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Comparative effects of endarterectomy and balloon angioplasty with stent implantation on carotid artery flow velocity in carotid artery stenosis

Dawid Leksa[1], Wiktoria Mytych[2], Natalia Leksa[3], Klaudia Dynarowicz[4], Dorota Bartusik-Aebisher[4], and David Aebisher[5]*

[1]Department of Vascular and Endovascular Surgery, Rzeszów Center for Vascular and Endovascular Surgery, Rzeszów, Podkarpackie, Poland

[2]English Division Science Club, Collegium Medicum, Faculty of Medicine, University of Rzeszów, Rzeszów, Podkarpackie, Poland

[3]Department of Neurology, MSWiA Hospital, Rzeszów, Podkarpackie, Poland

[4]Department of Biochemistry and General Chemistry, Collegium Medicum, Faculty of Medicine, University of Rzeszów, Rzeszów, Podkarpackie, Poland

[5]Department of Photomedicine and Physical Chemistry, Collegium Medicum, Faculty of Medicine, University of Rzeszów, Rzeszów, Podkarpackie, Poland

***Corresponding author:**
David Aebisher
(daebisher@ur.edu.pl)

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Abstract

Hemodynamically significant carotid artery stenosis is a major, modifiable contributor to ischemic stroke/transient ischemic attack (TIA), and both carotid endarterectomy (CEA) and carotid artery stenting (CAS) are established revascularization strategies aimed at restoring cerebral perfusion and normalizing carotid flow hemodynamics. This prospective study compared the outcomes of CEA and CAS with balloon angioplasty and stent implantation in patients with hemodynamically significant internal carotid artery stenosis. The goal was to assess the effectiveness of the techniques in reducing peak systolic velocity and improving quality of life. Between March 2019 and December 2020, 106 patients (47% male, 53% female; aged 40–75 years) were enrolled at the Rzeszów Center for Vascular and Endovascular Surgery, Poland. Inclusion criteria encompassed symptomatic stenosis ≥70% or selected 50–69%, as well as asymptomatic cases meeting clinical indications (e.g., prior stroke/TIA, plaque morphology, anatomy, comorbidities). Patients were assigned to the CEA or CAS group based on multidisciplinary evaluation; exclusions included lack of consent or surgical contraindications. All patients received perioperative antiplatelet therapy and statins. Evaluations included duplex ultrasound to measure peak systolic velocity and stenosis degree before the procedure and at 1 month post-intervention, along with quality-of-life questionnaires. Data were analyzed using Student's *t*-tests. Preoperative peak systolic velocities differed between groups, with overall higher values in CAS and gender-specific variations (men: 363.21 cm/s in CEA vs. 345 cm/s in CAS; women: 338.97 cm/s in CEA vs. 354.96 cm/s in CAS). Both interventions led to statistically significant postoperative reductions in blood flow velocity. Postoperative hemodynamic improvements and quality-of-life outcomes were comparable between groups, with similar comorbidity impacts observed. These results indicate that CEA and CAS offer equivalent short-term effectiveness in managing carotid artery disease and reducing stroke/TIA risk.

Keywords: Endarterectomy; Balloon angioplasty; Carotid artery stenting; Stroke; Transient ischemic attack; Blood flow velocity

1. Introduction

Stroke remains one of the most pressing global health challenges, ranking as the second leading cause of death worldwide, after ischemic heart disease.[1] As defined by the World Health Organization, stroke is a sudden onset of focal neurological deficit caused by the disruption of cerebral blood flow, typically lasting more than 24 h, and can result in death or permanent disability.[2,3] *Recent epidemiological data confirm that stroke remains a significant cause of long-term disability*.[4]

Despite advances in stroke prevention and treatment, the incidence remains high, and its impact on public health is profound, especially in high-risk populations.[5] In Europe, including Poland, stroke is a significant cause of both mortality and long-term disability.[6] Early intervention and precise diagnosis of the underlying causes of stroke are vital to improving patient outcomes.[7]

Among the most critical contributors to stroke is carotid artery disease, which leads to cerebrovascular episodes, such as transient ischemic attacks (TIAs) or full-blown strokes, primarily caused by atherosclerosis, resulting in cerebral perfusion abnormalities.[8] Carotid artery stenosis, a narrowing of the carotid arteries caused by atherosclerotic plaque buildup, is one of the leading risk factors for ischemic stroke.[9] The carotid arteries, responsible for supplying blood to the brain, become compromised in patients with stenosis, leading to reduced cerebral perfusion and increased susceptibility to ischemic damage.[10] Plaques that form in the arteries may cause partial or complete obstruction, resulting in the cessation or reduction of blood flow to critical regions of the brain. This can precipitate stroke or other cerebrovascular events.[11]

