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ORIGINAL ARTICLE
CAROTID DISEASE

Operative time and outcome after carotid endarterectomy for symptomatic and asymptomatic carotid stenosis: a retrospective multicenter cohort study

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ABSTRACT

Background: Carotid endarterectomy (CEA) is the standard treatment for asymptomatic and symptomatic carotid stenosis, but the impact of operative duration on outcomes remains unclear. Previous studies suggested longer procedures increase short-term complications. This multicenter study aimed to evaluate the relationship between operative time and perioperative as well as one-year outcomes, considering indication, surgical technique, and center-specific factors.

Methods: We retrospectively analyzed 1966 patients (70.7% male; 62.1% asymptomatic) undergoing CEA between 2015 and 2023. Of these, 1,560 (79.3%) underwent patch angioplasty and 406 (20.7%) eversion endarterectomy (EEA), under local (N.=918) or general anesthesia (N.=1048). All patients were followed for one year.

Results: Mean operative time was 99.9±31.8 minutes, longer in men, obese, and symptomatic patients, and varied between centers (69.9-121.6 minutes). EEA was faster than conventional CEA (83.1±26.3 *vs.* 104.3±31.7 minutes; P<0.001) with similar 30-day major adverse cardiovascular events (MACE) and stroke rates. EEA had lower rates of cranial nerve injury (OR 0.15, 95% CI 0.04-0.52) and early restenosis/occlusion (OR 0.27, 95% CI 0.07-0.97). No differences were observed in long-term MACE, restenosis, or reoperation. Longer operative time correlated with prolonged ICU and hospital stay, and MACE risk increased once operative time exceeded ~200 minutes.

Conclusions: Operative time alone is not a reliable quality metric. EEA provides a faster procedure than conventional CEA while maintaining comparable short- and long-term outcomes and lower peri-operative morbidity. It is a safe and efficient alternative in selected patients.

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Key words: Endarterectomy, carotid; Carotid artery diseases; Time factors; Treatment outcome; Hospitalization.

For patients undergoing carotid revascularization for asymptomatic or symptomatic carotid stenosis, carotid endarterectomy (CEA) remains the treatment of choice.[1] However, the influence of operative duration on outcomes has been only sparsely investigated.

Aziz *et al.*,[2] analyzing 10,423 carotid procedures from the National Surgical Quality Improvement Program (NSQIP) database, reported an association between prolonged operative times and an increased risk of postoperative complications, distinguishing procedures shorter and longer than 140 minutes. They further examined patient-related factors such as age, sex, history of myocardial infarction, ASA score, and the involvement of surgical trainees in relation to operative duration. Their findings indicated that procedures exceeding 140 minutes were associated with higher 30-day mortality, prolonged hospitalization, and an increased incidence of postoperative pneumonia. Nevertheless, whether 140 minutes represents a clinically relevant threshold remains uncertain. Moreover, their analysis was restricted to short-term outcomes and did not account for long-term results, which, like operative duration, may also depend on intraoperative findings. Perri *et al.*,[3] using data from the Vascular Quality Initiative (VQI) registry, reported a mean operative time of 114 minutes for CEA, with surgeon-specific durations ranging from 37 to 305 minutes. In this study, operative duration was inversely related to surgeon experience, with longer times observed among operators with lower annual case volumes.

Neither of these investigations provided details on surgical technique, nor did they distinguish between asymptomatic and symptomatic patients. According to the guidelines of the European Society for Vascular Surgery (ESVS),[1] CEA may be performed either as an eversion or patched endarterectomy, with the choice left to the discretion of the surgeon. Against this background, the present multicenter study was designed to more precisely investigate the relationship between operative duration and outcomes following CEA, with particular emphasis on the role of surgical technique. The objective was to determine the extent to which operative duration is influenced by surgical technique and anesthesia, and how this, in turn, relates to long-term outcomes after one year.

Materials and methods

Patients and procedures

A total of 1966 consecutive carotid procedures were retrospectively analyzed in this multicenter study conducted across eight German centers between 2015 and 2023. Of these, 746/1966 (37.9%) patients had symptomatic and 1220/1966 (62.1%) had asymptomatic carotid stenosis. Traditional CEA with patch angioplasty was performed in 1560/1966 (79.3%) patients, while eversion endarterectomy was carried out in 406/1966 (20.7%) patients. Procedures were performed under local anesthesia in 918/1966 (46.7%) cases and under general anesthesia in 1048/1966 (53.3%) cases. Intraoperative quality control was conducted in accordance with the internal standards of each center and was therefore mandatory, additional diagnostic procedures were however available if required. Three types of intraoperative quality control were applied: duplex sonography in 851/1966 patients (43.3%), angiography in 463/1966 patients (23.6%), and flow and resistance measurements in 471/1966 patients (24.0%). In one vascular surgery center, which contributed 181/1966 patients (9.2%), no instrumental quality control was performed. Procedure time was defined as the duration from skin incision to skin closure. To reduce potential bias, consecutive patient inclusion and predefined exclusion criteria were applied across all centers. The total number of included procedures was based on cases performed within a four-year period per center, with different enrollment periods, since not all centers joined the study at the same time, resulting in a study period from 2015 to 2023. Initially, 3105 patients were screened for eligibility, Of these, 752 patients were excluded due to carotid reconstructions using interposition grafts, reoperations, combined interventions, and transfemoral carotid artery stenting (TFCAS) or transcarotid artery revascularization (TCAR). Additionally, patients who could not be reached during follow-up (1 year) were considered lost to follow-up and excluded (N.=387); 1966 patients were included in the final analysis. Data collection was carried out using a standardized algorithm to ensure consistency and minimize selection and information bias. Patient characteristics as well as surgical and hospitalization data were obtained from patient records stored in hospital information systems. To determine the late outcomes, telephone interviews were conducted with patients or their general practitioners when follow-up documentation was missing. Data extraction and analysis were performed independently from the treating teams, and reporting adhered to the STROBE checklist for cohort studies.[4]

