

Article

Urgent Carotid Revascularization for Symptomatic High-Grade Carotid Stenosis Associated with Ipsilateral Hemispheric Hypoperfusion: A Single-Centre Retrospective Observational Study

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Simple Summary

Some patients with severe narrowing of the carotid artery have stroke-like symptoms because too little blood reaches one side of the brain, even though brain imaging does not show a large completed stroke. Current treatment recommendations do not clearly define whether these patients should be treated within the usual early time window or more urgently. This study reviewed 27 carefully selected patients with severe carotid narrowing and reduced blood flow on brain perfusion imaging who underwent urgent carotid treatment during the same hospital admission. Treatment was technically successful in all patients, and no deaths, strokes, brain bleeding, major complications, or repeat carotid procedures occurred within 30 days. Most patients had complete neurological recovery before discharge, and no late carotid-related neurological events were recorded during follow-up. These findings may help future studies define which patients with carotid disease and reduced brain blood flow could benefit from urgent treatment.

Abstract

Symptomatic high-grade carotid stenosis may present with extensive ipsilateral hemispheric hypoperfusion without a large infarct core, a grey-zone phenotype between standard early and truly urgent carotid revascularization. This single-centre retrospective observational study described the procedural and clinical outcomes of urgent carotid revascularization in this imaging-defined subgroup. Consecutive patients treated between June 2015 and August 2025 were included when they had recent ipsilateral anterior-circulation symptoms, ipsilateral internal carotid stenosis > 70%, objective hemispheric hypoperfusion involving at least one third of the anterior circulation territory on CT or MR perfusion, and no intracranial haemorrhage or large established infarction. Twenty-seven patients met the criteria. Median NASCET-style stenosis was 92%, and 14 patients (51.9%) had at least one collateral-limiting feature. Revascularization was performed within 48 h in all cases, by carotid endarterectomy in 25 patients and carotid artery stenting in two. Technical success was 100%. No 30-day death, stroke, intracranial haemorrhage, major adverse event,



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or target-lesion reintervention occurred. Complete neurological recovery at discharge was observed in 25 patients (92.6%). During median follow-up of 48.6 months, no late ipsilateral stroke, carotid-related neurological event, neurological death, or target-lesion reintervention was recorded. In this small, selected, uncontrolled cohort, urgent carotid revascularization was technically achievable, and no prespecified 30-day safety events were observed. These descriptive findings do not establish comparative safety or clinical benefit and require prospective multicentre validation.

Keywords: carotid stenosis; cerebral hypoperfusion; carotid endarterectomy; carotid artery stenting; urgent carotid revascularization; perfusion imaging; hemodynamic stroke; collateral circulation; computed tomography perfusion; magnetic resonance perfusion

1. Introduction

Stroke remains one of the leading causes of death and disability worldwide, with a major clinical and socioeconomic burden [1]. Extracranial carotid atherosclerotic disease is a relevant cause of ischemic stroke, particularly in the anterior circulation, and may produce neurological events through thromboembolism from an unstable plaque, hemodynamic impairment caused by severe flow limitation, or a combination of both mechanisms [2–4]. Although plaque embolization remains the dominant paradigm in symptomatic carotid disease, severe stenosis, near-occlusion, or restenosis may also reduce downstream cerebral perfusion, particularly when cerebrovascular reserve and collateral compensation are insufficient [5–8].

The benefit of carotid endarterectomy (CEA) in recently symptomatic carotid stenosis has been established by randomized evidence and subsequent pooled analyses, with the greatest benefit observed in patients with severe stenosis and when surgery is performed early after the index event [9–12]. Current European and North American guidelines recommend expedited revascularization for recently symptomatic carotid stenosis, provided that perioperative risk is acceptable and no major contraindication exists [13–15]. Urgent CEA may be considered in selected unstable presentations, including crescendo transient ischemic attacks (TIA) and stroke in evolution, whereas revascularization is generally deferred or avoided in patients with large established infarction, intracranial haemorrhage, or severe disabling stroke because of the risk of haemorrhagic transformation and reperfusion injury [13–16].

Modern acute stroke pathways increasingly incorporate Computed Tomography perfusion (CTp), diffusion-weighted Magnetic Resonance Imaging (DW-MRI), and MR perfusion techniques to distinguish infarct core from hypoperfused but potentially salvageable tissue. In this context, $T_{max} > 6$ s is widely used to define clinically relevant hypoperfusion, while relative cerebral blood flow $< 30\%$ and diffusion restriction on MRI are commonly used to approximate ischemic core [17–25]. These imaging concepts were developed primarily for thrombolysis and mechanical thrombectomy selection, but they may also be relevant in patients with symptomatic carotid stenosis and suspected hemodynamic compromise.

A clinical and decision-making gap therefore remains at the interface between standard early and truly urgent carotid revascularization. Current guideline-based timing categories are mainly driven by clinical instability, stenosis severity, infarct extent, haemorrhagic risk, and perioperative risk [13,14]. However, they do not specifically define whether a patient with symptomatic severe carotid stenosis, clinically stable or only mildly symptomatic presentation, extensive ipsilateral hemispheric hypoperfusion, and no large established infarct core should be managed as a conventional recently symptomatic carotid stenosis

requiring revascularization within 14 days, or as an urgent carotid syndrome requiring more immediate treatment. This “grey-zone” phenotype may be particularly relevant when advanced imaging suggests persistent low-flow ischemia rather than completed infarction or recurrent embolization alone. In this setting, stenosis severity alone may be insufficient: plaque morphology, contralateral carotid disease, vertebral artery patency, and completeness of the circle of Willis may all influence whether severe carotid narrowing becomes clinically hemodynamic.