Given the importance of cerebral perfusion in maintaining brain function, any abnormalities in blood flow dynamics, particularly in the carotid arteries, can significantly influence stroke risk and clinical outcomes.[12] Understanding how the changes in carotid artery flow velocity correlate with cerebral perfusion is therefore crucial in assessing the effectiveness of interventions designed to treat carotid artery stenosis.[13]

Ultrasound, particularly Doppler ultrasonography, has become an indispensable diagnostic tool for evaluating the hemodynamics of the carotid arteries.[14] This non-invasive, cost-effective method uses high-frequency sound waves to assess blood flow velocity and identify potential areas of stenosis or plaque buildup.[15] Doppler ultrasound allows clinicians to measure key flow parameters, such as peak systolic velocity (PSV) and end-diastolic velocity (EDV), which are essential indicators of the severity of carotid artery stenosis and associated hemodynamic changes.[16] By using both color Doppler and spectral Doppler modes, clinicians can visualize the flow patterns within the arteries, detect turbulence or altered flow, and evaluate the functional significance of atherosclerotic plaques.[17] These diagnostic capabilities are crucial not only for identifying patients at risk but also for determining the optimal intervention strategy.

For patients with significant carotid artery stenosis, two primary interventions are commonly employed: carotid endarterectomy (CEA) and carotid artery stenting (CAS) with balloon angioplasty.[18] CEA is a surgical procedure that involves the removal of atherosclerotic plaque from the arterial wall to restore blood flow.[19] In contrast, CAS with balloon angioplasty is a less invasive alternative, where a stent is inserted to keep the artery open following balloon dilation.[20] Both interventions aim to alleviate the obstruction, restore cerebral perfusion, and prevent stroke.[21] However, understanding the effect of these procedures on cerebral perfusion and subsequent carotid artery flow velocity is essential for evaluating their success and ensuring long-term efficacy.[22]

Recent studies have shown that abnormal cerebral perfusion, often resulting from stenosis or surgical intervention, can significantly influence carotid artery flow velocity.[23] After endarterectomy or stenting procedures, changes in blood flow dynamics are frequently observed.[24] These changes are important indicators of how well cerebral perfusion has been restored and whether the arterial structure remains patent.[25] Monitoring carotid artery flow velocity before and after these procedures is vital for understanding the impact of these treatments on cerebral circulation, the potential for restenosis, and the risk of further ischemic events.[26]

The European Society for Vascular Surgery 2023 Clinical Practice Guidelines on the management of atherosclerotic carotid and vertebral artery disease provide comprehensive recommendations for the management of carotid artery disease.[27] These guidelines emphasize the importance of individualized treatment plans, considering factors such as the degree of stenosis, symptomatology, and patient comorbidities.[28] For patients with symptomatic carotid stenosis, the guidelines recommend early intervention, ideally within 2 weeks of the last ischemic event, to reduce the risk of recurrent stroke.[29] The choice between CEA and CAS should be based on specific patient characteristics and the expertise of the medical team.[30] Additionally, the guidelines highlight the role of medical therapy, including antiplatelet agents and statins, in conjunction with surgical interventions to optimize patient outcomes.[31]

Similarly, the American Heart Association and American Stroke Association 2021 Guideline for the prevention of stroke in patients with stroke and TIA provides updated recommendations for the management of carotid artery disease.[32] The guidelines advocate for early intervention in patients with severe symptomatic carotid stenosis, with the choice between CEA and CAS guided by patient-specific factors and the anatomical characteristics of the stenosis.[33] The guidelines also emphasize the importance of comprehensive medical management, including the use of antiplatelet therapy, statins, and blood pressure control, to reduce the risk of recurrent stroke.[34]

Both sets of guidelines underscore the critical role of early and individualized intervention in the management of carotid artery disease to prevent recurrent cerebrovascular events. This article investigates the effect of cerebral perfusion abnormalities on carotid artery flow velocity in patients before and after undergoing endarterectomy or balloon angioplasty with stent implantation. The research question is: how do CEA and CAS affect carotid artery flow velocity differences in patients with stenosis? We hypothesized that both CEA and CAS would significantly reduce carotid artery flow velocity differences, with no significant difference between the two methods in terms of postoperative outcomes and quality of life.

