Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Propensity score matched analysis of 5-year outcomes of transcarotid revascularization, transfemoral carotid artery stenting, and carotid endarterectomy

Eunsaem Sam Cho
University of Colorado Anschutz Medical Campus
Aline Hikari Ishida
University of Colorado Anschutz Medical Campus
Zhixin Lun
University of Colorado Anschutz Medical Campus
Pedro J. Furtado Neves
University of Colorado Anschutz Medical Campus
Rafael D. Malgor
rafael.malgor@cuanschutz.edu
University of Colorado Anschutz Medical Campus
Emily A. Malgor
University of Colorado Anschutz Medical Campus

Research Article

Keywords: Carotid artery disease, Carotid revascularization, Carotid endarterectomy, Transcarotid artery revascularization, Transfemoral carotid artery stenting, Mortality, Propensity score matching, Vascular Quality Initiative

Posted Date: November 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10965002/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

Prior studies show variable perioperative mortality after transcarotid artery revascularization (TCAR), transfemoral carotid artery stenting (TFCAS), and carotid endarterectomy (CEA), but data beyond the first postoperative year are limited. This study evaluated 5-year mortality and perioperative neurological complication rates after TCAR, TFCAS, and CEA.

Methods

A retrospective analysis of patients undergoing carotid artery stenting and CEA from 2016 to 2022 was performed using the Vascular Quality Initiative (VQI) database. Patients were propensity score matched using clinically relevant baseline characteristics. Bivariate analysis, Kaplan–Meier survival, and Cox proportional hazards regression were used to evaluate 1- and 5-year mortality, with subgroup analyses based on symptomatic status and perioperative stroke.

Results

In 2,394 matched CEA–TCAR pairs, 1-year mortality was comparable (2,027 vs 1,923 at risk, $p = 0.41$), with no difference at 5 years (513 vs 51, $p = 0.21$). In 2,862 matched CEA–TFCAS pairs, CEA was associated with lower 1-year mortality (2,406 vs 2,397, $p < 0.0001$), and this difference persisted at 5 years (598 vs 284, $p < 0.0001$). In 1,758 matched TCAR–TFCAS pairs, TCAR was associated with lower 1-year mortality (1,401 vs 1,468, $p = 0.0055$), but this difference was no longer significant at 5 years (39 vs 165, $p = 0.11$). Perioperative stroke rates were low and similar across all comparisons; however, perioperative stroke was associated with significantly higher mortality at both 1 and 5 years. Higher mortality risk was associated with symptomatic status, age ≥ 70 years, diabetes, coronary artery disease, congestive heart failure, chronic obstructive pulmonary disease, and end-stage renal disease. Prior percutaneous coronary intervention was associated with lower mortality only in the TCAR–TFCAS comparison.

Conclusions

CEA and TCAR demonstrated comparable mortality outcomes at 1 and 5 years. In contrast, TFCAS was associated with significantly higher 1-year mortality than both CEA and TCAR, with this difference persisting through 5 years when compared with CEA. Although TCAR showed a 1-year mortality advantage over TFCAS, this difference attenuated over time and was no longer significant at 5 years. These findings support TCAR as a safe and durable alternative to CEA and suggest a less favorable early survival profile with TFCAS.

Background

Carotid artery stenosis is one of the leading causes of ischemic stroke, which remains one of the leading causes of mortality and disability globally [1]. Carotid revascularization remains the cornerstone of ischemic stroke prevention in these patients, through either carotid endarterectomy (CEA) or carotid artery stenting (CAS).

CEA has long been the gold standard for carotid revascularization. Trials such as the North American Symptomatic Carotid Endarterectomy Trial (NASCET) and the European Carotid Surgery Trial (ECST) established CEA as superior to best medical therapy for selected patients with symptomatic stenosis [2]. Current guidelines from the Society for Vascular Surgery continue to recommend CEA as first-line therapy for most surgically accessible disease [3].

Alternatives to CEA include CAS, performed through either the transcarotid artery revascularization (TCAR) or transfemoral carotid artery stenting (TFCAS) approach. CAS via either TCAR or TFCAS is a less invasive option compared with CEA and was initially adopted for patients at high surgical risk or with certain contraindications to CEA. Earlier trials and meta-analyses established a higher perioperative stroke risk with CAS overall compared with CEA, especially in older patients [4]. The Carotid Revascularization Endarterectomy versus Stenting Trial (CREST) demonstrated similar long-term outcomes between CAS and CEA, although perioperative stroke remained more frequent after stenting than after CEA [5]. TCAR in particular combines direct carotid access with flow reversal for neuroprotection, theoretically reducing embolic risk. The ROADSTER trial reported historically low 30-day stroke and death rates in high-risk patients undergoing TCAR [6]. Recent propensity score-matched analyses reiterate this finding, with lower stroke and mortality in the perioperative period with TCAR compared with TFCAS but comparable clinical outcomes at 1 year [7].

While there is an abundance of data on the perioperative and 1-year clinical outcomes of CEA, TCAR, and TFCAS, there is a paucity of data regarding clinical outcomes over a longer timeframe. Most studies have focused on perioperative or 1-year results, leaving uncertainty about 5-year survival. This study aimed to compare long-term survival and stroke risk at 5 years after TCAR, TFCAS, and CEA, using propensity score matching to account for baseline differences.

Methods

Study design, data source, and study population

We performed a retrospective cohort analysis of the CEA and CAS registries of the Society for Vascular Surgery Vascular Quality Initiative (VQI) database. We included all adult patients over the age of 40 years undergoing CEA or CAS from 2016 to 2022. Emergent procedures, operations concomitant with other procedures, non-atherosclerotic etiology, high-risk anatomy, prior neck radiation, patients with missing covariate data, and patients lost to 1-year follow-up were excluded. This retrospective analysis of fully

de-identified registry data was determined to be exempt from review by the Colorado Multiple Institutional Review Board (COMIRB), and the requirement for informed consent was waived.

Outcomes

The primary outcome was 5-year all-cause mortality. Secondary outcomes included 1-year survival, mortality according to symptomatic status, and mortality according to the occurrence of a perioperative stroke.