The aim of the present study was to evaluate perioperative and long-term outcomes of urgent carotid revascularization in patients with symptomatic high-grade carotid stenosis associated with ipsilateral hemispheric hypoperfusion, using explicit perfusion-imaging criteria and detailed carotid-collateral characterization to define the study population.

2. Materials and Methods

2.1. Study Design

This was a single-center retrospective observational study conducted at a high-volume University Polyclinic serving as a tertiary stroke hub. The study was conducted in accordance with the principles of the Declaration of Helsinki and reported according to the STROBE recommendations for observational studies [26]. Given the retrospective design and the use of anonymized data collected during routine clinical practice, the requirement for specific ethical approval and additional informed consent for study participation was waived according to local institutional policy. All patients had provided written informed consent for carotid revascularization.

2.2. Patient Population

All consecutive patients who underwent urgent carotid revascularization for symptomatic carotid stenosis associated with objective ipsilateral cerebral hypoperfusion between June 2015 and August 2025 were retrospectively reviewed.

At our institution, all patients presenting with symptomatic carotid stenosis through the stroke pathway undergo CT and/or MR perfusion imaging as part of the initial diagnostic work-up. The target cohort was specifically restricted to patients without a conventional clinical indication for hyperacute carotid revascularization based on neurological instability alone, such as recurrent or crescendo transient ischemic attacks or stroke in evolution. Perfusion imaging was therefore used to determine the urgency rather than the indication for revascularization. In patients without a conventional clinical indication for hyperacute treatment, objective extensive ipsilateral hemispheric hypoperfusion, together with the absence of intracranial haemorrhage or a large established infarction, prompted revascularization within 48 h; patients without this imaging phenotype who were otherwise eligible for intervention followed the standard pathway within 14 days rather than being assigned to conservative treatment on the basis of perfusion findings.

Patients were eligible when all of the following criteria were met: recent ipsilateral neurological symptoms compatible with anterior-circulation ischemia; ipsilateral internal carotid artery stenosis > 70%, classified according to North American Symptomatic Carotid Endarterectomy Trial (NASCET)-style criteria; objective ipsilateral hemispheric hypoperfusion involving at least one third of the anterior circulation territory on CTp and/or MR perfusion imaging; absence of intracranial haemorrhage or large established infarction; and urgent carotid revascularization during the index admission.

Patients were excluded if they underwent intravenous thrombolysis, mechanical thrombectomy, or any acute intracranial endovascular treatment; if they had haemorrhagic transformation before carotid revascularization; if imaging demonstrated a large established infarct involving more than one third of the middle cerebral artery territory; if a competing

non-carotid mechanism of the neurological presentation was considered more plausible after multidisciplinary assessment, including cardiac embolic, arrhythmic, or systemic low-flow causes; or if the indication for carotid treatment was not associated with objective ipsilateral hemispheric hypoperfusion.

All patients underwent preoperative cardiac screening with electrocardiography and transthoracic echocardiography, together with review of clinical presentation, neurovascular imaging, and perfusion findings. The study population was therefore restricted to patients in whom the ipsilateral high-grade carotid stenosis with hemispheric hypoperfusion was considered the most plausible mechanism of the neurological presentation, rather than a competing cardiac, intracranial, or systemic hemodynamic cause.

2.3. Neurological Assessment

All patients were evaluated by a neurologist at presentation. Neurological severity was graded using the National Institutes of Health Stroke Scale (NIHSS) before intervention, immediately after intervention, and at discharge. A high NIHSS value alone was not considered an absolute exclusion criterion when advanced imaging demonstrated extensive hypoperfusion without large established infarction, intracranial hemorrhage, or mass effect, and when the multidisciplinary team judged the deficit to be potentially related to hemodynamic impairment.

2.4. Carotid and Collateral Assessment

All patients underwent baseline brain imaging and carotid evaluation. Carotid stenosis was documented by duplex ultrasound (DUS) performed by at least two experienced vascular ultrasound operators and confirmed by computed tomography angiography (CTA) and/or magnetic resonance angiography (MRA) as part of the diagnostic work-up. Stenosis severity was classified using NASCET-style criteria, with the residual lumen at the maximal stenosis compared with the normal distal internal carotid artery when measurable [27]. DUS values were recorded as NASCET-equivalent percentages and peak systolic velocity (PSV).

Plaque morphology was classified on B-mode DUS according to the Gray-Weale/Geroulakos echogenicity classification [28]. Plaque morphology was recorded to support mechanistic interpretation of the neurological event, given the reported association between echolucent or complex plaques and symptomatic plaque instability [28–30].

Collateral and inflow assessment included contralateral internal carotid artery stenosis, vertebral artery patency or occlusion, and circle of Willis completeness on available CTA, MRA, and/or perfusion imaging. All vascular imaging and collateral findings were reviewed within the multidisciplinary team, which always included an experienced neuroradiologist. The circle of Willis was classified as complete or incomplete according to the neuroradiological report and imaging review. For descriptive purposes, a collateral-limiting feature was defined as any of the following: contralateral internal carotid artery stenosis $\geq 50\%$ or occlusion, unilateral vertebral artery occlusion, or incomplete circle of Willis [31,32].