2. Materials and methods

2.1. Ultrasound machine

A Philips Affiniti 50 ultrasound system (Philips, the Netherlands) equipped with C6-2, S4-2, and L12-4 transducers was used in this study (Figure 1). This choice of machine was supported by recent research demonstrating the economic and clinical value of the Philips Affiniti series in vascular ultrasound for preventing cerebrovascular complications through carotid screening in high-risk populations, such as cardiosurgical patients.[35]

Figure 1. Philips Affiniti 50 ultrasound machine

A 7–12 MHz linear-array transducer was utilized for carotid imaging. To assess the division of the common carotid artery, a cross-sectional image of the vessel was obtained, spanning from the base of the neck to the angle of the jaw. The Doppler function was then activated, allowing for visualization of pathologically altered areas exhibiting abnormal flow patterns through the longitudinal section in color-coded mode. This enabled a preliminary identification of any aberrant features of the vessel.

2.2. Patient selection

In this study, both men and women (Table 1) who experienced an episode of transient cerebral ischemia and ischemic stroke with hemodynamically significant carotid artery stenosis had their blood flow alterations assessed by Doppler ultrasonography. The surgical technique was modified based on the atherosclerotic plaque's location, shape, associated conditions, accessibility for surgical stenosis removal, and potential side effects. Patients were assessed using Doppler ultrasonography 1 month following surgery. Outcomes were compared between the CEA and CAS groups. The University of Rzeszów's Bioethics Committee provided ethical approval for the study (decision number 14/02/2019). Patient recruitment and data collection were conducted between March 2019 and December 2020 at the Rzeszów Center for Vascular and Endovascular Surgery, Poland. Written informed consent was obtained from all participants before enrollment in the study.

Eligibility for carotid revascularization (Table 2) was based on clinical presentation and degree of stenosis. Indications included (i) one or more episodes of transient cerebral ischemia within the past 6 months with internal carotid artery (ICA) stenosis ≥70%, and (ii) mild ischemic stroke with carotid artery stenosis ≥70%. Selection of the revascularization approach (CEA vs. CAS) was guided by plaque location relative to vessel anatomy and morphology.

2.3. Carotid artery ultrasound scanning

A key component of the ultrasonic assessment is measuring the degree of stenosis.[36] The baseline vessel diameter and residual lumen were recorded once the atherosclerotic plaque became clearly visible. In instances where plaque visualization was difficult due to complex structures or calcification, Doppler imaging was employed to determine the degree of stenosis. Additionally, the peak systolic and end-diastolic velocities of both the internal and common carotid arteries were measured, alongside the ratio of PSVs. For 50% stenosis, conservative treatment was indicated when the PSV in the ICA exceeded 1.25 m/s, and the EDV exceeded 0.4 m/s. Surgical intervention was recommended for 70% stenosis when the PSV in the ICA exceeded 2.3 m/s, and the EDV exceeded 1.0 m/s. Ultrasonography was also used to characterize atherosclerotic plaques. Plaques with high lipid content were identified as being more prone to rupture, potentially leading to clinical symptoms.[37] Further abnormalities, such as ulceration, plaque bleeding, or thrombus formation within the plaque, were also noted. Following a vascular incident, each patient underwent an ultrasound examination to assess the flow velocity in the affected vessels, along with the morphology, hemodynamics, and presence of other structures within the atherosclerotic plaque. Patient qualification for surgery was based on the results of the ultrasound examination, which also informed the decision on the appropriate surgical approach—either endovascular balloon angioplasty with stent implantation (CAS) or traditional endarterectomy (CEA). All evaluations were conducted at the Rzeszów Center for Vascular and Endovascular Surgery.

Table 1. Patients' characteristics

Parameter	Values (*n*=106)
Age range (years)	40–75 years old
Gender (%)	
Male	47.2
Female	52.8
Stroke	43 (40.6%)
Transient ischemic attack	13 (12.3%)
Asymptomatic	50 (47.2%)
Medications (%)	
Aspirin	100
Clopidogrel	89.7
Ticlopidine	44.9
Comorbidities (%)	
Diabetes mellitus	44 (41.5)
Hypertension	93 (87.7)
Dyslipidemia	87 (82.1)
Smoking history	76 (71.7)

Notes: Asymptomatic refers to no stroke or transient ischemia, serving as the control group. Data presented as *n* (%), unless stated otherwise.