Statistical analysis

Three comparisons were performed: CEA versus TCAR, CEA versus TFCAS, and TCAR versus TFCAS. Continuous variables were compared using analysis of variance (ANOVA) or Student's t test, as appropriate, and the Kruskal–Wallis rank-sum test for non-normally distributed variables. Categorical variables were compared using the chi-squared test or Fisher's exact test, as appropriate. Covariates such as diabetes, hypertension, and dialysis status were consolidated because severity-based coding differed between the CEA and CAS registries.

Propensity score matching

Because of the large disparity in both total sample size and covariates between the CEA and CAS registries, with the potential for confounding, propensity score matching was used. Propensity scores were calculated using logistic regression for each comparison (CEA vs TCAR, CEA vs TFCAS, TCAR vs TFCAS). Matching was performed in a 1:1 ratio with nearest-neighbor matching (caliper 0.1) without replacement. Covariate balance was confirmed with standardized mean differences (< 0.1), and covariate balance between study groups before and after matching was verified. Matching was based on covariates that were clinically relevant and/or statistically significantly different between the three comparison groups on univariable analysis. The covariates used to determine the propensity score were age, sex, hypertension, diabetes, coronary artery disease (CAD), prior coronary artery bypass grafting (CABG), prior percutaneous coronary intervention (PCI), congestive heart failure (CHF), chronic obstructive pulmonary disease (COPD), end-stage renal disease (ESRD), prior CEA or CAS, and American Society of Anesthesiologists (ASA) class. Survival was estimated using the Kaplan–Meier method and compared with log-rank tests. Cox proportional hazards models with time-varying effects were used to estimate hazard ratios (HRs) with 95% confidence intervals (CIs) for mortality outcomes. Statistical significance was defined as $P < 0.05$. All analyses were conducted using R statistical software, version 4.5.1 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Patient characteristics

Between 2016 and 2022, 68,980 patients underwent CEA, 2,396 underwent TCAR, and 2,887 underwent TFCAS. Baseline demographics and comorbidities are summarized in Table 1. There were no differences in sex, history of PCI, ESRD, or preoperative anticoagulation between the three procedural groups. However, there were statistically significant differences in age, smoking status, hypertension, diabetes, history of CAD, CABG, CHF, COPD, prior CEA/CAS, ASA class, preoperative angiotensin-converting enzyme (ACE) inhibitor use, and symptomatic status. Patients undergoing TCAR were more likely to have a history of smoking, CAD, CHF, a prior carotid procedure, an ASA class of 4 or greater, and aspirin, P2Y12 inhibitor, and statin use. Patients undergoing TFCAS were on average younger, with a larger proportion of patients under the age of 70 years; were less likely to have COPD, an ASA class of 4 or greater, or hypertension, or to use an ACE inhibitor; but were more likely to have diabetes. After matching, there were 2,394 CEA–TCAR pairs, 2,862 CEA–TFCAS pairs, and 1,758 TCAR–TFCAS pairs.

Table 1
Baseline characteristics of patients undergoing CEA, TCAR, and TFCAS, 2016–2022

Characteristic	Overall N = 74,263	CEA N = 68,980	TCAR N = 2,396	TFCAS N = 2,887	P-value
Age, years					< 0.001
Range (min, max)	(40.0, 90.0)	(40.0, 90.0)	(40.0, 90.0)	(40.0, 90.0)	
Mean (SD)	70.8 (8.8)	71.0 (8.8)	69.2 (7.6)	67.4 (8.2)	
Median (Q1, Q3)	71.0 (65.0, 77.0)	71.0 (65.0, 77.0)	70.0 (65.0, 73.0)	68.0 (62.0, 73.0)	
Age group, years					< 0.001
< 60	8,057 (11%)	7,347 (11%)	232 (9.7%)	478 (17%)	
60–69	23,694 (32%)	21,561 (31%)	955 (40%)	1,178 (41%)	
70–79	30,204 (41%)	28,167 (41%)	998 (42%)	1,039 (36%)	
80–90	12,308 (17%)	11,905 (17%)	211 (8.8%)	192 (6.7%)	
Sex					0.6
Male	45,144 (61%)	41,901 (61%)	1,473 (61%)	1,770 (61%)	
Female	29,119 (39%)	27,079 (39%)	923 (39%)	1,117 (39%)	
Smoking status					< 0.001
Never	19,358 (26%)	17,981 (26%)	559 (23%)	818 (28%)	
Prior	36,851 (50%)	34,469 (50%)	1,169 (49%)	1,213 (42%)	
Current	18,054 (24%)	16,530 (24%)	668 (28%)	856 (30%)	
Hypertension	66,824 (90%)	62,136 (90%)	2,161 (90%)	2,527 (88%)	< 0.001

Values are n (%) unless otherwise stated. P-values from the Kruskal–Wallis rank-sum test, Pearson's chi-squared test, or Fisher's exact test with simulated p-value (2,000 replicates). ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

Characteristic	Overall N = 74,263	CEA N = 68,980	TCAR N = 2,396	TFCAS N = 2,887	P-value
Diabetes	27,422 (37%)	25,358 (37%)	922 (38%)	1,142 (40%)	0.003
History of CAD	21,045 (28%)	18,854 (27%)	1,037 (43%)	1,154 (40%)	< 0.001
History of CABG	14,101 (19%)	13,257 (19%)	422 (18%)	422 (15%)	< 0.001
History of PCI	16,971 (23%)	15,730 (23%)	582 (24%)	659 (23%)	0.2
History of CHF	8,942 (12%)	8,293 (12%)	339 (14%)	310 (11%)	< 0.001
COPD	17,228 (23%)	16,029 (23%)	579 (24%)	620 (21%)	0.047
ESRD	856 (1.2%)	807 (1.2%)	19 (0.8%)	30 (1.0%)	0.2
Prior CEA/CAS	9,658 (13%)	8,778 (13%)	445 (19%)	435 (15%)	< 0.001
ASA class					< 0.001
1	316 (0.4%)	260 (0.4%)	11 (0.5%)	45 (1.6%)	
2	3,061 (4.1%)	2,468 (3.6%)	55 (2.3%)	538 (19%)	
3	54,794 (74%)	51,150 (74%)	1,703 (71%)	1,941 (67%)	
4	16,072 (22%)	15,082 (22%)	627 (26%)	363 (13%)	
5	20 (< 0.1%)	20 (< 0.1%)	0 (0%)	0 (0%)	
Preoperative aspirin	63,151 (85%)	58,506 (85%)	2,133 (89%)	2,512 (87%)	< 0.001
Preoperative P2Y12 inhibitor	29,449 (40%)	25,116 (36%)	2,058 (86%)	2,275 (79%)	< 0.001
Preoperative statin	63,816 (86%)	59,172 (86%)	2,185 (91%)	2,459 (85%)	< 0.001
Preoperative ACE inhibitor	40,064 (54%)	37,301 (54%)	1,318 (55%)	1,445 (50%)	< 0.001