Perioperative and late outcome

The complications were classified chronologically into perioperative – occurring during hospitalization or within 30 days postoperatively – and late, occurring >30 days and up to one year after the procedure. Complications included all-cause mortality, non-fatal myocardial infarction, and non-fatal stroke, summarized as MACE. In addition, nerve injuries, occlusions and restenosis (>50%) as well as any reinterventions of the target vessel (due to bleeding, wound healing disorders, stenosis, or occlusion) were documented. The assessment of occlusion/stenosis was performed perioperatively and during follow-up using Duplex ultrasonography, cross-sectional imaging was performed as needed.

Statistical analysis

Statistical analysis. All analyses were conducted in R 4.5.1 and Python 3.12.10. Missing data were handled with predefined single-imputation rules, yielding ≥99% complete datasets. Low-frequency categorical levels were collapsed (asterisk-marked in figures) to enhance model stability and clinical interpretability.

Binary endpoints (*e.g.*, 30-day and late MACE, perioperative bleeding) were analyzed with mixed-effects logistic regression, while continuous right-skewed outcomes – including operative time (minutes), length-of-stay and ICU days – were modelled with Gamma mixed-effects regression (log link). A random intercept for center captured between-center heterogeneity. Operative-time effects are reported per 10-minute increase; non-linear associations with MACE were examined using a natural cubic-spline term.

The comparative effect of eversion endarterectomy *versus* conventional endarterectomy was estimated after 1:1 nearest-neighbor propensity-score matching (caliper 0.20 SD, no replacement, exact on center); post-match balance was acceptable (all SMD <0.10). Matched outcomes were re-analyzed with only a center random intercept. Endpoints were assessed at fixed windows: MACE 30-day (perioperative events within 30 days) and late MACE (events from day 31 to day 365). Therefore, Kaplan-Meier methods were not applicable. Two-sided P<0.05 denoted statistical significance.

Results

Patient characteristics

Of the 1966 patients, 1389/1966 (70.7%) were men and 577/1966 (29.3%) were women. Men with asymptomatic carotid artery stenosis tended to be younger than those with symptomatic stenosis (71.4±8.3 *vs.* 72.2±9.3 years; P=0.08). Among women, the age difference between asymptomatic and symptomatic patients was more pronounced (71.9±8.4 *vs.* 73.6±9.0 years; P=0.021). Patients with asymptomatic stenosis more frequently had a history of tobacco use (468/1220 [38.4%] *vs.* 224/746 [30.0%]; P<0.001) and were more likely to have coronary artery disease (443/1220 [36.3%] *vs.* 209/746 [28.0%]; P<0.001) or prior cardiac surgery (382/1220 [31.3%] *vs.* 170/746 [22.8%]; P<0.001) compared to those with symptomatic stenosis. No other baseline parameters differed significantly between the two groups (Table I). At discharge, 1406/1966 (71.5%) patients received aspirin monotherapy, 80/1966 (4.1%) clopidogrel monotherapy, and 102/1966 (5.2%) dual antiplatelet therapy with aspirin plus clopidogrel. Anticoagulant therapy was prescribed in 149/1966 (7.6%), while 229/1966 (11.6%) received a combination of antiplatelet and anticoagulant therapy.

TABLE I.—*Patient characteristics.*

Patient characteristics	Patients with asymptomatic ICA stenosis N.=1220	Patients with symptomatic ICA stenosis N.=746	P value
Age, men			
Mean±SD (Median, min - max)	71.4±8.26 (72; 41-90)	72.2±9.27 (74; 49-93)	0.08
Age, women			
mean±SD (median, min-max)	71.9±8.36 (73; 44-89)	73.6±8.97 (75; 52 - 91)	0.02
BMI, mean±SD (median, min-max)	26.9±4.28 (26.7; 14.2-44.9)	27.4±5.1 (27.4; 16.1 - 68)	0.052
Diabetes	321 (26.3%)	225 (30.2%)	0.06
COPD	188 (15.4%)	100 (13.4%)	0.22
Chronic kidney disease stage 3-5	481 (39.4%)	318 (42.6%)	0.16
Dialysis	9 (0.7%)	6 (0.8%)	0.87
Arterial hypertension	1087 (89.1%)	650 (87.1%)	0.19
Coronary heart disease	443 (36.3%)	209 (28%)	<0.001
Heart surgery, anamnestic	382 (31.3%)	170 (22.8%)	<0.001
Congestive heart failure	193 (15.8%)	108 (14.6%)	0.42
Atrial fibrillation	172 (14.1%)	114 (15.3%)	0.47
Smoker	468 (38.4%)	224 (30%)	<0.001
Alcohol abuse	78 (6.4%)	47 (6.3%)	0.94

ICA: internal carotid artery; SD: standard deviation; BMI: Body Mass Index; COPD: chronic obstructive pulmonary disease. Categorical variables are presented as number with percentages. Continuous variables are expressed as both mean±standard deviation and median with range (min-max).

