severe stenosis (red arrow); (D–E): Bilateral posterior cerebral arteries provided compensatory blood supply to anterior circulation through the pial branches and the slender posterior communication artery. And the right deep cervical artery compensated for the supply of blood to the right vertebral artery via the intermuscular artery; (F) The left vertebral artery (LVA) was tenuous with multiple severe stenosis (red arrow); (G) HRMR showed the right ICA plaque was characterized by high and low mixed signals, and obvious high signals were present in the distal lumen of the lesion (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

carotid artery stent implantation or carotid endarterectomy (CEA) at the third stage. We performed the first stage of left ICA balloon dilatation plasty on November 10, 2020. For preoperative planning, we planned to adopt the different successful criteria for the first stage of balloon dilatation. Our prespecified successful criteria for balloon dilatation was as follows: 1. The Vm of the left MCA

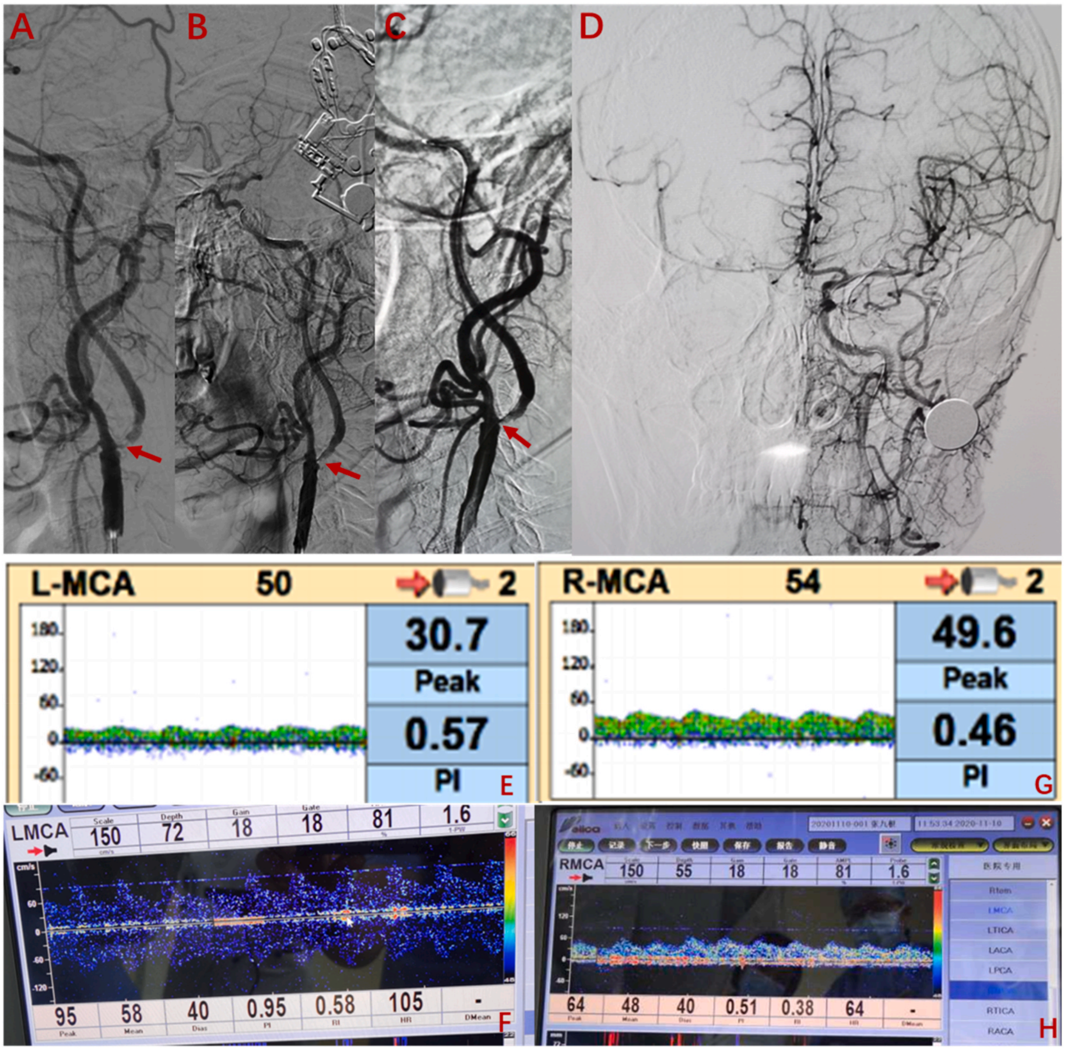

Fig. 4. The digital subtraction angiography (DSA) and transcranial doppler (TCD) of the patient. (A) The initial segment of bilateral internal carotid artery (ICA) were subtotal occlusion before balloon dilation; (B) The first time for 2.0 mm × 15 mm Sprinter balloon dilated the stenosis; (C–D): The second time for 3.0 × 15 mm Sprinter balloon dilated the stenosis; (E): The mean velocity (Vm) and systolic velocity (Vs) of the left middle cerebral artery (MCA) before surgery measured by intraoperative TCD; (F) The TCD showed the postoperative Vm of the left MCA reached 58cm/s and the Vs was 95cm/s; (G) The Vm and Vs of the right MCA before surgery measured by TCD; (H) The Vm and Vs of the right MCA before surgery measured by TCD after the surgery.

Table 1
TCD parameters at different stages of staged angioplasty.

	Vm of LMCA	Vs of LMCA	PI
Baseline	22.9	30.7	0.57
Immediately after balloon dilation at stage 1	58	95	0.95
Two weeks after balloon dilation at stage 1	51.2	77.8	0.89
Immediately after LCAS at stage 2	75	121	0.92
3 months after LCAS at stage 2	52	92.1	1.19

Vm:mean velocity; Vs: systolic velocity; LMCA: left middle cerebral artery; PI: pulse index; LCAS:left carotid artery stenting.

increased more than 50 % after balloon angioplasty. 2. After balloon angioplasty, there was no obvious dissection, plaque prolapse or rupture, and the forward blood flow was stable and could be maintained for more than 30 mins. Before the treatment, the left ICA was confirmed to be subtotal occlusion by DSA (Fig. 4A). 