2.5. Perfusion Imaging Assessment

Cerebral hypoperfusion was defined as an ipsilateral anterior-circulation perfusion deficit involving at least one third of the carotid territory. CT perfusion maps were generated using the institutional Siemens Healthineers neuroperfusion post-processing platform (Siemens Healthineers, Erlangen, Germany), according to the routine stroke imaging workflow. When quantitative maps were available, hypoperfusion corresponded to tissue with time-to-maximum (Tmax) > 6 s on CTP or dynamic susceptibility contrast/perfusion-weighted MRI. When quantitative values were not extractable from archived imaging,

hypoperfusion was adjudicated from the original neuroradiological report and visual review of perfusion maps showing delayed Tmax, time-to-peak (TTP), and/or mean transit time (MTT), with reduced cerebral blood flow compared with the contralateral hemisphere. Ischemic core was assessed by relative cerebral blood flow < 30% on CTp when available and by diffusion-weighted imaging/apparent diffusion coefficient (DWI/ADC) restriction on MRI. Patients with large established infarction were not treated urgently. Intracranial vascular imaging was reviewed to exclude an intracranial large-vessel occlusion or another intracranial lesion that would have better explained the neurological deficit or required acute intracranial reperfusion therapy.

2.6. Revascularization Strategy and Antithrombotic Management

Treatment strategy was decided by a multidisciplinary team including vascular surgeons, neurologists, neuroradiologists, and anesthesiologists. CEA was preferred whenever anatomically and clinically feasible. Carotid artery stenting (CAS) was reserved for selected restenosis or anatomically favorable cases.

All patients were managed according to the institutional ischemic stroke pathway for suspected carotid-related events. After exclusion of intracranial haemorrhage and of indications for intravenous thrombolysis or mechanical thrombectomy, best medical therapy (BMT) was initiated before carotid revascularization. Patients without a pre-existing indication for oral anticoagulation received dual antiplatelet therapy (DAPT) with aspirin and clopidogrel. Patients with atrial fibrillation were managed with oral anticoagulation plus a single antiplatelet agent and underwent revascularization under this antithrombotic strategy. After revascularization, patients treated by CEA were maintained on single antithrombotic therapy, whereas patients treated by CAS received DAPT for one month followed by long-term single antiplatelet therapy, according to institutional practice and contemporary antithrombotic recommendations for symptomatic carotid disease and carotid stenting [13,33–37].

CEA was performed under general anesthesia, with intraluminal shunt use according to the institutional operative strategy for this high-risk hemodynamic subgroup. Patch angioplasty, eversion CEA, or direct closure was selected according to arterial anatomy and surgeon preference. CAS was performed under local anesthesia.

2.7. Endpoints and Follow-Up

The primary endpoint was 30-day safety, defined as freedom from all-cause death, any stroke, intracranial hemorrhage, major adverse events (MAEs), or target-lesion reintervention. The 30-day interval represented the prespecified perioperative safety assessment window and not the overall duration of clinical follow-up. Longer-term outcomes were assessed until the last available outpatient evaluation or documented clinical contact.

Secondary endpoints included technical success, postoperative NIHSS evolution, discharge NIHSS, hospital length of stay, late survival, late ipsilateral stroke, and late target-lesion reintervention. Technical success was defined as successful completion of the intended carotid revascularization procedure with restoration of carotid patency and absence of intraoperative death, immediate target-lesion occlusion, or unplanned conversion to another carotid procedure.

Clinical follow-up was performed through scheduled outpatient visits and review of hospital and outpatient records. Follow-up assessment included survival status, recurrent ipsilateral neurological events, neurological recovery when available, and the need for target-lesion reintervention. All surviving patients underwent the last scheduled outpatient evaluation and were considered to have completed clinical follow-up.

2.8. Statistical Analysis

All analyses were descriptive. Data were entered, curated, and checked using Microsoft Excel (Microsoft Corp., Redmond, WA, USA). Continuous variables were summarized according to their distribution and measurement scale. Distributional characteristics were assessed by visual inspection of the data and supported by the Shapiro–Wilk test. Approximately symmetrically distributed continuous variables are reported as mean $\pm$ standard deviation, whereas skewed, bounded, or ordinal variables are reported as median and interquartile range. Range is reported when clinically informative. Categorical variables are reported as counts and percentages. Exact Clopper–Pearson 95% confidence intervals were calculated for key binary safety outcomes to avoid overinterpretation of zero-event rates in this small cohort. No comparative inferential testing was performed because there was no control group. Follow-up duration was calculated from the index revascularization date to the last completed outpatient visit or last documented clinical contact. For anonymized historical entries in which only procedure month and year were retained, the first day of the recorded month was used solely for descriptive follow-up calculation. Overall survival was estimated using the Kaplan–Meier method, with all-cause death considered as the event and surviving patients censored at their last completed clinical follow-up. Pointwise 95% confidence intervals were calculated using Greenwood’s variance with a log-log transformation. For anonymized historical entries in which only the procedure month and year were retained, the first day of the recorded month was used for follow-up and time-to-event calculations. The survival curve was truncated at 60 months for presentation.

3. Results

3.1. Baseline Clinical, Carotid, and Collateral Characteristics

During the study period, 481 patients with symptomatic carotid stenosis were managed at our institution, all of whom underwent CT and/or MR perfusion imaging as part of the institutional stroke pathway. Of these, 69 patients (14.3%) underwent urgent revascularization for conventional clinically unstable presentations independently of the perfusion findings. A further 368 patients (76.5%) presenting with a single non-progressive neurological event underwent carotid revascularization within 14 days according to the standard institutional pathway, whereas 17 patients (3.5%) were managed with best medical therapy alone because of prohibitive procedural risk. The remaining 27 patients (5.6%) met all study criteria and underwent urgent carotid revascularization within 48 h on the basis of objective extensive ipsilateral hemispheric hypoperfusion. All 27 patients were included in the final analysis. Baseline clinical, carotid, plaque, and collateral characteristics are reported in Table 1.