Values are n (%) unless otherwise stated. P-values from the Kruskal–Wallis rank-sum test, Pearson's chi-squared test, or Fisher's exact test with simulated p-value (2,000 replicates). ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

Characteristic	Overall N = 74,263	CEA N = 68,980	TCAR N = 2,396	TFCAS N = 2,887	P-value
Preoperative anticoagulation	9,033 (12%)	8,409 (12%)	277 (12%)	347 (12%)	0.6
Indication					< 0.001
Asymptomatic	38,009 (51%)	35,567 (52%)	1,425 (59%)	1,017 (35%)	
Symptomatic	36,254 (49%)	33,413 (48%)	971 (41%)	1,870 (65%)	

Values are n (%) unless otherwise stated. P-values from the Kruskal–Wallis rank-sum test, Pearson's chi-squared test, or Fisher's exact test with simulated p-value (2,000 replicates). ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

Matched analyses

CEA versus TCAR

There were 2,394 matched pairs of CEA versus TCAR, with a c-statistic for the propensity score model of 0.6462. One-year mortality was comparable between the groups (number at risk 2,027 [95.9%] vs 1,923 [95.5%], p = 0.41; Fig. 1a). When stratified by symptomatic status, there continued to be no difference in mortality between CEA and TCAR at 1 year in either asymptomatic (p = 0.58) or symptomatic (p = 0.51) patients (Fig. 1b).

At 5 years, there was also no difference in mortality between CEA and TCAR (number at risk 513 [88.9%] vs 51 [86.4%], p = 0.21; Fig. 2a), nor when stratified by asymptomatic (p = 0.39) or symptomatic (p = 0.36) status (Fig. 2b).

In the time-dependent Cox model, there was no significant difference in the hazard of mortality for TCAR compared with CEA, and no significant effect of time on this hazard ratio (Table 2). Characteristics associated with higher mortality in the matched cohort included age over 70 years, diabetes, history of CAD, CHF, COPD, ESRD, and symptomatic status (Table 3).

Table 2
Time-dependent Cox model for mortality: TCAR versus CEA (reference) in the matched cohort

Variable	HR	95% CI	P-value
CEA	Reference	—	
TCAR	1.91	0.72, 5.05	0.2
TCAR × time (time dependence)	0.91	0.76, 1.08	0.3

Cox proportional hazards model with a time-varying effect for procedure type; 2,394 matched pairs. CEA, carotid endarterectomy; CI, confidence interval; HR, hazard ratio; TCAR, transcarotid artery revascularization

Table 3
Covariates associated with mortality in the matched CEA–TCAR cohort

Characteristic	HR	95% CI	P-value
Age group, years			
Under 60	Reference	—	
60–69	1.47	0.94, 2.32	0.092
70–79	2.05	1.32, 3.18	0.001
80–90	2.56	1.53, 4.27	< 0.001
Sex			
Female	Reference	—	
Male	1.04	0.84, 1.29	0.7
Hypertension	1.20	0.78, 1.87	0.4
Diabetes	1.38	1.12, 1.70	0.002
History of CAD	1.38	1.06, 1.79	0.016
History of CABG	0.95	0.72, 1.25	0.7
History of PCI	0.85	0.66, 1.11	0.2
History of CHF	2.43	1.90, 3.12	< 0.001
COPD	1.60	1.28, 1.99	< 0.001
ESRD	3.49	1.91, 6.36	< 0.001
Prior CEA/CAS	1.19	0.93, 1.53	0.2
Indication			
Asymptomatic	Reference	—	
Symptomatic	1.35	1.10, 1.65	0.004

Cox proportional hazards model; 2,394 matched pairs. ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; CI, confidence interval; HR, hazard ratio

There was no overall difference in the perioperative stroke rate between CEA and TCAR, nor was there a difference in stroke rate when comparing asymptomatic with symptomatic patients (Table 4).

Table 4
Perioperative stroke or TIA in the matched CEA–TCAR cohort

Characteristic	Overall N = 4,788	CEA N = 2,394	TCAR N = 2,394	P-value
TIA or stroke	71 (1.5%)	30 (1.3%)	41 (1.7%)	0.2
Time of onset of stroke				> 0.9
During procedure	2 (8.0%)	0 (0%)	2 (8.0%)	
< 6 hours	11 (44%)	0 (0%)	11 (44%)	
> 5 hours	12 (48%)	0 (0%)	12 (48%)	
Unknown	4,763	2,394	2,369	
Stroke treatment				> 0.9
Medical	20 (83%)	0 (0%)	20 (83%)	
Systemic lysis	3 (13%)	0 (0%)	3 (13%)	
Intracranial catheter	1 (4.2%)	0 (0%)	1 (4.2%)	
Unknown	4,764	2,394	2,370	
Indication				0.5
Asymptomatic	2,824 (59%)	1,401 (59%)	1,423 (59%)	
Symptomatic	1,964 (41%)	993 (41%)	971 (41%)	

Values are n (%) unless otherwise stated. Percentages for time of onset and treatment are calculated among strokes with known timing or treatment; timing and treatment of stroke were not available for the CEA patients (recorded as unknown). P-values from Pearson's chi-squared test or Fisher's exact test. CAS, carotid artery stenting; CEA, carotid endarterectomy; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack

CEA versus TFCAS

There were 2,862 matched pairs of CEA versus TFCAS, with a c-statistic for the propensity score model of 0.7377. CEA was associated with a significantly lower 1-year mortality than TFCAS (number at risk 2,406 [96.7%] vs 2,397 [94.0%], $p < 0.0001$; Fig. 3a). When stratified by symptomatic status, CEA remained associated with lower 1-year mortality in both asymptomatic ($p = 0.012$) and symptomatic ($p < 0.0001$) patients (Fig. 3b).