2 M microguide wire Syncro and microcatheter Echlon 10 were applied through the stenosis segment, and the microcatheter Echlon was placed far away from the C1 stenosis segment. After the 2 M microguide wire was withdrawn, contrast agent was first pushed into the microcatheter to correct the cavity, and 3 M microguide wire Syncro was sent along the microcatheter, and the microcatheter was removed. The 2.0mm × 15mm Sprinter balloon was used to slowly dilate the stenosis for 30 seconds (s) to 6 atm. The stenosis was slightly improved by re-examination (Fig. 4B). Intraoperative TCD monitoring indicated that the blood flow velocity of the left MCA did not increase significantly (Table 1). Then, the 3.0 × 15mm Sprinter balloon was used to slowly dilate the stenosis for 45s to 9 atm. After dilatation, re-examination of the DSA still showed significant residual stenosis, and the inner diameter of the narrowest lumen was less than 1mm (Fig. 4C and D), which was far from the successful criterion required by previous studies for staging treatment of first stage of balloon dilatation. Intraoperative TCD monitoring in the anterior flow rural operation indicated that the blood flow velocity of the left MCA had increased significantly. The Vm was more than twice preoperative level, and the Vs more than three times preoperative level (Fig. 4E–Table 1). The Vm of right MCA also increased significantly compared with preoperative level (Fig. 4G). The re-examination showed that the intracranial blood supply of the left ICA was improved compared with that before surgery, and the ACA and MCA on the opposite side can be faintly developed (The contrast agent dosage for left common carotid artery was at a flow rate of 5 m/s, a total volume was 8ml, and a pressure was 250 pounds per square inch). Such "unqualified" stenosis improvement unexpectedly brought such a huge improvement in blood flow. The forward blood flow was stable, after half an hour observation. The vascular wall was relatively orderly after the stenosis site was expanded, and there were no conditions requiring urgent treatment such as dissection. We consider that although the patient's residual stenosis and excessive primary balloon dilation did not meet the successful criteria according to previous studies. However, combined with TCD monitoring values, we believed that the first stage of balloon angioplasty reached or even exceeded the successful criteria specified by us before surgery. After the surgery, we re-examined TCD, compared with the intraoperative detection, in left MCA, the blood flow velocity did not decrease significantly. In right MCA, the blood flow velocity was increase. The patient did not present any manifestations of CHS, such as headache, nausea, and epilepsy during the perioperative period. The patient was discharged from the hospital and the second stage of left CAS was scheduled for 2–4 weeks later.