Mean age was 72.9 ± 8.5 years, and 9 patients (33.3%) were female. Cardiovascular risk factors were common, including hypertension in 20 patients (74.1%), dyslipidemia in 20 (74.1%), active or previous smoking in 16 (59.3%), diabetes mellitus in 9 (33.3%), coronary heart disease in 9 (33.3%), chronic kidney disease in 8 (29.6%), and atrial fibrillation in 2 (7.4%). Median preoperative NIHSS was 3 (IQR, 0–4; range, 0–16).

All patients had symptomatic severe ipsilateral carotid disease. Median NASCET-style stenosis was 92% (IQR, 89.5–94; range, 84–95), and median ipsilateral PSV was 528 cm/s (IQR, 463–580.5; range, 381–610). Plaque morphology was Gray-Weale type III in 17 patients (63.0%) and type IV in 10 patients (37.0%); no patient had a type I or II plaque.

Any contralateral internal carotid artery disease was present in 22 patients (81.5%). Median contralateral stenosis was 35% (IQR, 27–52.5; range, 0–100). Contralateral internal carotid artery stenosis of 50–99% was present in 7 patients (25.9%), and complete contralateral internal carotid artery occlusion was present in one patient (3.7%). Uni-

lateral vertebral artery occlusion was present in 4 patients (14.8%). The circle of Willis was incomplete in 6 patients (22.2%): absent anterior communicating artery in 2 patients (7.4%), absent right posterior communicating artery in 2 (7.4%), and absent left posterior communicating artery in 2 (7.4%). Overall, 14 patients (51.9%) had at least one collateral-limiting feature.

Table 1. Baseline clinical, carotid, plaque, and collateral characteristics.

Variable	Overall Cohort, <i>n</i> = 27
Age, years	72.9 ± 8.5; range, 54–90
Female sex	9 (33.3%)
Smoking history	16 (59.3%)
Diabetes mellitus	9 (33.3%)
Dyslipidemia	20 (74.1%)
Hypertension	20 (74.1%)
Coronary heart disease	9 (33.3%)
Atrial fibrillation	2 (7.4%)
Chronic kidney disease	8 (29.6%)
Ejection fraction, %	55 (53.5–55); range, 40–65
Creatinine, mg/dL	1.0 (1.0–1.15); range, 0.7–2.2
Preoperative NIHSS	3 (0–4); range, 0–16
Ipsilateral NASCET-style stenosis, %	92 (89.5–94); range, 84–95
Ipsilateral peak systolic velocity, cm/s	528 (463–580.5); range, 381–610
Gray-Weale plaque type III	17 (63.0%)
Gray-Weale plaque type IV	10 (37.0%)
Any contralateral ICA stenosis/occlusion	22 (81.5%)
Contralateral ICA stenosis, %	35 (27–52.5); range, 0–100
Contralateral ICA stenosis 50–99%	7 (25.9%)
Contralateral ICA occlusion	1 (3.7%)
Unilateral vertebral artery occlusion	4 (14.8%)
Incomplete circle of Willis	6 (22.2%)
Absent anterior communicating artery	2 (7.4%)
Absent right posterior communicating artery	2 (7.4%)
Absent left posterior communicating artery	2 (7.4%)
At least one collateral-limiting feature	14 (51.9%)

ICA: internal carotid artery; NIHSS: National Institutes of Health Stroke Scale.

Representative pre- and postoperative imaging in a patient with severe left internal carotid artery stenosis and contralateral right internal carotid artery occlusion demonstrated that the haemodynamic impairment was not restricted to the hemisphere ipsilateral to the treated stenosis. Perfusion delay was bilateral and more pronounced in the hemisphere associated with the occluded carotid artery, whereas left carotid endarterectomy was followed by marked bilateral improvement on Tmax maps (Figure 1).