At 5 years, CEA continued to be associated with a significantly lower mortality than TFCAS (number at risk 598 [90.9%] vs 284 [87.5%], p < 0.0001; Fig. 4a). When stratified by symptomatic status, this difference persisted in both asymptomatic (p = 0.011) and symptomatic (p = 0.00025) patients at 5 years (Fig. 4b).

In the time-dependent Cox model with CEA as the reference, TFCAS was associated with a higher hazard of mortality early in follow-up (HR 5.01, 95% CI 2.03–12.4, p < 0.001) relative to CEA. This association decreased over time, with evidence of an attenuating effect (time-dependent HR 0.81, 95% CI 0.69–0.95, p = 0.008) (Table 5).

Table 5
Time-dependent Cox model for mortality: TFCAS versus CEA (reference) in the matched cohort

Variable	HR	95% CI	P-value
CEA	Reference	—	
TFCAS	5.01	2.03, 12.4	< 0.001
TFCAS × time (time dependence)	0.81	0.69, 0.95	0.008

Cox proportional hazards model with a time-varying effect for procedure type; 2,862 matched pairs. CEA, carotid endarterectomy; CI, confidence interval; HR, hazard ratio; TFCAS, transfemoral carotid artery stenting

In the matched CEA–TFCAS cohort, characteristics associated with higher mortality included age, with an increasing HR for each additional decade over 60 years, diabetes, history of CHF, COPD, ESRD, prior CEA/CAS, and symptomatic status (Table 6).

Table 6
Covariates associated with mortality in the matched CEA–TFCAS cohort

Characteristic	HR	95% CI	P-value
Age group, years			
Under 60	Reference	—	
60–69	1.65	1.16, 2.33	0.005
70–79	2.24	1.59, 3.16	< 0.001
80–90	3.44	2.28, 5.20	< 0.001
Sex			
Female	Reference	—	
Male	1.04	0.85, 1.26	0.7
Hypertension	0.90	0.66, 1.23	0.5
Diabetes	1.41	1.16, 1.71	< 0.001
History of CAD	1.27	1.00, 1.63	0.051
History of CABG	1.16	0.90, 1.50	0.3
History of PCI	0.87	0.68, 1.12	0.3
History of CHF	1.54	1.20, 1.99	< 0.001
COPD	1.98	1.62, 2.43	< 0.001
ESRD	2.04	1.14, 3.64	0.016
Prior CEA/CAS	1.37	1.08, 1.73	0.009
Indication			
Asymptomatic	Reference	—	
Symptomatic	1.34	1.09, 1.65	0.006

Cox proportional hazards model; 2,862 matched pairs. ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; CI, confidence interval; HR, hazard ratio

There was no overall difference in the perioperative stroke rate between CEA and TFCAS, nor was there a difference in stroke rate when comparing asymptomatic with symptomatic patients (Table 7).

Table 7
Perioperative stroke or TIA in the matched CEA–TFCAS cohort

Characteristic	Overall N = 5,724	CEA N = 2,862	TFCAS N = 2,862	P-value
TIA or stroke	98 (1.7%)	46 (1.6%)	52 (1.8%)	0.5
Time of onset of stroke				> 0.9
During procedure	2 (6.9%)	0 (0%)	2 (6.9%)	
< 6 hours	11 (38%)	0 (0%)	11 (38%)	
> 5 hours	16 (55%)	0 (0%)	16 (55%)	
Unknown	5,695	2,862	2,833	
Stroke treatment				> 0.9
Medical	21 (78%)	0 (0%)	21 (78%)	
Systemic lysis	2 (7.4%)	0 (0%)	2 (7.4%)	
Intracranial catheter	4 (15%)	0 (0%)	4 (15%)	
Unknown	5,697	2,862	2,835	
Indication				0.030
Asymptomatic	1,956 (34%)	939 (33%)	1,017 (36%)	
Symptomatic	3,768 (66%)	1,923 (67%)	1,845 (64%)	

Values are n (%) unless otherwise stated. Percentages for time of onset and treatment are calculated among strokes with known timing or treatment; timing and treatment of stroke were not available for the CEA patients (recorded as unknown). P-values from Pearson's chi-squared test or Fisher's exact test. CAS, carotid artery stenting; CEA, carotid endarterectomy; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack

TCAR versus TFCAS

There were 1,758 matched pairs of TCAR versus TFCAS, with a c-statistic for the propensity score model of 0.7313. TCAR was associated with a significantly lower 1-year mortality than TFCAS (number at risk 1,401 [95.5%] vs 1,468 [93.4%], p = 0.0055; Fig. 5a). When stratified by symptomatic status, this difference remained statistically significant in both asymptomatic (p = 0.048) and symptomatic (p = 0.049) patients (Fig. 5b).

At 5 years, the difference in mortality between TCAR and TFCAS was no longer statistically significant (number at risk 39 [86.8%] vs 165 [86.8%], p = 0.11; Fig. 6a). Likewise, when stratified by symptomatic status, there was no statistically significant difference in mortality between TCAR and TFCAS at 5 years in either asymptomatic (p = 0.23) or symptomatic (p = 0.28) patients (Fig. 6b).

In the time-dependent Cox model with TCAR as the reference, TFCAS was associated with a higher hazard of mortality early in follow-up (HR 2.90, 95% CI 1.03–8.15, p = 0.043) relative to TCAR. This association decreased over time, with evidence of an attenuating effect (time-dependent HR 0.85, 95% CI 0.71–1.03), although the time-interaction term was not statistically significant (p = 0.092) (Table 8).