Predictors of 30-day and late MACE

In this cohort, current smoking was a strong and statistically significant risk factor for late MACE (OR 2.29 [95% CI, 1.31-4.01]; P=0.004). Coronary artery disease was significantly associated with 30-day MACE (OR 2.60 [95% CI, 1.35-4.98]; P=0.004) and showed a borderline association with late MACE (OR 1.77 [95% CI, 1.00-3.15]; P=0.050). Age ≥80 years was strongly associated with 30-day MACE (OR 2.75 [95% CI, 1.47-5.12]; P=0.001), but not with late MACE. Symptomatic stenosis was associated with an increased risk of 30-day MACE (OR 2.36 [95% CI, 1.29-4.32]; P=0.005) and showed a nonsignificant trend toward late MACE (OR 2.07 [95% CI, 0.95-4.54]; P=0.070). Other covariates – including ASA class (≥III), atrial fibrillation, chronic kidney disease, diabetes, obesity, and perioperative medications – were not significant predictors of MACE (Figure 1).

Complication rates

In men, overall mortality was 36/1389 (2.6%), stroke 33/1389 (2.4%), myocardial infarction 21/1389 (1.5%), and MACE 86/1389 (6.2%). In women, mortality was 11/577 (1.9%), stroke 14/577 (2.4%), myocardial infarction 8/577 (1.4%), and MACE 31/577 (5.4%). Comparison between men and women showed similar rates of overall mortality (P=0.25), myocardial infarction (P=0.83), stroke (P=0.95), and MACE (P=0.46).

Perioperative and late complications for symptomatic *versus* asymptomatic carotid stenosis are detailed in Table II. Compared with symptomatic patients, those with asymptomatic stenosis had lower 30-day death rates (3/1220 [0.3%] *vs.* 10/746 [1.3%]; P=0.004) and 30-day MACE (21/1220 [1.7%] *vs.* 30/746 [4.0%]; P=0.002). During follow-up (31 to 365 days), asymptomatic patients experienced a higher rate of recurrent stenoses or reocclusion of the target vessel (55/1217 [4.5%] *vs.* 18/736 [2.4%]; P=0.002).

Perioperative and late complications by center

Center-specific perioperative and late complication rates are summarized in Table III. The overall perioperative complication rate was 193/1966 (9.8%), ranging from 8/194 (4.1%) to 38/203 (18.7%) across centers (P=0.001). Perioperative MACE occurred in 51/1966 (2.6%; range 3/386 [0.8%]-11/262 [4.2%]; P=0.02), stroke in 30/1,966 (1.5%; range 3/386 [0.8%]-7/262 [2.3%]; P=0.61), and death in 13/1966 (0.7%; range 0-5/219 [2.3%]).

The late complication rate (31 to 365 days) was 139/1953 (7.1%; range 3/194 [1.5%]-26/219 [11.9%]; P<0.001), including MACE 66/1953 (3.4%; range 11/277

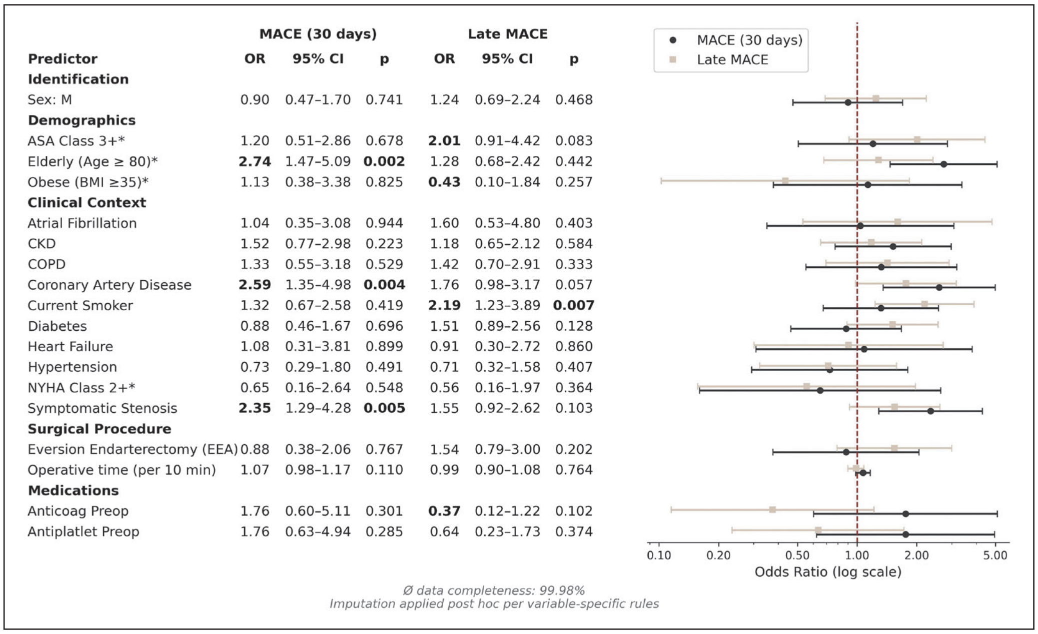

Figure 1.—Predictors of 30-day and late MACE.
Age ≥80 years, coronary artery disease, and symptomatic stenosis were associated with 30-day MACE, whereas current smoking was associated with late MACE. Variables marked with an asterisk (*) were derived as binary predictors for the regression analysis. MACE: major adverse cardiovascular event.