Table 2. Inclusion and exclusion criteria

Criteria	Description
Inclusion	Adults with symptomatic, hemodynamically significant extracranial internal carotid artery stenosis after a transient cerebral ischemic episode or ischemic stroke
	Provision of written informed consent for diagnostic evaluation of the causes of cerebral vascular episodes and surgery
Exclusion	Lack of patient consent for surgical treatment
	Contraindications to surgery due to general condition

2.4. CEA and endovascular balloon angioplasty with stent implantation

When qualifying a patient for CEA or CAS, two non-invasive arterial studies were performed. Double Doppler ultrasound of the carotid artery was the primary test in assessing the degree of stenosis of the vessel. When findings were equivocal, classical intra-arterial angiography was performed, which is the most accurate, but invasive, imaging method used to assess the degree of ICA stenosis.[38] Patients with carotid artery stenosis, regardless of whether they qualified for CEA or CAS, received antiplatelet therapy and statins according to their clinical condition, as well as adherence to recommendations on cardiovascular risk factors. Based on the arterial examination, patients were classified for treatment according to the recommendations for performing CEA and CAS, which are shown in Table 3.

2.5. Quality of life questionnaire

The EQ-5D-3L questionnaire was used to assess health-related quality of life. It comprises five dimensions (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression), each rated on three levels (no problems, moderate problems, and severe problems).

Table 3. Recommendations for endarterectomy and balloon angioplasty with stent placement

Procedure	Recommendations
Carotid endarterectomy (CEA)	May be indicated in some patients with 50–69% stenosis without significant neurological impairment. The decision about the procedure should be made individually for each patient, after weighing the benefits of such treatment and the risk of perioperative complications[39]
	Recommended primarily for patients with symptomatic carotid artery stenosis of a significant degree (70–99%), without profound neurological deficit, who have suffered an ischemic stroke or TIA. This recommendation applies only to surgical centers where the risk of all perioperative complications (stroke or death) is <6%[40]
	Patients should receive antiplatelet drugs before and after CEA surgery. Acetylsalicylic acid (ASA) can be used before and after the procedure. One month after the procedure, alternatively, clopidogrel or a combination of ASA and modified-release dipyridamole can also be used[41]
	If CEA is indicated, it should be performed preferably within 2 weeks of a stroke or TIA[42]
	There is no indication to perform CEA in patients with <50% stenosis[43]
	Qualification for surgery and follow-up of patients after carotid CEA should be conducted jointly by a neurologist and a vascular surgeon, using radiological imaging[44]
Carotid artery stenting (CAS)	Should be performed in centers where the risk of death or complications associated with the procedure is <6%[45]
	Can be performed during mechanical thrombectomy in the acute phase of stroke as a prevention of another ischemic incident[46]
	May be considered for large (>70%) symptomatic carotid artery stenosis, in surgically inaccessible areas, patients with restenosis after CEA, or a history of major neck surgery, artery stenosis after radiation therapy, contralateral carotid artery obstruction, contralateral laryngeal nerve injury, or severe heart or lung disease. Better effects of CAS are observed in younger patients <70 years of age[47]
	Recommended for post-stroke or TIA patients with contraindications to CEA if carotid artery stenosis at study >70%[48]
	Patients should receive clopidogrel and ASA immediately before CAS and for ≥1 month afterwards[49]

Abbreviation: TIA: Transient ischemic attack.

Participants also rated their current health status on the EQ-5D visual analogue scale (0–100, where 0 indicates the worst imaginable health state and 100 indicates the best imaginable health state). The questionnaire was self-administered, with staff assistance provided if needed, at 2 time points: baseline (during pre-procedural qualification) and 1 month after the intervention during a follow-up visit at the Rzeszów Center for Vascular and Endovascular Surgery.

2.6. Statistical analysis

In each case, we calculated the standard deviation, mean value, and *p*-value for both men and women using a *t*-test for equality of means. Statistical significance was defined as $p<0.05$. Data were analyzed using Statistica 13.1 software (StatSoft Polska Sp. z o.o., Poland).[50-52]

3. Results

The study included 106 patients who underwent CEA or CAS, comprising 56 symptomatic patients (stroke/TIA) and 50 asymptomatic patients. In both groups, Group 1 (56 patients) and Group 2 (50 asymptomatic), the age range was 40–75 years. All patients underwent serial clinical evaluations during enrollment and follow-up. The study findings are clinically relevant and may directly influence surgical decision-making and, consequently, treatment outcomes.