Table 8
Time-dependent Cox model for mortality: TFCAS versus TCAR (reference) in the matched cohort

Variable	HR	95% CI	P-value
TCAR	Reference	—	
TFCAS	2.90	1.03, 8.15	0.043
TFCAS × time (time dependence)	0.85	0.71, 1.03	0.092

Cox proportional hazards model with a time-varying effect for procedure type; 1,758 matched pairs. CI, confidence interval; HR, hazard ratio; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

In the matched TCAR–TFCAS cohort, characteristics associated with higher mortality included age, with an increasing HR for each additional decade over 60 years, diabetes, history of CAD, CHF, COPD, ESRD, and symptomatic status (Table 9). History of PCI was associated with a lower hazard of mortality (HR 0.75, 95% CI 0.56–0.98, p = 0.039) in the combined TCAR and TFCAS matched cohort.

Table 9
Covariates associated with mortality in the matched TCAR–TFCAS cohort

Characteristic	HR	95% CI	P-value
Age group, years			
Under 60	Reference	—	
60–69	1.35	0.87, 2.09	0.2
70–79	1.99	1.29, 3.05	0.002
80–90	3.33	1.99, 5.56	< 0.001
Sex			
Female	Reference	—	
Male	1.08	0.85, 1.37	0.5
Hypertension	1.22	0.80, 1.87	0.4
Diabetes	1.44	1.14, 1.82	0.002
History of CAD	1.39	1.07, 1.81	0.015
History of CABG	0.92	0.69, 1.23	0.6
History of PCI	0.75	0.56, 0.98	0.039
History of CHF	1.72	1.30, 2.27	< 0.001
COPD	1.69	1.32, 2.15	< 0.001
ESRD	2.87	1.61, 5.12	< 0.001
Prior CEA/CAS	1.26	0.96, 1.67	0.095
Indication			
Asymptomatic	Reference	—	
Symptomatic	1.34	1.06, 1.69	0.015

Cox proportional hazards model; 1,758 matched pairs. ACE, angiotensin-converting enzyme; ASA, American Society of Anesthesiologists; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CAS, carotid artery stenting; CEA, carotid endarterectomy; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; ESRD, end-stage renal disease; PCI, percutaneous coronary intervention; SD, standard deviation; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; CI, confidence interval; HR, hazard ratio

There was no overall difference in the perioperative stroke rate between TCAR and TFCAS, nor was there a difference in stroke rate when comparing asymptomatic with symptomatic patients (Table 10).

Table 10
Perioperative stroke or TIA in the matched TCAR–TFCAS cohort

Characteristic	Overall N = 3,516	TCAR N = 1,758	TFCAS N = 1,758	P-value
TIA or stroke	61 (1.7%)	31 (1.8%)	30 (1.7%)	0.9
Time of onset of stroke				> 0.9
During procedure	2 (5.3%)	1 (5.6%)	1 (5.0%)	
< 6 hours	15 (39%)	7 (39%)	8 (40%)	
> 5 hours	21 (55%)	10 (56%)	11 (55%)	
Unknown	3,478	1,740	1,738	
Stroke treatment				> 0.9
Medical	30 (83%)	15 (88%)	15 (79%)	
Systemic lysis	3 (8.3%)	2 (12%)	1 (5.3%)	
Intracranial catheter	3 (8.3%)	0 (0%)	3 (16%)	
Unknown	3,480	1,741	1,739	
Indication				0.8
Asymptomatic	1,615 (46%)	812 (46%)	803 (46%)	
Symptomatic	1,901 (54%)	946 (54%)	955 (54%)	

Values are n (%) unless otherwise stated. Percentages for time of onset and treatment are calculated among strokes with known timing or treatment. P-values from Pearson's chi-squared test or Fisher's exact test. TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack

Mortality according to perioperative stroke

Patients who underwent CEA, TCAR, or TFCAS were divided into two comparative groups: patients with a perioperative stroke or transient ischemic attack (TIA) and patients without a perioperative stroke. The rate of perioperative stroke was similar between CEA, TCAR, and TFCAS (p = 0.2; Table 11). At 1 year, patients who had a perioperative stroke or TIA had significantly higher mortality than patients who had not (1-year survival 96.0% vs 90.1%, p < 0.0001; Fig. 7a). This difference persisted at 5 years (number at risk 14,640 [88.8%] vs 234 [81.4%], p < 0.0001; Fig. 8a) and was observed regardless of the index procedure (Fig. 7b and Fig. 8b).

Table 11
Perioperative neurologic event prior to discharge in the mortality analysis, by procedure

Characteristic	Overall N = 5,978	CEA N = 5,528	TCAR N = 172	TFCAS N = 272	P-value
Perioperative stroke or TIA	165 (2.8%)	147 (2.7%)	8 (4.5%)	10 (3.7%)	0.2

Values are n (%). P-value from Pearson's chi-squared test. CEA, carotid endarterectomy; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack

Discussion

This propensity score-matched analysis demonstrates that CEA and TCAR have comparable short- and long-term outcomes, with no significant differences in 1- or 5-year mortality, even when stratified by symptomatic status. These findings support TCAR as a durable and safe alternative to CEA for both symptomatic and asymptomatic patients. In contrast, TFCAS was associated with worse survival than both CEA and TCAR, particularly during the first year after intervention. Compared with TFCAS, CEA was associated with significantly lower 1-year mortality (number at risk 2,406 [96.7%] vs 2,397 [94.0%], $p < 0.0001$), and this advantage persisted at 5 years (598 [90.9%] vs 284 [87.5%], $p < 0.0001$). Similarly, TCAR was associated with lower 1-year mortality than TFCAS (1,401 [95.5%] vs 1,468 [93.4%], $p = 0.0055$). However, the mortality difference between TCAR and TFCAS was no longer statistically significant at 5 years (39 [86.8%] vs 165 [86.8%], $p = 0.11$). These findings suggest that the excess risk associated with TFCAS is most pronounced early after intervention and diminishes over longer follow-up.