Table II.—*Perioperative and late complications after CEA in Patients with symptomatic (S-ICA) and asymptomatic internal carotid artery stenosis (AS-ICA).*

Events	Early (30 days)			Late (31-365 days)		
	AS-ICA N.=1220	S-ICA N.=746	P value	AS-ICA N.=1217	S-ICA N.=736	P value
Death	3 (0.25%)	10 (1.3%)	0.004	19 (1.6%)	15 (2%)	0.45
Stroke	14 (1.1%)	16 (2.1%)	0.08	10 (0.8%)	7 (0.9%)	0.78
Myocardial infarction	5 (0.4%)	4 (0.5%)	0.69	10 (0.8%)	10 (1.4%)	0.26
MACE	21 (1.7%)	30 (4%)	0.002	37 (3%)	29 (3.9%)	0.31
Nerve injury	52 (4.3%)	22 (3%)	0.14	0	0	-
Occlusion/ Stenosis	20 (1.6%)	8 (1.1%)	0.3	55 (4.5%)	18 (2.4%)	0.02
Reoperation	42 (3.4%)	21 (2.8%)	0.44	25 (2.1%)	8 (1.1%)	0.1

MACE: major adverse cardiovascular event.

Table III.—*Complication rate by center, perioperative and late complications.*

Center	Patients total N.=1966	Perioperative complication rate (patients) 30-day	Nerve injury 30-day	Occlusion/ stenosis 30-day	Reoperation (all-cause) 30-day	MACE 30-day	Late complication rate (patients) 31-365 days	Occlusion/ stenosis 31-365 days	Reoperation (all-cause) 31-365 days	MACE late 31-365 days
A	181 (9.2%)	13 (7.2%)	6 (3.3%)	4 (2.2%)	3 (1.7%)	2 (1.1%)	17 (9.4%)	12 (6.6%)	2 (1.1%)	4 (2.2%)
B	219 (11.1%)	22 (10%)	4 (1.8%)	2 (0.9%)	9 (4.1%)	8 (3.7%)	26 (11.9%)	12 (5.5%)	1 (0.5%)	15 (6.8%)
C	194 (9.9%)	8 (4.1%)	0	2 (1%)	1 (0.5%)	5 (2.6%)	3 (1.5%)	2 (1%)	0	1 (0.5%)
D	386 (19.6%)	26 (6.7%)	15 (3.9%)	2 (0.5%)	9 (2.3%)	3 (0.7%)	38 (9.8%)	27 (7%)	19 (4.9%)	12 (3.1%)
E	262 (13.3%)	37 (14.1%)	17 (6.5%)	9 (3.4%)	3 (1.1%)	11 (4.2%)	23 (8.8%)	14 (5.4%)	8 (3.1%)	9 (3.4%)
F	277 (14.1%)	37 (13.4%)	12 (4.3%)	1 (0.4%)	20 (7.2%)	11 (3.9%)	15 (5.4%)	4 (1.5%)	2 (0.7%)	11 (0.4%)
G	203 (10.3%)	38 (18.7%)	18 (8.9%)	8 (3.9%)	12 (5.9%)	5 (2.5%)	8 (3.9%)	1 (0.5%)	0	7 (3.5%)
H	244 (12.4%)	12 (4.9%)	2 (0.8%)	0	6 (2.5%)	6 (2.5%)	9 (3.7%)	1 (0.4%)	1 (0.4%)	7 (2.9%)
Total	1966	193 (9.8%)	74 (3.8%)	28 (1.4%)	63 (3.2%)	51 (2.6%)	139 (7.1%)	73 (3.7%)	33 (1.7%)	66 (3.3%)
P value	-	<0.001	-	<0.001	<0.001	0.022	<0.001	<0.001	-	0.001

MACE: major adverse cardiovascular event. Categorical variables are presented as number with percentages.
Categorical variables are presented as number with percentages.

[0.4%]-15/219 [6.8%]; P=0.001), death 34/1953 (1.7%; range 1/194 [0.5%]-6/219 [2.7%]; P=0.47), and stroke 17/1953 (0.9%; range 0-4/203 [2.0%]; P=0.84).

Conventional CEA *vs.* eversion endarterectomy

In the 1:1 propensity score-matched analysis (all covariate standardized mean differences <0.10), EEA showed no significant differences compared with CEA regarding 30-day MACE (OR 0.51 [95% CI, 0.19-1.37]; P=0.18) or 30-day stroke (OR 1.94 [95% CI, 0.35-10.75]; P=0.45). Perioperatively, EEA was associated with a lower incidence of cranial nerve injury (OR 0.15 [95% CI, 0.04-0.52]) and a reduced rate of stenosis/occlusion (OR 0.27 [95% CI, 0.07-0.97]), but no difference in 30-day all-cause reoperation (OR 0.78 [95% CI, 0.33-1.86]). During follow-up (31-365 days), EEA demonstrated no differences compared with CEA in rates of stenosis/occlusion (OR 0.94 [95% CI, 0.42-2.11]), all-cause reoperation (OR 0.84 [95% CI, 0.31-2.24]; P=0.73), or late MACE (OR 1.58 [95% CI, 0.70-3.57]; P=0.27). Other matched covariates, including symptomatic status, showed no significant associations after matching.