The findings can inform patient treatment by offering a tailored set of strategies to reduce perioperative stress, thereby improving quality of life. The ICAs are two of the four arterial vessels responsible for supplying blood to the brain. Table 1 shows the characteristics of the 106 patients studied and analyzed.

Among women, a total of 56 surgical procedures were performed, of which 30 were qualified for endarterectomy, and 26 were qualified for percutaneous balloon angioplasty with stent implantation. Right ICA stenosis was observed in 21 patients, and left ICA stenosis was observed in 35 patients.

Among men, a total of 50 surgical procedures were performed, of which 34 patients qualified for endarterectomy, and 16 patients qualified for percutaneous balloon angioplasty with stent implantation. Stenosis of the right ICA in the extracranial segment was diagnosed in 21 patients, and stenosis of the left ICA in the extracranial segment was diagnosed in 29 patients.

3.1. Changes in blood flow velocity

Mean blood flow velocity differed significantly before and after the treatment of post-stroke patients (Table 4) ($p<0.05$). For patients with TIA, a statistically significant difference was observed in the mean blood flow velocity before and after treatment (Table 4) ($p<0.05$). Moreover,

Table 4. Comparison of the mean blood flow velocity before and after the procedure across groups

Condition/ procedure	No. of patients	Mean blood flow velocity, cm/s (mean±standard deviation)		*p*-value
		Before procedure	After procedure	
Stroke				
Female	20	365.74±69.85	84.60±30.54	0.00008
Male	23	366.48±99.01	79.43±25.03	0.00008
Transient ischemia				
Female	12	289.50±110.58	79.58±22.78	0.01998
Male	1	360.00±0.00	60.00±0.00	0.02100
Asymptomatic group				
Female	25	347.56±98.02	82.88±30.20	0.00004
Male	26	349.23±121.76	85.77±22.85	0.00005
Balloon angioplasty with stent implantation				
Female	26	354.96±76.91	90.12±29.17	0.00037
Male	16	345.00±101.19	88.63±29.46	0.00042
Endarterectomy				
Female	30	338.97±98.58	77.63±26.75	0.00188
Male	34	363.21±114.51	79.38±20.51	0.00198
Left carotid artery stenosis				
Female	35	351.74±78.24	78.11±22.13	0.00062
Male	29	362.45±120.40	86.72±26.50	0.00065
Right carotid artery stenosis				
Female	21	337.48±105.46	92.29±35.30	0.00156
Male	21	350.39±95.48	76.29±18.50	0.00144

there was a significant difference between the mean blood flow velocity before and after the procedure in asymptomatic patients (Table 4) ($p<0.05$).

Statistically significant differences between the mean blood flow velocity before and after the procedure were also observed in patients who underwent balloon angioplasty with stent implantation ($p<0.05$) and endarterectomy ($p<0.05$) (Table 4). Additionally, both patients with left ($p<0.05$) and right artery stenosis ($p<0.05$) exhibited significant differences in mean blood flow velocity before and after the procedure (Table 4).

3.2. Inter-group comparisons and overall findings

Statistical analysis compared blood flow velocity values before the procedure with those after the procedure in patients with stroke, transient ischemia, and asymptomatic status. The standard deviations of the mean blood flow velocity were within 20–30%. In the arterial stenosis group, analyses were stratified by sex and procedure type (CAS vs. CEA). Standard deviations of the mean blood flow velocity were within 5–20%. The analysis of blood flow in the carotid arteries of patients before and after endarterectomy and balloon angioplasty with stent implantation showed that both methods are beneficial. The results showed that the techniques have similar, not substantially different, effects on the quality of life of patients before and after the procedures.

The blood flow velocity before and after the procedure in women and men with stroke was statistically significant ($p=0.00008$ for both). In patients with transient ischemia, comparison of mean blood flow velocity before and after the procedure showed a statistically significant difference in both women ($p=0.01998$) and men ($p=0.02100$). Similarly, among asymptomatic patients without symptoms in the preceding 6 months, significant differences were observed in women ($p=0.00004$) and men ($p=0.00005$). Comparison of mean blood flow values before and after balloon angioplasty with stent implantation demonstrated statistically significant differences in both women ($p=0.00037$) and men ($p=0.00042$). Similarly, endarterectomy was associated with significant changes in mean blood flow in women ($p=0.00188$) and men ($p=0.00198$).

Significant differences were also observed when comparing pre- and post-surgical mean blood flow values in patients with left-sided carotid stenosis, in both women ($p=0.00062$) and men ($p=0.00065$). For right-sided carotid artery stenosis, statistically significant results were obtained in women ($p=0.00156$) and men ($p=0.00144$).