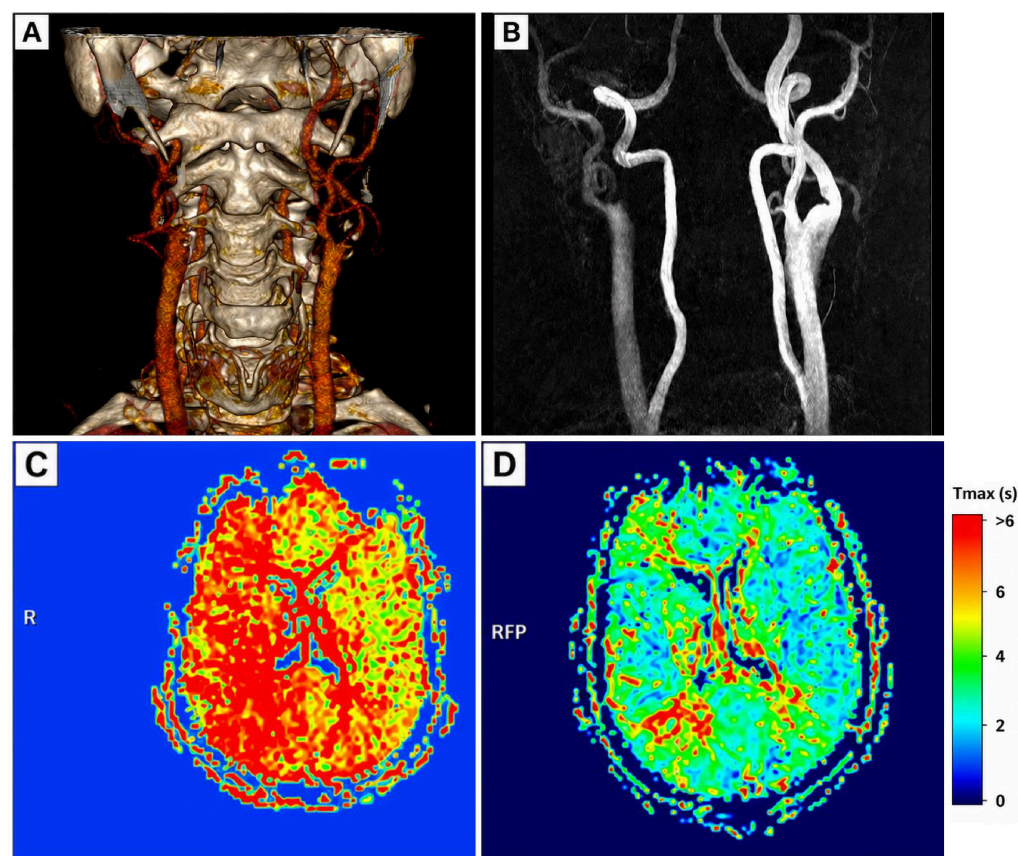


Figure 1. Bilateral cerebral hypoperfusion and haemodynamic improvement after left carotid endarterectomy in the presence of contralateral carotid occlusion. (A) Preoperative three-dimensional computed tomography angiography demonstrating severe left internal carotid artery stenosis and contralateral right internal carotid artery occlusion. (B) Postoperative coronal magnetic resonance angiography confirming patency of the treated left internal carotid artery, with persistent contralateral occlusion. (C) Preoperative axial Tmax perfusion map showing extensive bilateral hemispheric perfusion delay, involving the hemisphere ipsilateral to the treated stenosis and even more pronounced in the right hemisphere associated with carotid occlusion. Red areas indicate Tmax > 6 s. (D) Corresponding postoperative Tmax map showing a marked bilateral reduction in delayed perfusion and improved hemispheric symmetry after left carotid endarterectomy. Perfusion maps are displayed according to radiological convention, with the patient's right side appearing on the left of the image. CTA, computed tomography angiography; CEA, carotid endarterectomy; ICA, internal carotid artery; MRA, magnetic resonance angiography.

3.2. Perfusion Imaging and Procedural Characteristics

All patients had ipsilateral hemispheric hypoperfusion involving at least one third of the ipsilateral anterior circulation territory according to the predefined perfusion-imaging criteria. Perfusion imaging consisted of combined MRI and CTp assessment in 18 patients (66.7%), MRI-based assessment alone in 8 (29.6%), and CTp assessment alone in 1 (3.7%). The symptomatic carotid lesion was left-sided in 14 patients (51.9%) and right-sided in 13 (48.1%). No patient underwent intravenous thrombolysis or mechanical thrombectomy before carotid revascularization.

All patients underwent urgent carotid revascularization within 48 h during the index admission. Median time from admission to the beginning of the intervention was 14 h (IQR, 8–28.5; range, 4–44). CEA was performed in 25 patients (92.6%), whereas CAS was performed in 2 patients (7.4%). Among patients treated by CEA, patch angioplasty was used in 22 cases (22/25, 88.0%), eversion CEA in 2 (2/25, 8.0%), and direct suture in 1 (1/25, 4.0%). All CEA procedures were performed under general anaesthesia with

intraluminal shunt use. Both CAS procedures were performed under local anaesthesia, with no intraoperative neurological symptoms. Technical success was achieved in all patients.

Perfusion imaging and procedural characteristics are summarized in Table 2.

Table 2. Perfusion imaging and procedural characteristics.

Variable	Overall Cohort, <i>n</i> = 27
MRI + CT perfusion assessment	18 (66.7%)
MRI-based assessment alone	8 (29.6%)
CT perfusion assessment alone	1 (3.7%)
Left-sided carotid lesion	14 (51.9%)
Right-sided carotid lesion	13 (48.1%)
Revascularization within 48 h	27 (100%)
Admission-to-intervention start time, hours	14 (8–28.5); range, 4–44
CEA	25 (92.6%)
CAS	2 (7.4%)
CEA with patch angioplasty	22/25 (88.0%)
Eversion CEA	2/25 (8.0%)
CEA with direct suture	1/25 (4.0%)
General anaesthesia among CEA patients	25/25 (100%)
Intraluminal shunt among CEA patients	25/25 (100%)
Local anaesthesia among CAS patients	2/2 (100%)
Technical success	27 (100%; 95% CI, 87.2–100)

CAS: carotid artery stenting; CEA: carotid endarterectomy; CI: exact Clopper–Pearson confidence interval; CT: computed tomography; MRI: magnetic resonance imaging.

3.3. Early Outcomes

Median postoperative NIHSS was 0 (IQR, 0–0; range, 0–8), and median discharge NIHSS was 0 (IQR, 0–0; range, 0–2). Complete neurological recovery at discharge, defined as discharge NIHSS 0, was observed in 25 patients (92.6%; 95% CI, 75.7–99.1). Residual neurological deficit at discharge was present in 2 patients: one patient had unchanged NIHSS 2 at discharge, whereas the other improved from preoperative NIHSS 16 to discharge NIHSS 2. No patient had a discharge NIHSS higher than the preoperative NIHSS.

There were no intraoperative deaths and no 30-day deaths, strokes, intracranial hemorrhages, major adverse events (MAEs), or target-lesion reinterventions. Freedom from the 30-day primary safety endpoint event was 100% (95% CI, 87.2–100). The observed 30-day event rate for each major safety endpoint was 0%, with an exact 95% confidence interval upper bound of 12.8%, reflecting the uncertainty inherent to the cohort size. Median ICU stay was 1 day (IQR, 1–2; range, 1–7), and median hospital stay was 7 days (IQR, 6–8; range, 3–35).