The time-dependent hazard models further support this interpretation. Compared with CEA, TFCAS was associated with a markedly higher early hazard of mortality (HR 5.01, $p < 0.001$), but this excess hazard attenuated over time (time-dependent HR 0.81, $p = 0.008$). In contrast, there was no significant difference in mortality hazard between TCAR and CEA (HR 1.91, 95% CI 0.72–5.05, $p = 0.2$), and no evidence that this relationship changed over time. When TCAR and TFCAS were compared directly, TFCAS demonstrated greater early mortality (HR 2.90, $p = 0.043$) that attenuated over time. Collectively, these findings indicate that TCAR may have outcomes more similar to those of CEA than does TFCAS with respect to long-term survival. Another factor to consider is that the volume of TCAR grew rapidly, from 18 cases in 2016 to 858 in 2020, whereas TFCAS volume peaked in 2019 and declined thereafter. The sharp attrition in the number of TCAR patients at risk beyond 3 years, reflecting its later adoption, compared with the relatively larger number of TFCAS patients at risk at 5 years, suggests that differences in procedural volume over time may have affected the completeness of long-term follow-up data and the assessment of long-term outcomes.

Across all matched analyses, rates of perioperative stroke or TIA remained low and did not differ significantly between CEA, TCAR, and TFCAS. Subgroup analysis also revealed markedly worse survival

among patients who experienced a perioperative stroke or TIA, regardless of the index procedure. This suggests that the observed mortality differences are unlikely to be driven solely by perioperative neurologic events or by the covariates included in the propensity score model, and may instead reflect differences in patient selection, frailty, or residual confounding not fully captured within the VQI database.

These findings support prior studies demonstrating comparable long-term outcomes between TCAR and CEA, while suggesting that TFCAS may be associated with less favorable early and intermediate-term survival [6, 7]. Across all matched cohorts, older age (≥ 70 years), diabetes, congestive heart failure, COPD, ESRD, and symptomatic presentation were associated with worse survival, whereas hypertension and sex were not. History of CAD was associated with higher mortality in the CEA–TCAR and TCAR–TFCAS cohorts and was of borderline significance in the CEA–TFCAS cohort ($p = 0.051$), and a prior carotid intervention was associated with higher mortality only in the CEA–TFCAS cohort. These risk patterns mirror those described in CREST and in pooled high-risk analyses [2, 5].

Overall, our findings are consistent with the existing literature. The ROADSTER trial reported a 30-day stroke rate of 1.4% with flow-reversal neuroprotection and the lowest mid-term stroke rate among FDA-approved stents [6]. As mentioned previously, prior propensity score-matched analyses confirmed similar 1-year outcomes between TCAR and CEA, with lower perioperative stroke or death compared with TFCAS [7]. Our analysis extends these findings, showing that although TCAR is associated with lower 1-year mortality than TFCAS, this advantage diminishes over long-term follow-up.

Interestingly, prior PCI was associated with lower mortality in the matched TCAR–TFCAS cohort (HR 0.75, $p = 0.039$). This finding may reflect differences in the clinical profile of patients selected for TCAR or TFCAS rather than a direct protective effect of PCI itself. Patients with prior PCI may represent a group with more stable, medically optimized coronary disease and closer longitudinal cardiovascular follow-up. In addition, prior coronary revascularization may influence procedural selection. Patients with extensive coronary disease or prior PCI are often considered higher risk for open surgery and therefore may be preferentially selected for TCAR or TFCAS. Nevertheless, this association should be interpreted cautiously and likely reflects residual differences in patient selection that are not fully captured within the registry.

Limitations

This study is limited by its retrospective design and reliance on registry data. Despite rigorous propensity score matching, residual confounding from unmeasured variables cannot be excluded. Long-term follow-up completeness differed across procedural groups, particularly among TFCAS patients, which may limit generalizability. Event rates for neurological complications were low, reducing the power to detect modest differences. The number at risk was relatively small for TCAR and TFCAS beyond 3 years, increasing the potential for attrition bias. Additionally, although this study examined 5-year mortality, carotid revascularization is primarily performed for stroke prevention rather than to improve long-term

survival. Consequently, differences in mortality beyond the early postoperative period are unlikely to be attributable solely to the procedure itself and may instead reflect baseline patient selection, comorbidity burden, frailty, and longitudinal medical management. The absence of a long-term mortality difference between CEA and TCAR therefore reinforces the durability of both approaches, whereas the higher early mortality observed after TFCAS suggests that procedural selection may be most relevant in the perioperative period and the first postoperative year.

Conclusions

CEA and TCAR demonstrated comparable perioperative neurologic complication rates as well as similar 1- and 5-year mortality in this large propensity score-matched cohort. In contrast, TFCAS was associated with significantly higher mortality than both CEA and TCAR at 1 year, with the difference persisting through 5 years when compared with CEA. Although TCAR demonstrated lower 1-year mortality than TFCAS, this advantage attenuated over time and was no longer statistically significant at 5 years. Across all treatment groups, mortality was primarily associated with advanced age, diabetes, coronary artery disease, congestive heart failure, COPD, end-stage renal disease, and symptomatic presentation. These findings support TCAR as a durable and safe alternative to CEA and suggest that TCAR may offer a safer early mortality profile than TFCAS. Further prospective studies with larger long-term at-risk populations are needed to clarify the durability of these differences.

Abbreviations

ACE
angiotensin-converting enzyme
ANOVA
analysis of variance
ASA
American Society of Anesthesiologists
CABG
coronary artery bypass grafting
CAD
coronary artery disease
CAS
carotid artery stenting
CEA
carotid endarterectomy
CHF
congestive heart failure
CI
confidence interval
COMIRB

Colorado Multiple Institutional Review Board
COPD
chronic obstructive pulmonary disease
CREST
Carotid Revascularization Endarterectomy versus Stenting Trial
ECST
European Carotid Surgery Trial
ESRD
end-stage renal disease
FDA
Food and Drug Administration
HR
hazard ratio
NASCET
North American Symptomatic Carotid Endarterectomy Trial
PCI
percutaneous coronary intervention
SD
standard deviation
SVS PSO
Society for Vascular Surgery Patient Safety Organization
TCAR
transcarotid artery revascularization
TFCAS
transfemoral carotid artery stenting
TIA
transient ischemic attack
VQI
Vascular Quality Initiative

Declarations

Ethics approval and consent to participate

This study was a retrospective analysis of fully de-identified data from the Society for Vascular Surgery Vascular Quality Initiative registry. The study was determined to be exempt from review by the Colorado Multiple Institutional Review Board (COMIRB) of the University of Colorado Anschutz Medical Campus, and the requirement for informed consent was waived because only de-identified registry data were analyzed. Access to the data was approved by the SVS PSO VQI Research Advisory Committee.