Statistical comparison of the blood flow velocity between groups showed that the blood flow velocity in the stroke group was significantly higher than in the TIA group before the procedure ($p<0.05$), but was not significant after the procedure ($p>0.05$). Additionally, there was no significant difference in the blood flow velocity between stroke patients and asymptomatic patients before the procedure ($p>0.05$). After the procedure, the blood flow velocity was slightly lower in the asymptomatic group compared to the stroke group; however, this difference was not statistically significant ($p>0.05$). Before the procedure, the blood flow velocity in TIA patients was significantly lower compared to the asymptomatic group ($p<0.05$), but the asymptomatic group had a slightly higher post-procedure blood flow velocity compared to the TIA group ($p<0.05$), though the effect size was small. Before the procedure, stroke patients had significantly higher blood flow velocity compared to TIA patients, suggesting that their stenosis may be more severe or their compensatory mechanisms different. After the procedure, the blood flow velocity for all groups decreased significantly, which is a natural outcome of the interventions performed (CEA and CAS). There was no significant difference in post-procedure blood flow velocity between stroke and TIA patients, but asymptomatic patients exhibited slightly higher blood flow post-procedure.

3.3. Imaging results

Figure 2 shows the ultrasound images of the arteries of selected patients. Figure 2A-E shows the flow analysis before the procedure, and Figure 2F-H shows the flow analysis after the procedure.

4. Discussion

The analysis of blood flow in carotid arteries before and after CEA and CAS procedures provided significant insights into the effectiveness of these interventions in treating patients with stroke, TIA, and asymptomatic status. The current study demonstrated a statistically significant reduction in mean blood flow velocity following both CEA and CAS procedures across patient groups. In post-stroke patients, both women and men showed highly significant reductions (p=0.00008); similar significant results were observed in patients with TIA (p=0.01998 for women and p=0.02100 for men) and in the asymptomatic group (p=0.00004 for women and p=0.00005 for men). These findings indicate improved hemodynamics post-revascularization, potentially reducing stroke risk.

4.1. Insights from the international carotid stenting study and related fluid dynamics studies

A 2023 study on early cerebral hemodynamic changes following unilateral CAS in 104 patients with varying degrees of carotid stenosis demonstrated significant increases in ipsilateral middle cerebral artery (MCA), PSV, and pulsatility index (PI) within hours post-procedure. Overall, ipsilateral MCA-PSV rose from 81.3 ± 23.0 cm/s pre-CAS to 98.5 ± 28.6 cm/s at 1 h and 97.5 ± 27.3 cm/s at 3 h post-CAS (p<0.001). The magnitude of increase was greater with higher stenosis severity: 8.1% in severe stenosis (70–89%), 20.8% in extreme stenosis (≥90%), and 45.8% in near-occlusion groups. PI also increased significantly across groups. These early improvements in cerebral hemodynamics highlight the risk of hyperperfusion, particularly in near-occlusion cases.[53] These findings align with substudies from the International Carotid Stenting Study, where post-procedural flow velocities in the external carotid artery (ECA) increased gradually after CAS (with significant elevations at 12 and 24 months compared to baseline) while remaining stable after CEA, without increasing ECA occlusion rates in the first 2 years. This suggests potential differences in post-procedural hemodynamics favoring more dynamic flow after CAS in certain vessels, consistent with computational fluid dynamics studies showing higher distal velocities and kinetic energy after CAS compared to CEA.[54,55]

4.2. Role of ECA patency and collateral circulation

One of the critical factors influencing CAS outcomes is the patency of the ECA. A study of 231 CAS cases with ECA occlusion and 32 cases without occlusion found no significant differences in treatment outcomes. However, antegrade ICA flow was observed in 42.9% of cases,