Early outcomes are summarized in Table 3.

3.4. Long-Term Follow-Up

Clinical follow-up was available for all patients. All surviving patients underwent the last scheduled outpatient evaluation and were considered to have completed clinical follow-up. Median follow-up duration was 48.6 months (IQR, 29.8–63.4; range, 13.0–130.7), calculated from the index revascularization date to the last outpatient visit in surviving patients or to the date of death in deceased patients.

Table 3. Early Outcomes.

Outcome	Overall Cohort, <i>n</i> = 27
Intraoperative death	0
Postoperative NIHSS	0 (0–0); range, 0–8
Discharge NIHSS	0 (0–0); range, 0–2
Complete neurological recovery at discharge	25 (92.6%; 95% CI, 75.7–99.1)
ICU stay, days	1 (1–2); range, 1–7
Hospital stay, days	7 (6–8); range, 3–35
Freedom from 30-day primary safety endpoint event	27 (100%; 95% CI, 87.2–100)

CI: exact Clopper–Pearson confidence interval; MAE: major adverse event; NIHSS: National Institutes of Health Stroke Scale.

During follow-up, 3 patients (11.1%) died from non-neurological causes. Causes of death were myocardial infarction in 2 patients (7.4%) and pneumonia in 1 (3.7%). No late ipsilateral stroke, carotid-related neurological event, neurological death, or target-lesion reintervention was recorded. Median overall survival was not reached. Kaplan–Meier-estimated overall survival at 5 years was 90.0% (95% CI, 47.3–98.5%), with 8 patients remaining at risk at 60 months (Figure 2).

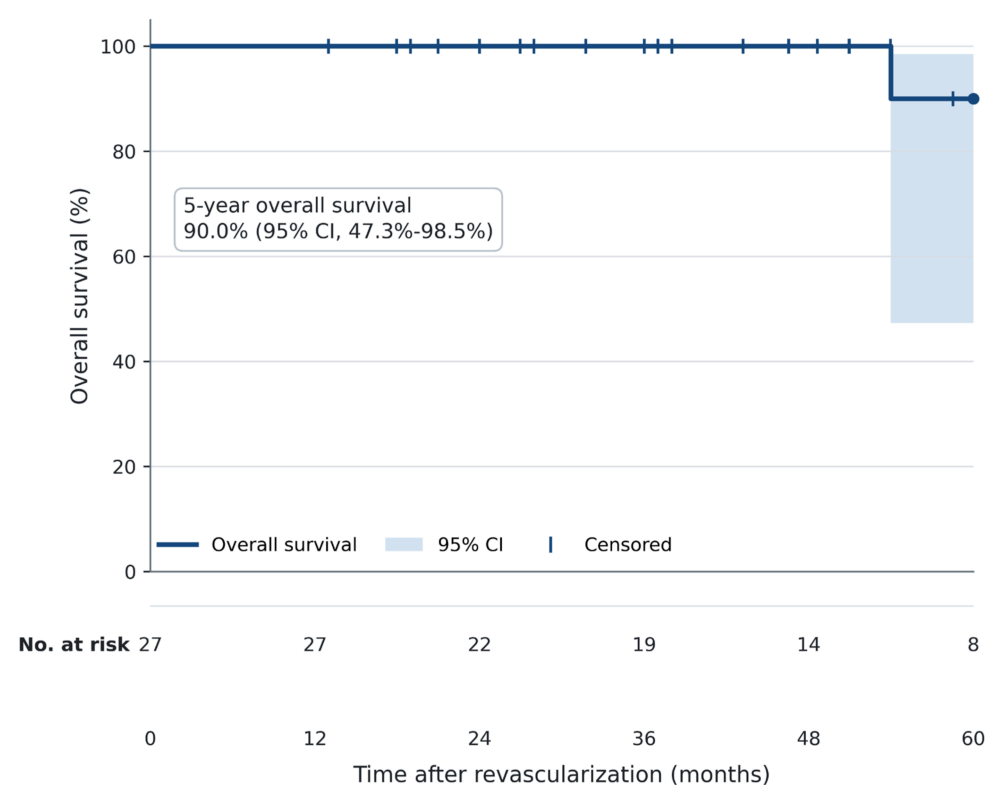


Figure 2. Kaplan–Meier estimate of overall survival after urgent carotid revascularization. The shaded area represents the pointwise 95% confidence interval, and vertical tick marks indicate censored observations. Numbers at risk are reported at 12-month intervals. The curve is displayed through 60 months; one of the three deaths recorded during the entire follow-up occurred within this 5-year period.

4. Discussion

This study describes a carefully selected cohort of patients with symptomatic high-grade carotid stenosis, extensive ipsilateral hemispheric hypoperfusion, and no large

established infarction who underwent urgent carotid revascularization. The main findings were: first, all patients had objective ipsilateral perfusion impairment involving at least one third of the anterior circulation territory; second, all patients had severe ipsilateral carotid stenosis, with median NASCET-style stenosis of 92%; third, plaque morphology was Gray-Weale type III or IV in all cases, without predominantly echolucent type I–II plaques; fourth, approximately half of the cohort had at least one collateral-limiting feature involving the contralateral carotid artery, vertebral arteries, or circle of Willis; fifth, urgent revascularization was technically successful in all patients and was not associated with observed 30-day death, stroke, intracranial hemorrhage, MAEs or reintervention; and sixth, three patients died from non-neurological causes during follow-up, whereas no late ipsilateral stroke or target-lesion reintervention was recorded.