After two weeks, the patient returned to the hospital and the condition was improved significantly. The patient's memory was significantly improved, the NIHSS score decreased to 2. Before surgery, we re-examined the TCD, the blood flow velocity in both MCA was slightly decreased compared with the TCD on the second day after surgery, but it was not obvious (Table 1). Prior to treatment, the left ICA was still severely stenosis (Fig. 5A).

During the operation, under the protection of the EV3 spider 5.0mm protection umbrella, we pre-expanded twice with the 4 × 30mm Viatrac balloon, with the pressured of 6 atm and 7 atm respectively. After pre-expansion, the residual stenosis was still about 80 % (Fig. 5B). We implanted a 6–8 × 40mm Protégé self-expandable stent, and the post-stent residual stenosis was about 35 % (Fig. 5C and D). Interestingly, intraoperative TCD monitoring indicated no significant change in left MCA blood flow speed immediately after stent implantation (Fig. 5E). After about 3 mins later, the left MCA blood flow speed began to increase significantly compared to before, the surgery was completed (Table 1).

After the surgery, we initially controlled the blood pressure at 100–120/60-80 mmHg. On the second day of post-operation, the patient began to have mild headaches, restlessness, nausea, and vomited once. A repeated CT scan of the brain did not show any signs of cerebral edema or bleeding. TCD re-examination indicated in left MCA, the blood flow speed had not changed significantly compared to before. The brain MR imaging and CTP was not reviewed due to the patient's refusal. Based on the patient's symptoms, we first considered CHS and empirically gave more stricter blood pressure control. The systolic pressure was kept below 100 mmHg and the patient's symptoms of headache, nausea, and restlessness were quickly relieved. The patient was eventually stabilized and discharged. We informed the patient to return to the hospital 1–2 months after discharge for the third stage of treatment, which would be either the implantation of a stent in the right CAS or CEA.

The patient returned to the hospital for the third stage of surgical treatment nearly 3 months later on, because of personal matters.

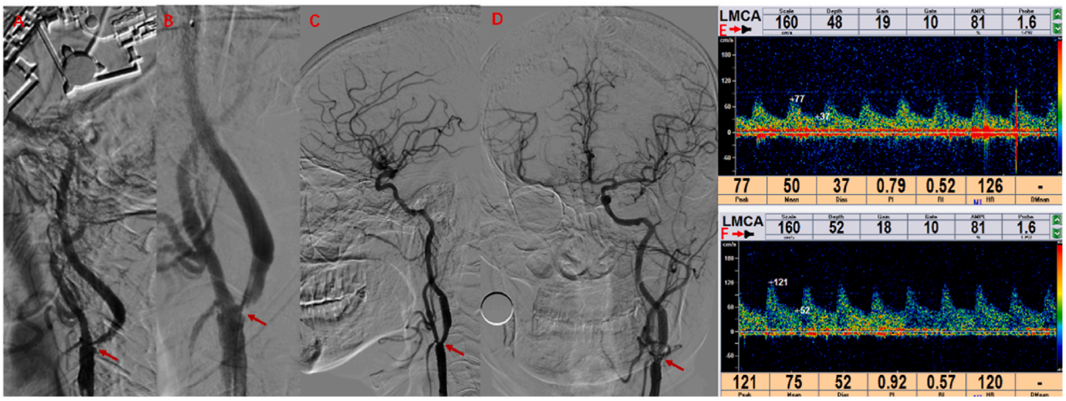

Fig. 5. The digital subtraction angiography (DSA) and transcranial doppler (TCD) of the patient when the patient returned to accept the second stage of staged angioplasty. (A) DSA revealed stenosis of the patient's left internal carotid artery (ICA) before the second stage of staged angioplasty; (B) DSA revealed the residual stenosis of the initial segment of the left ICA was still about 80 % after balloon dilated; (C–D): The post-stenting residual stenosis was about 35 %, after implanted a 6–8 × 40 mm Protégé self-expandable stet; E: The blood flow speed of left middle cerebral artery (MCA) revealed by intraoperative TCD after stent implantation immediately; (F) The blood flow speed of left MCA revealed by TCD after stent implantation about 3 minutes later.