Procedure times

Mean operative time was 99.9±31.8 minutes. Women had shorter procedure times than men (94.4±30.5 *vs.* 102.2±32.1 minutes; P<0.001). A comparable trend was noted for operations performed for asymptomatic *versus* symptomatic stenoses (97.5±29.9 *vs.* 104.0±34.4 minutes; P<0.001). Operative time tended to be shorter under general anesthesia (95.0±32.6 minutes) than under local anesthesia (105.5±30.1 minutes), with no meaningful difference observed (OR 0.98 [95% CI, 0.93-1.04]; P=0.51). Across centers, mean operative times ranged from 69.9±19.5 to 121.6±34.5 minutes (P<0.001) (Table IV). With intraoperative quality control (duplex ultrasound, angiography, or flow/resistance measurement), the mean operative time was 103.0±31.3 minutes compared with 69.9±19.5 minutes without such assessments (P<0.001). The perioperative complication rate was 180/1,785 (10.1%) in centers using quality control and 13/181 (7.2%) in the center without it (P=0.21).

EEA was faster than CEA (83.1±26.3 *vs.* 104.3±31.7 minutes; P<0.001) across symptomatic and asymptomatic patients, and among those with and without perioperative or late complications – except for patients with late complications, in whom times did not differ by technique. Within CEA cases, procedure time was longer in patients with perioperative complications (110.8±36.6 *vs.* 103.5±31.0 minutes; P=0.01), whereas in EEA it did not differ between patients with and without perioperative complications, nor between those with and without late complications.

Predictors of operative time

In our study, EEA, compared with conventional CEA, was associated with a substantially shorter operative time (Relative Mean Ratio [RMR] 0.77 [95% CI, 0.75-0.79]; P<0.001), corresponding to a 23% reduction in procedure duration. Operations in patients aged ≥80 years were slightly shorter (RMR 0.96 [95% CI, 0.93-0.99]; P=0.009, 4% shorter). Obesity (BMI≥35) was associated with longer procedures (RMR 1.11 [95% CI, 1.06-1.17]; P<0.001, 11% longer), while male sex showed a modest prolongation (RMR 1.07 [95% CI, 1.04-1.10]; P<0.001, 7% longer). Symptomatic stenosis was weakly associated with increased operative time (RMR 1.03 [95% CI, 1.00-1.05]; p=0.031, 3% longer). Other comorbidities, perioperative risk factors, and anesthesia type did not significantly influence operative duration (Figure 2).

Effect of operative time on 30-day and late MACE

The relationship between operative duration and MACE risk was nonlinear. The spline curve demonstrated low

Table IV.—*Number of procedures, operating times and length of stay by center.*

Center	Number of procedures	Local anesthesia	Operating time (min)	Length of stay (days)
A*	181 (9.2%)	0	69.9±19.5	5 (IQR 4-5)
B	219 (11.1%)	199 (90.1%)	108.7±31.5	3 (IQR 3-3)
C	194 (9.9%)	1 (0.5%)	109.7±46.9	4 (IQR 3-5)
D	386 (19.6%)	0	94.3±22.5	3 (IQR 3-4)
E	262 (13.3%)	221 (84.4%)	121.6±34.5	5 (IQR 4-6)
F	277 (14.1%)	260 (93.9%)	98.7±28.1	5 (IQR 4-5)
G	203 (10.3%)	1 (0.5%)	95.4±25.1	4 (IQR 4-6)
H	244 (12.4%)	236 (96.7%)	96.9±19.6	4 (IQR 4-4)
Total	N.=1966	N.=918	99.9±31.8	4 (IQR 3-5)

*Center without intraoperative completion imaging.
Categorical variables are presented as number with percentages. Continuous variables are presented as means and standard deviations.
Length of stay is reported as median (interquartile range, IQR).

Predictor	Operative Time (per min) Ratio	95% CI	p
Identification			
Sex: M	1.07	1.04–1.10	**<0.001**
Demographics			
ASA Class 3+*	1.02	0.99–1.05	0.131
Elderly (Age ≥ 80)*	0.96	0.93–0.99	**0.009**
Obese (BMI ≥35)*	1.11	1.06–1.17	**<0.001**
Clinical Context			
CKD	1.00	0.97–1.03	0.982
Coronary Artery Disease	1.02	0.99–1.05	0.152
Diabetes	1.01	0.99–1.04	0.410
Symptomatic Stenosis	1.03	1.00–1.05	**0.030**
Surgical Procedure			
Eversion Endarterectomy (EEA)	**0.77**	0.75–0.79	**<0.001**
Local Anesthesia	0.99	0.93–1.04	0.598

Ø data completeness: 99.97%
Imputation applied post hoc per variable-specific rules

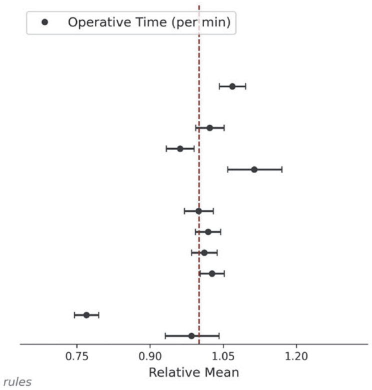

Figure 2.—Predictors of operative time.
Male sex and obesity were associated with increased operative time, whereas elderly age and eversion endarterectomy (EEA) were associated with decreased operative time. Effects of each predictor are presented as relative mean ratios (RMR). Variables marked with an asterisk (*) were derived as binary predictors for the regression analysis.