The clinical relevance of this subgroup lies in the mismatch between conventional timing categories and modern imaging information. Current guidelines strongly support early revascularization after symptomatic carotid events, particularly within 14 days, and urgent CEA may be considered in selected unstable presentations such as crescendo TIA or stroke in evolution [13–15]. However, the phenotype described in this study does not fit neatly into either category. These patients may not fulfil classic clinical definitions of unstable symptomatic carotid disease, yet their perfusion imaging suggests an unstable tissue-level hemodynamic condition. Conversely, treating them as ordinary recently symptomatic carotid stenosis may underestimate the potential risk of persistent hemispheric low-flow ischemia. Therefore, the relevant question is not only whether the carotid lesion is symptomatic, but whether advanced imaging identifies an ongoing hemodynamic threat in the absence of a large established infarct core. This represents the specific guideline and evidence gap addressed by the present study.

The carotid and collateral characterization supports the interpretation of an imaging-defined hemodynamic phenotype. All patients had severe ipsilateral stenosis by NASCET-style criteria and high duplex velocities. At the same time, all plaques were classified as Gray-Weale type III or IV, indicating predominantly or uniformly echogenic morphology [28]. Echolucent, heterogeneous, or complex plaques have been more consistently associated with symptomatic embolic plaque instability and future cerebrovascular events [29,30]. Therefore, the absence of type I–II predominantly echolucent plaques, together with the absence of a more plausible cardiac, intracranial, or systemic hemodynamic mechanism after multidisciplinary assessment, does not exclude embolism but makes a purely embolic or non-carotid low-flow explanation less compelling and supports a predominant carotid-related hemodynamic contribution.

This interpretation is further supported by the collateral profile. Eight patients had contralateral internal carotid artery stenosis $\geq 50\%$ or occlusion, four had unilateral vertebral artery occlusion, and six had an incomplete circle of Willis. Overall, 14 patients had at least one feature that could theoretically reduce compensatory capacity during severe ipsilateral carotid flow limitation. Computational and clinical literature supports the role of the circle of Willis and collateral pathways in modulating cerebral blood flow during internal carotid artery stenosis or occlusion [31,32]. Accordingly, severe stenosis alone may be insufficient to produce hemispheric hypoperfusion in many patients; the hemodynamic event may emerge when severe ipsilateral stenosis coexists with inadequate cross-flow, limited posterior collateralization, contralateral carotid disease, vertebral artery compromise, or incomplete Willis anatomy. More broadly, the importance of preserving supra-aortic inflow is also reflected in contemporary endovascular aortic arch repair: dedicated single-branch platforms are designed to maintain left subclavian artery perfusion and thereby support vertebrobasilar and collateral cerebral circulation, while recent propensity-matched

evidence has associated left subclavian artery reconstruction with a lower incidence of postoperative cerebral infarction than partial coverage [38,39].

Perfusion imaging provides a practical framework for identifying this phenotype. In acute stroke trials and automated imaging workflows, $T_{max} > 6$ s is widely used to define hypoperfused tissue, whereas relative cerebral blood flow $< 30\%$ and DWI/ADC abnormalities are used to approximate infarct core [17–25]. Although these thresholds were validated mainly for reperfusion therapy in large-vessel occlusion, they offer a reproducible language to distinguish delayed perfusion from established infarction. In the present study, the key selection principle was not the presence of any small ischemic lesion, but the combination of broad hemispheric hypoperfusion, severe carotid stenosis, and absence of large established infarction or hemorrhage.

The absence of intracranial haemorrhage and haemorrhagic transformation is particularly relevant. Historical concerns regarding early CEA after stroke relate mainly to reperfusion injury in patients with large infarct burden, impaired blood–brain barrier integrity, or haemorrhagic transformation [16]. In contrast, the patients in this cohort were selected because imaging suggested potentially reversible hypoperfusion rather than extensive completed infarction. This distinction is essential because the present study does not propose a broad expansion of urgent carotid revascularization to all symptomatic patients. Rather, it suggests that perfusion-defined hemispheric hypoperfusion without a large infarct core may identify a narrow subgroup that occupies an intermediate position between standard early treatment and classically urgent carotid presentations.

The neurological trajectory was favourable. Most patients had complete recovery by discharge. Of the two patients with residual deficits, one improved from a preoperative NIHSS of 16 to 2 at discharge, whereas the other had an unchanged NIHSS of 2. This observation supports the hypothesis that at least part of the neurological impairment was driven by hemodynamic dysfunction rather than irreversible infarction. Nevertheless, causal inference remains limited. Neurological improvement and absence of recurrent early ischemic events cannot be attributed to revascularization alone, because all patients also received immediate BMT as part of the ischemic stroke pathway, including DAPT in patients without atrial fibrillation and anticoagulation plus antiplatelet therapy in those with atrial fibrillation. Therefore, antithrombotic treatment represents an important co-intervention and potential confounder. However, in this imaging-defined phenotype, medical therapy and urgent carotid revascularization should be interpreted as complementary components of a multidisciplinary strategy rather than as competing isolated treatments.

This study also has practical implications. In rare patients with symptomatic severe carotid stenosis, broad ipsilateral hypoperfusion, small or absent infarct core, and no haemorrhage, a purely time-based approach may be insufficient. These patients may deserve consideration for urgent or very early carotid revascularization, provided that decision-making is multidisciplinary and guided by advanced imaging. A pragmatic future selection scheme should include ipsilateral stenosis severity using NASCET-style criteria, plaque morphology, perfusion-core mismatch, contralateral carotid status, vertebral artery patency, and circle of Willis completeness. In this context, emerging ultrasound technologies, including high-frame-rate vector-flow imaging and 3D arterial analysis, may further refine plaque, geometry, and flow characterization beyond conventional color-DUS [40], although their role in this specific hemodynamic phenotype remains to be validated. Such a scheme would not replace guideline-based care but could refine risk stratification in a subgroup that remains poorly represented in current evidence.