Upon admission, we performed a preoperative TCD examination, the blood flow speed in left MCA decreased compared with the TCD after surgery of the left ICA stent implantation (Table 1). We also re-examined CTA and CTP, which showed that the lumen inside the left carotid artery stent was unobstructed, and the perfusion deficiency of both anterior circulations had significantly improved (Fig. 6A). During this hospital stay, the patient informed us that he had financial difficulties recently and required a more affordable treatment option. Considering factors such as the length of the patient's right ICA lesion and plaque instability aforementioned, we finally transferred the patient to the neurosurgery. On March 21, 2021, the patient underwent right-sided CEA, and the plaque that was tripped off showed thrombus (non-acute) at the distal end of the lesion (Fig. 6B). The patient's condition was relatively stable during perioperative period. A review of the CTA on March 26, 2021 (Fig. 6C) showed that the postoperative effect of right CEA was satisfactory, with no signs of CHS or other complication. The patient was discharged from hospital in a stable condition. The timeline clinical evolution with the most important information of the patient was described in Fig. 7.

3. Discussion

CHS is a serious complication of CAS or CEA, and staging treatment has been shown in several studies to effectively reduce the risk of CHS in high-risk carotid artery stenosis patients without significantly increasing the risk of ischemic stroke [3–11]. Undoubtedly, the first stage of balloon dilatation is critical for staged treatment, and the successful criterion of the first stage balloon dilatation is still an unresolved issue [9]. The previous studies have used criteria that focus on setting a uniform standard for the degree of improvement local stenosis, or residual stenosis less than 70 % [11], or MLD exceeding 2mm [3]. Some researchers have suggested that the optimal MLD might be slightly less than 2mm and believed that further studies are necessary to confirm the best MLD [9]. Breaking away from the current research, we realized that the essential purpose of the first stage for percutaneous transluminal angioplasty (PTA) in staged treatment is not only to moderately improve the ischemic state of the "downstream" cerebral circulation on the lesioned side, but not excessively. This approach reduced the "impact" on the damaged cerebral vascular automatic regulation ability and decreased the time for recovery and adaptation, thus reducing the risk of CHS. For patients with severe carotid artery stenosis, the improvement of blood flow downstream from the proximal carotid artery stenosis of the carotid artery not only depends on the improvement of the proximal stenosis but also on the patient's basic stenosis level, the collateral circulation, the strength of cerebrovascular automatic regulation, as well as the nature of the plaque. The standard value of optimal stenosis improvement in the first stage of balloon dilatation that we have been searching for is just one of the multiple variables affecting intracranial blood flow [3,7,9,11]. Moreover, for patients with extremely narrowed or pseudo-occluded carotid arteries, if the collateral circulation compensates well, they can directly undergo CAS without staging [12]. In addition, due to the plaque, it might be impossible to achieve the goal of an MLD of 2mm with balloon dilation alone. Therefore, we believe that pursuing the "optimal value" of just one variable while ignoring changes in other variables is difficult to achieve in reality. Previous studies have found no answers of how to consider more comprehensively to set the successful criteria for stage treatment in the first phase of balloon dilation.

TCD has been widely used and plays an important role in CEA surgery. Previous studies have suggested that changes in blood pressure and CO_2 have little effect on the diameter of major vessels, so the blood flow velocity of major vessels in TCD can better reflect the blood flow volume [13]. The absolute value of MCA blood flow velocity had a weak correlation with the magnitude of cerebral blood flow (CBF) because of the significant variations among individuals. However, changes in MCA blood flow velocity are closely