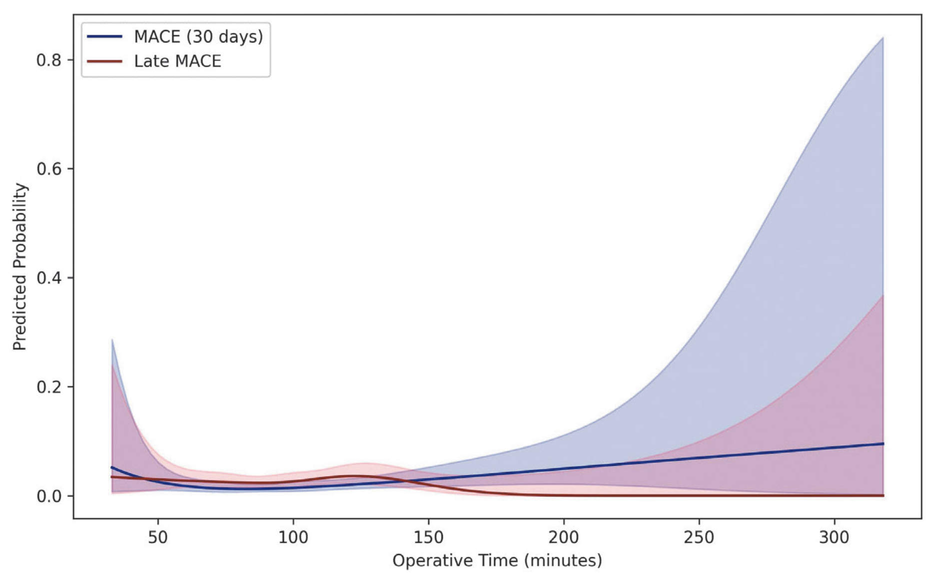

Figure 3.—Effect of operative time on the risk of MACE.
The observed effect was non-linear, with a substantially increased risk for procedures exceeding approximately 200 minutes. Short to average operative times were not associated with an elevated risk.
MACE: major adverse cardiovascular event.

event probabilities between approximately 60 and 180 minutes. Beyond ≈ 200 minutes, however, the risk increased sharply, with wide confidence intervals reflecting the limited number of prolonged cases. No discrete "safe threshold" was identified, as the risk rose gradually at first and then more steeply with longer operative times. This pattern was consistent for both 30-day and late MACE. Short to average operative durations were not associated with an increased risk, whereas prolonged procedures exceeding ≈200 minutes were associated with a substantially higher risk of 30-day and late MACE (Figure 3).

Length of ICU and hospital stay

The median postoperative length of stay (LoS) was 4 days (IQR 3-5), and the median ICU LoS was 1 day (IQR 0-1). Patients with perioperative complications had longer postoperative LoS (5 days [IQR 4-7] *vs.* 4 days [IQR 3-5]; P<0.001) and ICU stay (1 day [IQR 0-1] *vs.* 1 day [IQR 1-1]; P<0.001).

Prolonged postoperative LoS was significantly associated with higher ASA class (≥III) (RMR 1.07 [95% CI, 1.02-1.13]; P=0.006, 7% longer), atrial fibrillation (RMR

1.18 [95% CI, 1.11-1.25]; P<0.001, 18% longer), chronic kidney disease (RMR 1.08 [95% CI, 1.03-1.14]; P=0.003, 8% longer), symptomatic stenosis (RMR 1.10 [95% CI, 1.06-1.15]; P<0.001, 10% longer), and operative time (per minute: RMR 1.002, 0.2% increase per minute; P<0.001).

Prolonged ICU stay was associated with atrial fibrillation (RMR 1.36 [95% CI, 1.25-1.48]; P<0.001, 36% longer), chronic kidney disease (RMR 1.18 [95% CI, 1.09-1.26]; P<0.001, 18% longer), hypertension (RMR 1.15 [95% CI, 1.05-1.27]; P=0.004, 15% longer) and operative time (per minute: RMR 1.005, 0.5% increase per minute; P<0.001).

Shorter ICU stay was observed in patients aged ≥80 years (RMR 0.90 [95% CI, 0.83-0.96]; P=0.003, 10% shorter) and those with coronary artery disease (RMR 0.91 [95% CI, 0.85-0.97]; P=0.003, 9% shorter). Hyperlipidemia was associated with reduced postoperative LoS (RMR 0.93 [95% CI, 0.88-0.99]; P=0.03, 7% shorter) and slightly shorter ICU stay (RMR 0.96 [95% CI, 0.92-1.00]; P=0.04, 4% shorter). Other covariates showed no significant or only borderline associations. Center-specific LoS data are summarized in Table IV.

Discussion

This multicenter analysis identified key patient- and procedure-related factors influencing outcomes after carotid endarterectomy. Advanced age, coronary artery disease, and symptomatic stenosis were associated with 30-day MACE, while current smoking was linked to late MACE. EEA demonstrated no significant differences compared with conventional CEA in 30-day MACE or stroke and was associated with a lower incidence of cranial nerve injury and a reduced rate of early restenosis or occlusion. Midterm outcomes – including late MACE, reintervention, and restenosis – were comparable between the two techniques. Longer operative times were observed in men, obese patients, and those with symptomatic stenosis, and were associated with prolonged ICU and hospital stay. The risk of MACE increased with markedly prolonged procedures, particularly when operative duration exceeded approximately 200 minutes. Overall, cardiovascular outcomes after carotid surgery appear primarily determined by patient comorbidity and risk profile, whereas procedural duration influences recovery time and, in very long operations, may affect perioperative risk.