In the present cohort, CEA remained the preferred revascularization strategy, consistent with the established role of surgery as the reference treatment for most patients with recently symptomatic carotid stenosis [13,14]. However, CAS may retain a role in

carefully selected symptomatic patients, particularly when surgical risk is increased or anatomical and clinical factors favour an endovascular approach. Earlier evidence in high-surgical-risk patients supported protected CAS as a potential alternative to CEA, while more contemporary real-world experiences with dual-layer mesh-covered carotid stents, including the IRONGUARD-2 study, have reported encouraging short- and mid-term neurological outcomes in cohorts that included symptomatic patients [41–43]. Future studies on this imaging-defined hypoperfusion phenotype should therefore not only evaluate urgent versus delayed revascularization, but also clarify whether selected high-risk surgical candidates may be safely treated with modern CAS platforms within standardized multidisciplinary protocols.

The small cohort size is an important limitation. No 30-day primary safety events were observed among 27 patients; however, the corresponding two-sided exact 95% confidence interval was 0–12.8%. Thus, at the 95% confidence level, this sample excludes only underlying complication rates above 12.8% and cannot rule out clinically relevant rates up to this threshold. Accordingly, the zero-event finding should not be interpreted as establishing the absence of perioperative risk. Nevertheless, the cohort size should be interpreted in context. These 27 patients were identified over a 10-year period at a high-volume tertiary stroke hub, after exclusion of patients treated with thrombolysis, thrombectomy, large established infarction, hemorrhage, competing cardiac, intracranial, or systemic hemodynamic mechanisms, or symptomatic carotid disease without objective hemispheric hypoperfusion. This very low case accrual despite broad institutional exposure supports the rarity of this imaging-defined phenotype. It also explains why prospective randomized evidence would be difficult to generate: adequately powered studies would likely require many years of enrollment, multicentre participation, strict and reproducible perfusion-imaging criteria, standardized cardiac and intracranial exclusion pathways, and homogeneous urgent-treatment protocols. For this reason, detailed imaging-defined observational reports may be clinically relevant, provided that conclusions remain appropriately cautious.

Additional limitations include the retrospective design, absence of a control group treated with delayed revascularization or medical therapy alone, and non-uniform availability of quantitative perfusion volumes. Hypoperfusion was therefore defined using a combination of quantitative thresholds, original neuroradiological reports, and visual perfusion-map adjudication. The cohort also spans several years, during which imaging protocols and perioperative practices may have evolved. Plaque morphology was based on DUS classification rather than systematic histopathological confirmation, and circle of Willis completeness was derived from clinically available CTA/MRA rather than from a standardized research protocol. Finally, because all patients were treated at a single institution and the sample size was limited, external validity remains constrained.

Despite these limitations, the study addresses an underreported clinical scenario and proposes a transparent imaging-based definition for future research. The findings suggest that patients with symptomatic severe carotid stenosis and extensive ipsilateral hypoperfusion, but without large established infarction, may represent a rare high-risk subgroup in whom urgent revascularization can be considered after multidisciplinary evaluation. The target imaging-defined phenotype accounted for only 27 of the 481 patients (5.6%) with symptomatic carotid stenosis managed during the 10-year study period, supporting its rarity even within a high-volume tertiary stroke hub. Prospective multicentre studies should validate perfusion thresholds, quantify hypoperfusion and core volumes, standardize plaque and collateral assessment, and compare urgent versus early-but-delayed treatment strategies.

5. Conclusions

Urgent carotid revascularization for symptomatic high-grade carotid stenosis associated with ipsilateral hemispheric hypoperfusion was feasible in this carefully selected cohort and was not associated with observed 30-day death, stroke, intracranial haemorrhage, MAEs, or target-lesion reintervention. All patients had severe ipsilateral NASCET-style stenosis, extensive perfusion-imaging evidence of ipsilateral hypoperfusion involving at least one third of the anterior circulation territory, and no large established infarction or hemorrhage.

These findings suggest that, although rare, carotid-related cerebral events may occur through a predominantly hemodynamic pathway when severe stenosis coexists with limited collateral compensation. In such cases, perfusion imaging and collateral assessment may help identify patients who should be considered for urgent or very early carotid revascularization with the same clinical attention usually reserved for unstable symptomatic carotid presentations. Given the retrospective design, single-centre setting, and small sample size, these conclusions remain hypothesis-generating and require prospective multicentre validation.

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Abbreviations

The following abbreviations are used in this manuscript:

ADC	Apparent diffusion coefficient
BMT	Best medical therapy
CAS	Carotid artery stenting
CEA	Carotid endarterectomy
CI	Confidence interval
CT	Computed tomography
CTA	Computed tomography angiography
CTp	Computed tomography perfusion
DAPT	Dual antiplatelet therapy
DUS	Doppler Ultrasound
DWI	Diffusion-weighted imaging
DW-MRI	Diffusion-weighted magnetic resonance imaging
ICA	Internal carotid artery
ICU	Intensive care unit

IQR	Interquartile range
MAE	Major adverse event
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
MR	Magnetic resonance
MTT	Mean transit time
NASCET	North American Symptomatic Carotid Endarterectomy Trial
NIHSS	National Institutes of Health Stroke Scale
PSV	Peak systolic velocity
TIA	Transient ischemic attack
Tmax	Time-to-maximum
TTP	Time-to-peak

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