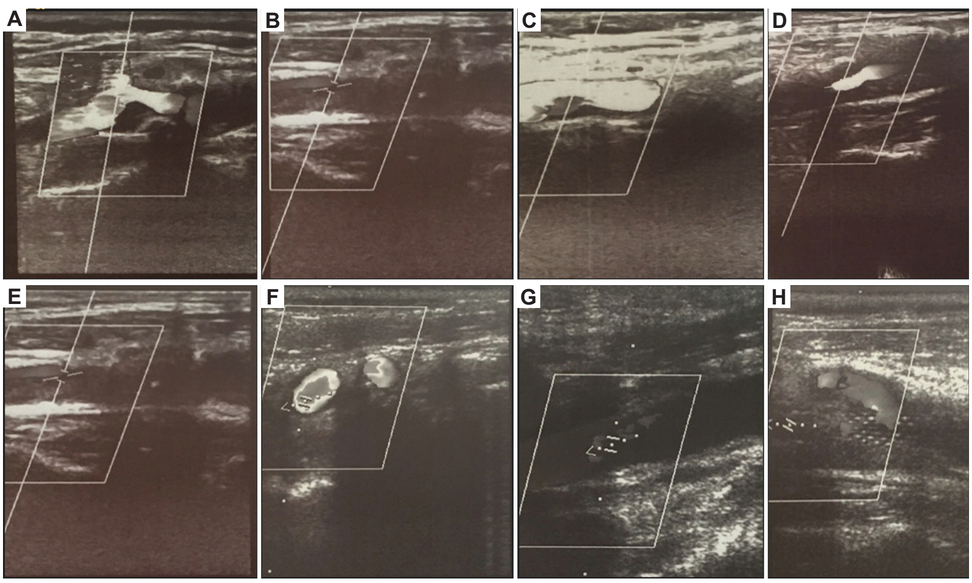

Figure 2. Ultrasound images. (A-E) Ultrasound images of blood flow in the patient's carotid artery before surgery. (F-G) Ultrasound images of blood flow in the carotid artery of a patient after the carotid endarterectomy procedure. (H) Ultrasound image of blood flow in the carotid artery of a patient after carotid artery stenting treatment.

correlating with a lower collateral circulation index and a larger ECA diameter. This highlights the importance of adequate collateral circulation and the use of filtration protection to minimize complications,[56] aligning with a 2023 study on bilateral stenosis showing that anterior communicating artery patency influences post-CEA PSV and EDV reductions in the contralateral artery.[57]

4.3. Major clinical trials in asymptomatic patients

For asymptomatic patients, the ACST-2 study compared CAS and CEA in 3,625 individuals with severe carotid artery stenosis. The study found no significant difference in the risk of disabling stroke or death within 30 days (1% in both groups). Long-term follow-up revealed similar rates of fatal or disabling stroke (~2.5% in each group), although the overall stroke rate was slightly higher for CAS (5.3% vs. 4.5% for CEA; relative risk: 1.16; p=0.33). A meta-analysis confirmed no significant difference in long-term stroke prevention (relative risk: 1.11; p=0.21),[58] further supported by a 2020 systematic review and meta-analysis indicating CEA's edge in reducing stroke events while CAS lowers myocardial infarction risk.[59] The SPACE-2 trial analyzed CEA combined with best medical therapy (BMT), CAS with BMT, and BMT alone. In 1-year interim results, stroke or death were 2.5% for CEA + BMT, 4.4% for CAS+BMT, and 3.1% for BMT alone (no statistically significant differences between revascularization + BMT vs. BMT alone), highlighting the importance of careful patient selection.[60] In 2019, the CREST study evaluated CAS and CEA outcomes in asymptomatic patients who remained symptom-free for more than 180 days before intervention. In a subgroup analysis, no significant differences were found in perioperative stroke and/or death risk, long-term stroke risk, or overall outcomes between patients who were previously symptomatic (but asymptomatic for >180 days) and those who were never symptomatic.[61]