These findings are consistent with Schneider *et al.*,[5] who – using VQI registry data – also reported significantly shorter operative times for EEA *versus* CEA (median 99 *vs.* 114 minutes; P<0.001) and concluded that both techniques "appear to provide similar freedom from neurological morbidity, death, and reintervention." They did note, however, that one-year freedom from recurrent stenosis >50% was lower after EEA (88.8% vs. 94.3%; P<0.001), though freedom from reoperation was virtually identical (99.5% *vs.* 99.6%). In contrast to Schneider *et al.*, our data demonstrated perioperatively a lower rate of restenosis/occlusion after EEA, while all-cause reoperation rates remained similar.

Reports on CEA operative times vary. Veraldi *et al.*[6] described a modified EEA in 837 patients with a mean duration of 63.9±15.1 minutes, 94.9% under local anesthesia. Shukuzawa *et al.*,[7] using a "mini-incision" EEA, reported a mean operative time of 171.0±50.7 minutes in 120 cases, highlighting a low perioperative complication rate (MACE 2.5%) and favorable cosmetic results. Jeon *et al.*[8] compared 41 patients undergoing a high mini-incision approach with 110 patients using conventional access: operative time averaged 100.9±15.9 minutes *versus* 154.5±42.6 minutes (P<0.001), attributed to better exposure of the carotid bifurcation. Qumsiyeh *et al.*[9] studied 851 CEA patients, 277 (33%) of whom had primary closure without patch – these procedures lasted 87±28 minutes *versus* 102±26 minutes with patch (P<0.001), with no differences in perioperative or up to four-year outcomes. Mukerji *et al.*[10] reported on 728 CEAs by a single surgeon (84.6% under local anesthesia), with a mean operative time of 134.8±38.1 minutes, 30-day mortality of 0.8%, perioperative stroke 2.3%, and cardiac events 2.9%.

In our cohort, operative time under general anesthesia (95.0±32.6 minutes) showed a trend towards shorter duration than under local anesthesia (105.5±30.1 minutes) but this difference was not statistically significant (OR 0.98 [95% CI, 0.93-1.04]; P=0.51). Furthermore, women had shorter procedure times than men. Chou *et al.*,[11] in 41,442 CEAs from the NSQIP database (24,568 men, 16,874 women), likewise reported shorter operative times in women than in men under both regional and general anesthesia. In both sexes, procedures under general anesthesia were longer than under regional anesthesia. Grieff *et al.*[12] also observed shorter operative times – and a lower rate of cranial nerve injury – with regional *versus* general anesthesia in the NSQIP database. In our series, the type of anesthesia was not associated with cranial nerve injury (OR 0.99; 95% CI, 0.20-6.10; P=0.951), and perioperative complication rates were comparable between local and general anesthesia.

Our analysis suggests that multiple factors influence procedure duration – including the surgical team, operative technique (EEA *vs.* CEA), use of a patch, and incision type. This is illustrated by the wide range of mean times across our centers (69.9±19.5 to 121.6±34.5 minutes; overall mean 99.9±31.8 minutes) without significant differences in perioperative or one-year outcomes (Table III). Additionally, in CEA – but not in EEA – procedures for asymptomatic stenosis were shorter (102.0±30.0 minutes) than for symptomatic stenosis (107.5±33.8 minutes; P<0.001), perhaps reflecting differences in plaque morphology that have not received sufficient attention.

Whether intraoperative completion imaging (angiography, Duplex ultrasound, or flow measurement), as recommended by the ESVS guidelines[1] (Class IIa, Level B)), affects procedure duration significantly is also critical. In our series, operations with intraoperative quality control averaged 103.0±31.3 minutes *versus* 69.9±19.5 minutes without it (P<0.001). No separate data on the duration of intraoperative imaging were available, although such information would have been of interest given potential differences in time requirements between flow and resistance measurements, angiography, and duplex ultrasound. Furthermore, the observation that the perioperative complication rate was 10.1% in centers with quality control compared to 7.2% in the center without quality control (P=0.21) suggests that a reduction in operative time was achieved without compromising clinical outcomes, however, this comparison is based on a single center's experience and may not be generalizable. Dakour-Aridi *et al.*,[13] analyzing 98,055 CEAs in the VQI registry, reported completion imaging in 27.3% of cases; 45% of surgeons never performed it. They found operative times of 119 minutes (IQR 92-148) with completion imaging *versus* 105 minutes (IQR 82-132) without (P<0.001). Completion imaging proved safe despite an increase in immediate re-explorations. However, when used infrequently by less experienced surgeons, it was associated with higher odds of adverse events – underscoring the importance of surgical experience to avoid unnecessary re-explorations.