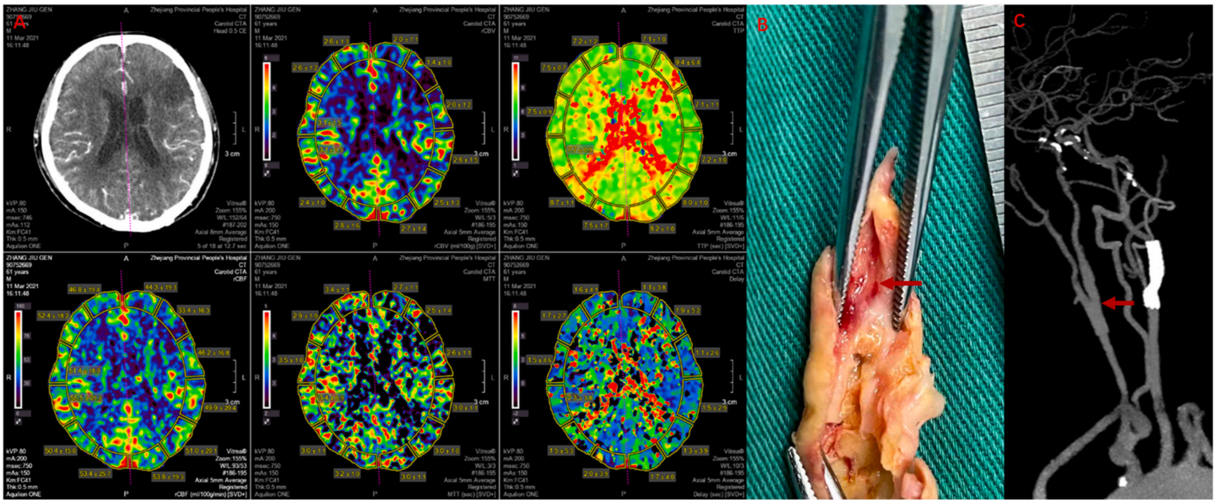

Fig. 6. The computer tomography perfusion (CTP) and cerebral computer tomography angiography (CTA) of the patient during the third stage of staged angioplasty. (A) Before right carotid artery endarterectomy (CEA), the CTP showed bilateral anterior circulation perfusion was significant improved compared to that before the third stage of staged angioplasty; (B) The plaque that was tripped off during CEA showed thrombus (non-acute) at the distal end of the lesion (red arrow); (C) The cerebral CTA showed that the postoperative effect of right CEA was satisfactory (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