Consent for publication

Not applicable.

Competing interests

RDM reports consulting and advisory relationships with W. L. Gore & Associates, Terumo Aortic, and Boston Scientific. ESC, AHI, ZL, PJFN, and EAM declare that they have no competing interests.

Authors' information

ESC is a medical student at the University of Colorado School of Medicine. AHI, PJFN, RDM, and EAM are vascular surgeons in the Division of Vascular Surgery and Endovascular Therapy, and ZL is a biostatistician in the Department of Biostatistics and Informatics, Colorado School of Public Health, University of Colorado Anschutz Medical Campus.

Funding

The authors received no specific funding for this work.

Author Contribution

E.S.C. contributed to the study design, performed the data analysis and interpretation, prepared Figures 1–8 and Tables 1–11, and wrote the main manuscript text. A.H.I. conceived the study, contributed to the study design, data interpretation and figure preparation, and critically revised the manuscript. Z.L. curated the Vascular Quality Initiative dataset, developed the statistical code, performed the propensity score matching and survival analyses, and validated the results. P.J.F.N. contributed to the study design, data interpretation and figure preparation, and critically revised the manuscript. R.D.M. conceived the study, contributed to the study design and validation of the results, supervised the analysis and manuscript preparation, and critically revised the manuscript for important intellectual content. E.A.M. conceived the study, contributed to the study design, supervised the project and provided project administration, and critically revised the manuscript for important intellectual content. All authors interpreted the data, read and approved the final version of the manuscript, and agree to be accountable for all aspects of the work. R.D.M. is the corresponding author and takes responsibility for the integrity of the data and the accuracy of the analysis.

Acknowledgements

Not applicable.

Data Availability

The data that support the findings of this study are available from the Society for Vascular Surgery Patient Safety Organization (SVS PSO) Vascular Quality Initiative, but restrictions apply to the availability of these data, which were used under license for the current study and are not publicly available. Data are, however, available from the corresponding author upon reasonable request and with permission of the SVS PSO.

References

1. GBD 2019 Stroke Collaborators. Global, regional, and national burden of stroke and its risk factors, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet Neurol. 2021;20:795–820.
2. Rothwell PM, Eliasziw M, Gutnikov SA, Warlow CP, Barnett HJ. Carotid Endarterectomy Trialists Collaboration. Endarterectomy for symptomatic carotid stenosis in relation to clinical subgroups and timing of surgery. Lancet. 2004;363:915–24.
3. AbuRahma AF, Avgerinos ED, Chang RW, Darling RC 3rd, Duncan AA, Forbes TL, et al. Society for Vascular Surgery clinical practice guidelines for management of extracranial cerebrovascular disease. J Vasc Surg. 2022;75:S4–22.
4. Howard G, Roubin GS, Jansen O, Hendrikse J, Halliday A, Fraedrich G, et al. Association between age and risk of stroke or death from carotid endarterectomy and carotid stenting: a meta-analysis of pooled patient data from four randomised trials. Lancet. 2016;387:1305–11.
5. Brott TG, Calvet D, Howard G, Gregson J, Algra A, Becquemin JP, et al. Long-term outcomes of stenting and endarterectomy for symptomatic carotid stenosis: a preplanned pooled analysis of individual patient data. Lancet Neurol. 2019;18:348–56.
6. Kwolek CJ, Jaff MR, Leal JI, Hopkins LN, Shah RM, Hanover TM, et al. Results of the ROADSTER multicenter trial of transcarotid stenting with dynamic flow reversal. J Vasc Surg. 2015;62:1227–34.
7. Malas MB, Elsayed N, Naazie I, Dakour-Aridi H, Yei KS, Schermerhorn ML. Propensity score-matched analysis of 1-year outcomes of transcarotid revascularization with dynamic flow reversal, carotid endarterectomy, and transfemoral carotid artery stenting. J Vasc Surg. 2022;75:213–e221.