A primary aim of this study was to examine the relationship between operative time and both perioperative and one-year long-term outcomes. Aziz *et al.*[2] retrospectively assessed the effect of procedure duration on 30-day perioperative complication rates in 10,423 carotid interventions from the NSQIP database. They found that operations exceeding 140 minutes (the cohort median) were associated with increased perioperative mortality, longer hospital stay, prolonged ventilator weaning, and higher rates of pneumonia. In another analysis, Perri *et al.*[3] reported on 26,327 CEAs performed by 1,188 surgeons across 249 centers in the VQI registry. Mean operative time was 114 minutes (median 108), and surgeons' median annual volume was 13 cases. They demonstrated a significant inverse relationship between surgeon volume and operative time, and – in turn – a significant association between longer operative times and higher complication rates. Exceeding 110 minutes was linked to a 40% increase in cardiac complications and a 25% increase in technical complications. Bennett *et al.*[14] analyzing, 3,845 CEA patients in NSQIP, similarly reported significantly higher 30-day major morbidity when operative time exceeded 150 minutes (median cut-off 120 minutes) *versus* under 90 minutes. In a separate study, Bennett *et al.*[15] compared 84 CEA patients with cranial nerve injury to 3678 without, finding that procedures longer than 90 minutes (median 135 minutes) conferred an increased risk of nerve injury. In our cohort, the mean operative time was 99.9±31.8 minutes. Event probabilities for MACE remained very low between approximately 60 and 180 minutes, rising gradually at first and then more sharply for procedures exceeding 200 minutes. No discrete cut-off for operative time was identified, as the risk rose gradually at first and then more steeply with prolonged durations.

Operative time cannot serve as a standalone quality metric due to the multitude of influencing factors. Nonetheless, we observed a consistent association between procedure duration and postoperative length of stay, both in the ICU and overall hospital stay. Median hospital stay in our cohort was 4 days (IQR 3-5), ranging from 3 days (IQR 3-3) to 5 days (IQR 4-5) across centers. Each additional minute of operative time corresponded to a modest increase in total hospital and ICU stay (relative mean ratios 1.002-1.005), which becomes clinically relevant in prolonged procedures, consistent with the non-linear increase in MACE risk observed beyond 200 minutes. Length of hospital stay corresponded to that reported by Knappich *et al.*[16] for Germany (median hospital stay 5 days, IQR 4-6 in 119,800 CEAs) and contrasts with the VQI registry data, in which Aridi *et al.*[17] identified a median stay of just one day for 118,625 carotid revascularizations, with any stay beyond one day classified as prolonged. Differences in cost reimbursement could explain the differences between the two healthcare systems.

Limitations of the study

Limitations of our study include the lack of data on symptom onset and time to procedure in symptomatic patients, missing clamp-time information, absence of shunt usage data, and no documentation of intraoperative lesion complexity or technical difficulty – factors likely influencing procedure duration. Furthermore, no data were available regarding the use or type of intraoperative neurological monitoring. As outcomes after CEA were assessed at predefined time windows (30 days and 1 year) rather than as continuous survival times with censoring, Kaplan-Meier analysis was not applicable. Binary outcomes were therefore modeled using mixed-effects logistic regression, which accounted for clustering effects while appropriately addressing the fixed follow-up intervals. Additionally, no analysis of the correlation between surgeons' annual case volume and postoperative outcomes was performed, and there was no reliable information on the annual procedural volumes of the participating centers. The extent to which CEAs were performed by trainees represents another important limitation that remains unassessed.

This retrospective multicenter study is subject to potential selection and information bias. Loss to follow-up and center-specific differences in intraoperative quality control may have led to underestimation or variability of complication rates. Although standardized data collection and propensity score matching were applied, residual confounding cannot be excluded. The observational design limits causal interpretation of associations between risk factors and outcomes.

Nevertheless, we were able to perform a detailed analysis of operative time and perioperative outcomes. Strengths of the study include the consecutive enrolment of all patients and complete one-year follow-up for every case, allowing – for the first time – a correlation of operative time not only with perioperative outcomes but also with one-year results.

Conclusions

This study found a nonlinear relationship between operative duration and MACE after carotid endarterectomy, with risk rising sharply for procedures exceeding approximately 200 minutes. Operative time alone is not a reliable quality metric due to multiple patient- and procedure-related factors. Longer procedures were consistently associated with extended ICU and total hospital stay. EEA was faster than conventional CEA across symptomatic and asymptomatic patients, while maintaining comparable outcomes for MACE and reoperation. In addition, EEA demonstrated lower rates of cranial nerve injury and restenosis/occlusion supporting its role as a safe and efficient alternative to conventional CEA.

The multicenter, consecutive cohort enhances external validity by reflecting routine practice across diverse vascular centers in Germany. However, variations in surgical technique and perioperative management may limit transferability to other healthcare contexts.

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Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions
Radu Tabac contributed to conceptualization, data curation, formal analysis, methodology, resources, and software, and was involved in drafting and critically revising the manuscript; Corneliu Lisii contributed to conceptualization, data curation, formal analysis, methodology, resources, and software, and critically revised the manuscript; Mareike Ruckert, Carlotta Linder, Igor Cebotari, Daniel Kleinschmidt, Jessica Nentwig, and Marie Schröder contributed to data curation, methodology, and critically revised the manuscript for important intellectual content; Shervin Taheripour contributed to resources, software, methodology, formal analysis, and drafting the manuscript;. Eike S. Debus contributed to conceptualization, supervision, and critical revision; Reinhart T. Grundmann contributed to conceptualization, formal analysis, methodology, drafting and revising the manuscript, supervision, and project administration. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All authors read and approved the final version of the manuscript.

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