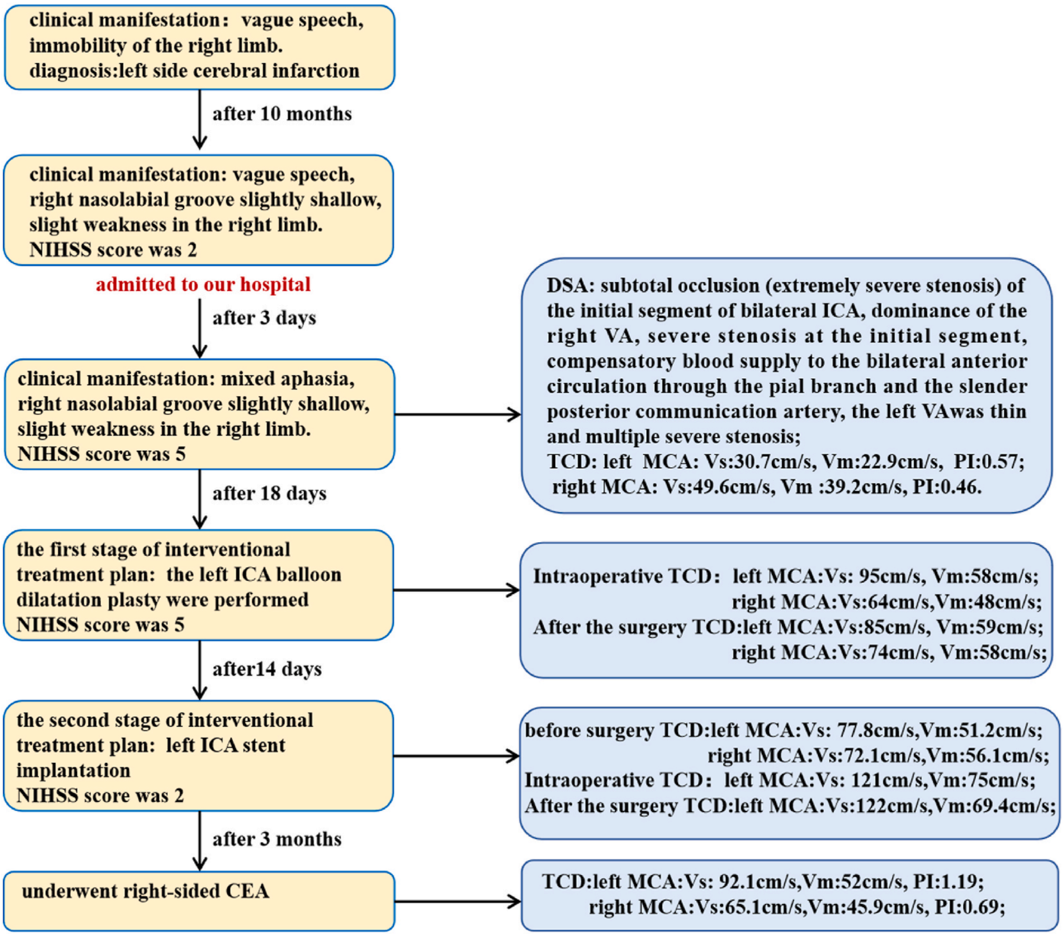

Fig. 7. The timeline clinical evolution with the most important information of the patient.

associated with changes in CBF on the same side [14]. Generally, CBF is related to V mean [15,16]. The changes in the MCA V mean determined by TCD correlate well with the changes in CBF ipsilateral to the operation side [17–19]. Based on previous experiences, as detected by TCD, an increase in the postoperative mean blood flow velocity of the MCA by 1.5–2.0 times the preoperative value can predict the occurrence of CHS [20–22]. The method we adopted in this patient is to rely on intraoperative TCD monitoring in our center, using the blood flow velocity of the ipsilateral MCA as the main reference, combined with intraoperative DSA imaging. We take into account more variables by using the ipsilateral MCA blood flow velocity as a reference, which is relatively more result-oriented and more intuitive to represent the essential effect of staging treatment. In detail, considering the significantly low pulsatility in the patient's left MCA, with a preoperative Vs was 30.7cm/s and Vm was 22.9cm/s, for this patient, our surgery plan set two successful criteria for the first stage of balloon dilation: 1. After the first stage of balloon dilation, the Vm should increase by more than 50 % compared to preoperative level; 2. After balloon dilation, there should no evident dissection, plaque prolapse, or rupture at the lesion site, and forward blood flow should be stable and sustainable (observed for more than 30 mins). Notably, this criterion did not mention the requirements for residual stenosis after balloon dilation, which is significantly different from the thinking of previous research. During the patient's first stage of treatment, the residual stenosis remained over 90 % after two balloon dilations, and the MLD was also much less than 2mm, neither of which met the successful criteria in the first stage of balloon dilation in previous staged treatments. However, according to intraoperative TCD monitoring, the Vm of the ipsilateral MCA exceeded our expectations and stably reached more than twice the preoperative level (58cm/s VS 22.9cm/s). We then had a conclusion that contrasts with previous studies, suggesting that the balloon dilation for this patient was not insufficient. On the contrary, it might have been adequate or even somewhat excessive. Moreover, DSA imaging indicated that the vessel wall was smooth at the site after balloon dilation. After observing for 30 mins with no significant change in blood flow speed. Although, the ipsilateral MCA Vm was more than twice the preoperative level, the patient did not exhibit any signs of hyperperfusion or ischemic events after the first stage of balloon dilation. The second stage of CAS was administered as planned. To our knowledge, this is the first case that intraoperative TCD monitoring values were used as the successful criteria for the first phase balloon dilation of CAS treatment. In cases where previous standards such as MLD or degree of residual stenosis determined unsuccessful results, using intraoperative TCD monitoring indicated successful. There was no need for an emergency coexisting stent. After 30 mins of observation to ensure stable blood flow, the first phase of surgery was concluded and the patient ultimately achieved an ideal endovascular treatment result. Despite intra-operative measurements are associated with both false positive and false negative results [23], intra-operative changes in the MCA velocity with TCD monitoring has been the gold standard for prediction of CHS after CEA [24,25].