4.4. Recent comparative studies on hemodynamics and outcomes

Comparative studies since 2021 further elucidate differences between CEA and CAS in flow dynamics and outcomes. For instance, a 2021 analysis of pre- and post-CAS cerebral blood flow velocities in 36 patients with median 90% ICA stenosis showed significant ipsilateral MCA cerebral blood flow velocities, increasing from 52.5 cm/s to 64.5 cm/s at 3 days post-procedure (p=0.0011), with sustained elevation at 3 months, alongside bilateral PI rises.[62] A 2024 retrospective study of 129 bilateral stenosis patients found that ipsilateral revascularization (CEA or CAS) led to contralateral PSV decreases in 67.2% of cases, with no significant difference between procedures (69.4% for CEA vs. 61.3% for CAS, p=0.402), though less likely in those with coronary artery disease or diabetes.[63] The Carotis7T study, using 7T magnetic resonance imaging in 15 symptomatic patients with high-degree carotid stenosis, showed the following changes 3 months post-CEA: a postoperative increase in MCA mean velocity (+14.2%) and PI (+10.7%); slight decrease in mean velocity in perforating arteries of the basal ganglia (−5.6%) and semi-oval center (−13.2%); and an increase in PI in these regions (+12.8% and +11.0%, respectively). These trends in MCA velocity were not statistically significant (p=0.16 for velocity increase), while changes in perforating arteries also lacked statistical significance (p>0.05).[23] A 2023 systematic review on duplex ultrasound for post-procedure restenosis highlighted higher PSV thresholds for significant in-stent restenosis after CAS (≥50%: 125–240 cm/s; ≥70%: 170–450 cm/s) compared to post-CEA or native stenosis, attributing this to biomechanical changes, like reduced compliance.[64] On clinical outcomes, a 2021 meta-analysis of CEA vs. CAS in contralateral carotid occlusion patients (6,953 cases) found no differences in stroke or major events but reduced death risk with CEA (odds ratio: 0.45; p<0.001).[65] Similarly, a 2024 propensity-matched study of 538 patients showed equivalent 30-day composite stroke/TIA/acute myocardial infarction/death rates (1.5% overall) between CEA and CAS, with shorter hospital stays for asymptomatic CAS cases.[66] Recent hemodynamic simulations in carotid web patients demonstrated that both CEA and CAS reduced recirculation zones and thrombosis risk, but CAS yielded higher distal kinetic energy and helical flow patterns favorable for endothelial stability.[54]

4.5. Contribution of the current study

This study contributes to the existing literature by providing granular data on pre- and post-procedural flow velocity reductions across stratified patient groups (post-stroke, TIA, and asymptomatic), building on recent evidence from computational models and clinical cohorts since 2021. For instance, the results align with 2022 hemodynamic simulations demonstrating velocity increases post-CEA and CAS in carotid web cases, reducing recirculation and thrombosis risk.[54] They also align with a 2023 analysis showing collateral pathways, such as anterior communicating artery patency, modulate contralateral velocity changes after CEA.[57]. Unlike broader meta-analyses focusing on clinical outcomes,[59] this work emphasizes velocity metrics as surrogates for improved perfusion, offering insights for optimizing procedure selection in diverse stenosis etiologies and reinforcing the efficacy of revascularization amid advancing medical therapies. It also complements studies on post-intervention velocity shifts, such as those showing MCA velocity trends post-CEA[23] and higher PSV in CAS restenosis,[64] by providing sex-specific p-values and group comparisons not always detailed in prior work.

4.6. Limitations

Despite these insights, the study has several limitations. It relies on a relatively small sample size from a single center, potentially limiting generalizability.[67] Although the study was prospectively designed, it was limited by the duration of follow-up, which did not extend beyond the early post-procedural period. As a result, delayed changes in flow dynamics or late clinical events may not have been captured.[68,69] Additionally, direct head-to-head comparisons of CEA versus CAS were not performed in all subgroups, and advanced imaging modalities like computational fluid dynamics were not integrated to model individual variations.[70]

4.7. Future directions

Future research should prioritize prospective, multicenter randomized controlled trials with extended follow-up to track long-term flow velocity stability and correlate it with stroke recurrence. Incorporating advanced tools, such as four-dimensional flow magnetic resonance imaging or machine learning-based simulations, could refine predictions of hemodynamic responses. Comparisons with optimized BMT alone in low-risk asymptomatic patients would further clarify the role of interventions in modern practice.

5. Conclusion

This study demonstrated that both CEA and CAS effectively improved blood flow in patients with carotid artery stenosis, with significant postoperative changes in blood flow velocity observed across various patient categories. While post-stroke patients showed a decrease in blood flow, those with TIA and asymptomatic status exhibited improvements after treatment. These findings confirm that both interventions, CEA and CAS, are effective in restoring blood flow and alleviating perioperative stress, contributing to improved quality of life. Ultimately, while the primary goal of both interventions is to enhance blood flow, the decision between CEA and CAS must be personalized to ensure optimal outcomes, considering both the immediate and long-term effects on cerebral perfusion.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Investigation: All authors
Methodology: All authors
Writing-original draft: All authors
Writing-review & editing: All authors

Ethics approval and consent to participate

The research project was conducted in accordance with the Declaration of Helsinki and approved by the Bioethics Committee at the University of Rzeszów (resolution number 17/02/2019 and date of approval 14/02/2019). Written informed consent was obtained from all participants before enrollment in the study.

Consent for publication

All study participants consented to participate in the study and received appropriate information to enable them to express informed consent despite anonymity.

Availability of data

All data supporting the findings of this study are included within the manuscript.

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