Compared with MCA velocity before clamping, a 100 % increase in MCA velocity 3 mins after carotid artery clamping was the most common parameter used to predict CHS after CEA [26]. Typically, patients requiring staged treatment for carotid artery stenosis have extremely severe, or even near-total, occlusion of the carotid artery. Such patients often exhibit marked low pulsatility distally. Some patient even showed the Vm of ipsilateral MCA below 20cm/s. In these instances, the increased risk assessment of hyperperfusion, might be attenuated, due to a certain relative proportion of increase in MCA. For patients undergoing staged treatment, the MCA Vm after first stage of balloon dilation should at least reach over 50 % of the final anticipate MCA Vm after the whole process of staged angioplasty. Otherwise, the risk of hyperperfusion during the second phase of CAS remains high, as MCA Vm may increase by 100 % after CAS. We believe that assessing the risk of hyperperfusion might require considering both the relative multiplicity and the absolute increment. In this patient, the Vm increased to 2.5 times the preoperative level after first phase of balloon dilation, with no post-operative hyperperfusion symptoms. However, after the second phase of CAS, the Vm increase was less than twice, yet there were no suspicious signs of hyperperfusion. Regrettably, no further examinations were conducted to clarify the suspicious hyperperfusion symptoms after the second phase of CAS. Since this is a singular case, further extensive research is warranted to validate the findings.

Besides blood flow velocity, the PI is observed to offer a significant reference point for the occurrence of hyperperfusion. It is acknowledged that the PI value serves as an indicator of vascular resistance. After the first stage of balloon dilation, an elevation in the PI value from 0.57 to 0.95 has been noted. Such a change suggests that the dilated vessels retain their autoregulatory capacity, even with the recuperation of blood flow [27]. If the PI value did not increase or even decline, the risk of hyperperfusion of the patient might be heightened.

Additionally, during the patient's first phase of PTA, neither proximal nor distal embolic protection strategies were employed, diverging from many previous studies [3,11]. The rationale for this decision includes the following: 1. For patients with extreme stenosis, the process of positioning the protection umbrella itself constitutes a high-risk phase for embolization. 2. The patient exhibited compensatory flow from the left external carotid artery to the ICA, proximal protection could potentially diminish this compensatory ability. 3. Slow dilation (30s–45s) with a balloon not exceeding 3mm in diameter tends to present a relatively low risk of embolism. 4. Preoperative high-resolution MR imaging indicated that the plaque within the left carotid artery was comparatively stable. For this patient, our pre-determined successful criteria in the first stage of balloon dilation increased more than 50 % of the ipsilateral MCA V mean. Meanwhile, because of concerns about high perfusion risk, we believed that the increase in V mean should not be more than 100 %. As mentioned earlier, this patient showed a more than 150 % increase in postoperative V mean after the first stage of balloon dilation, and no manifestations of CHS were found. This new staging treatment evaluation method that relies on TCD monitoring also has some limitations. Firstly, TCD depends on operators, and optimal image acquisition is not always feasible. Secondly, the presence of concomitant stenosis in the intracranial segment of the ICA or the MCA will affect the interpretative significance of changes in TCD blood flow velocity. Thirdly, an increase of 1.5–2.0 times in the post-operative MCA average blood flow speed compared to the pre-operative value can predict the occurrence of CHS. Whether this prediction is universally applicable to extremely low baseline blood flow speeds remains to be determined, which implies that the TCD evaluation criteria for phased treatments are still undefined. Lastly, as there are variations in the blood flow speed for a certain period after the surgery, relying only on intraoperative TCD monitoring of MCA flow to assess hyperperfusion risks is inherently limited in scope. In summary, the initial balloon dilation procedure, as a crucial step in the staged treatment of high-risk carotid artery stenosis, requires further research to define its success criteria. The approach of blood flow velocity in the brain based on intraoperative measurement of TCD during the treatment of this patient is a new idea that needs further explorations, but it is expected to be a more reasonable method, compared with the judgment method adopted in previous studies.

The idea of the above criterias is to find a uniform quantitative measurement of improvement in proximal stenosis in order to provide an effective but not excessive improvement in blood supply for the distal end of the stenosis lesion. But this unified quantitative scale seems to be too rigid without taking into account the differences in the degree of baseline stenosis, the condition of distal blood vessels, collateral circulation and so on. If the improvement degree of distal blood flow after primary balloon angioplasty as the main scale, it seems to be more suitable for the nature of staging therapy.

CRediT authorship contribution statement

Peng Jiang: Writing – original draft, Project administration, Methodology. **Houwen Zhang:** Methodology, Data curation. **Xu Wang:** Methodology. **Fangzheng Cao:** Resources. **Chunrong Li:** Writing – review & editing.

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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