Figures

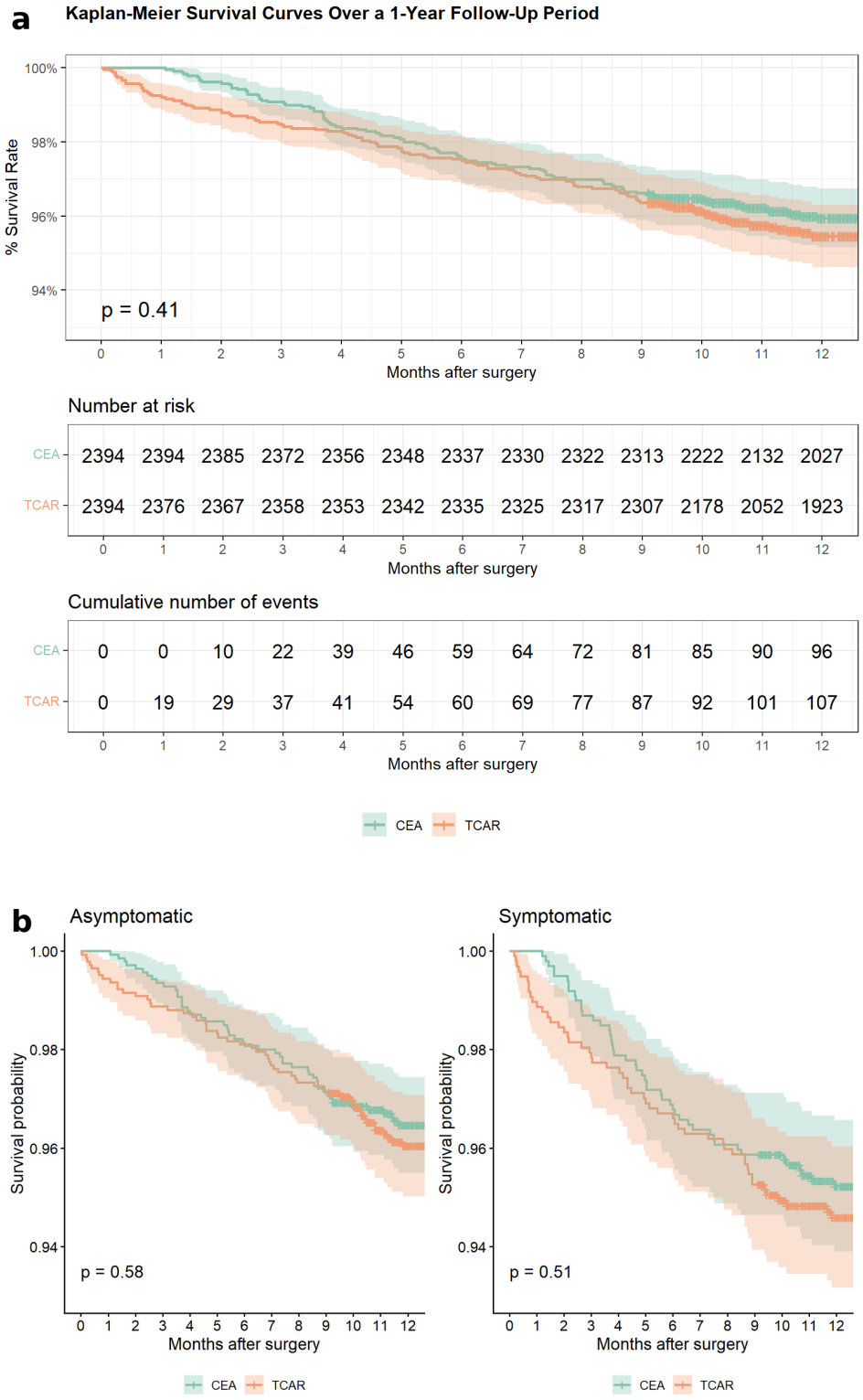


Figure 1

One-year survival after CEA versus TCAR in the propensity score-matched cohort.

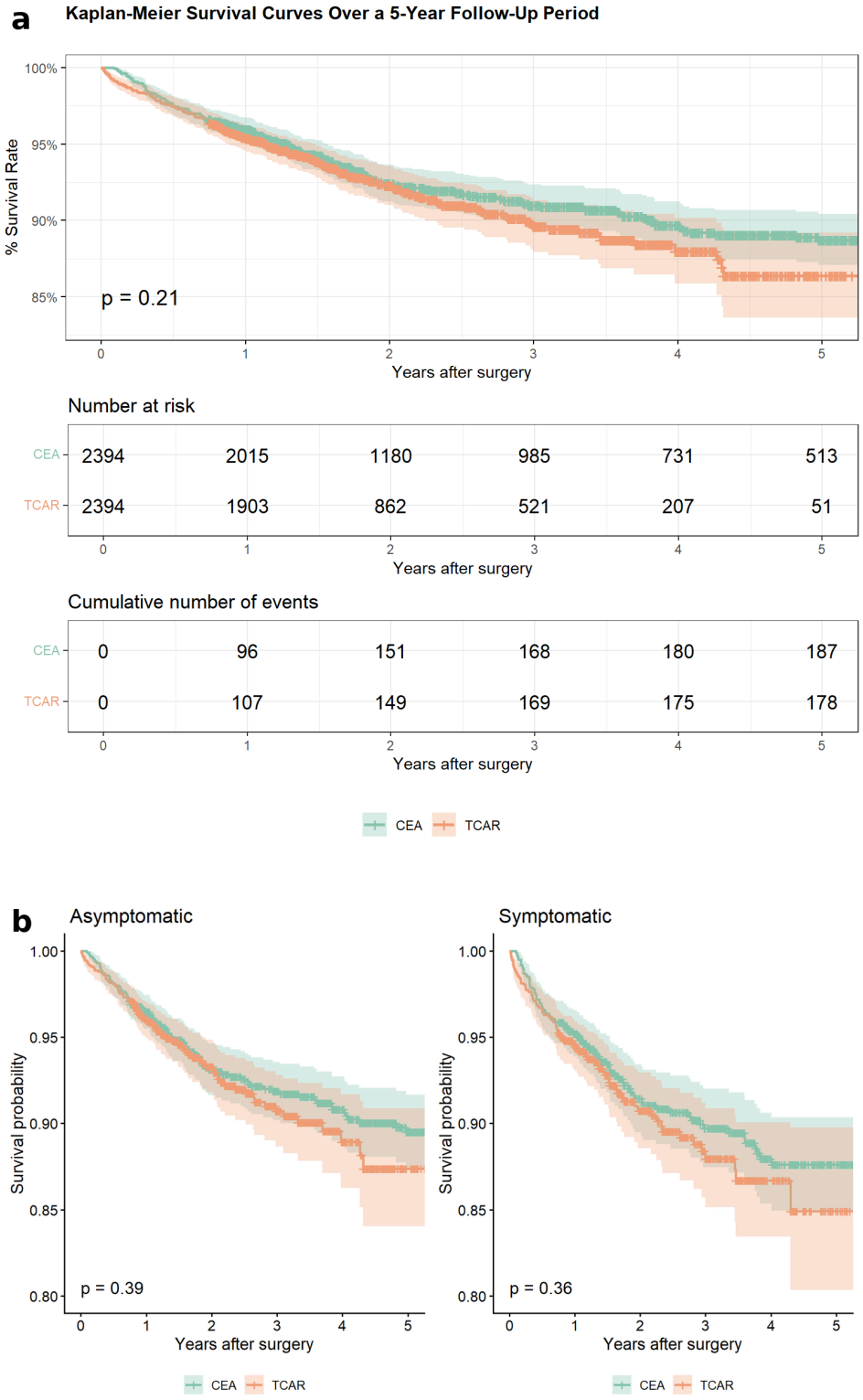


Figure 2

-year survival after CEA versus TCAR in the propensity score-matched cohort.

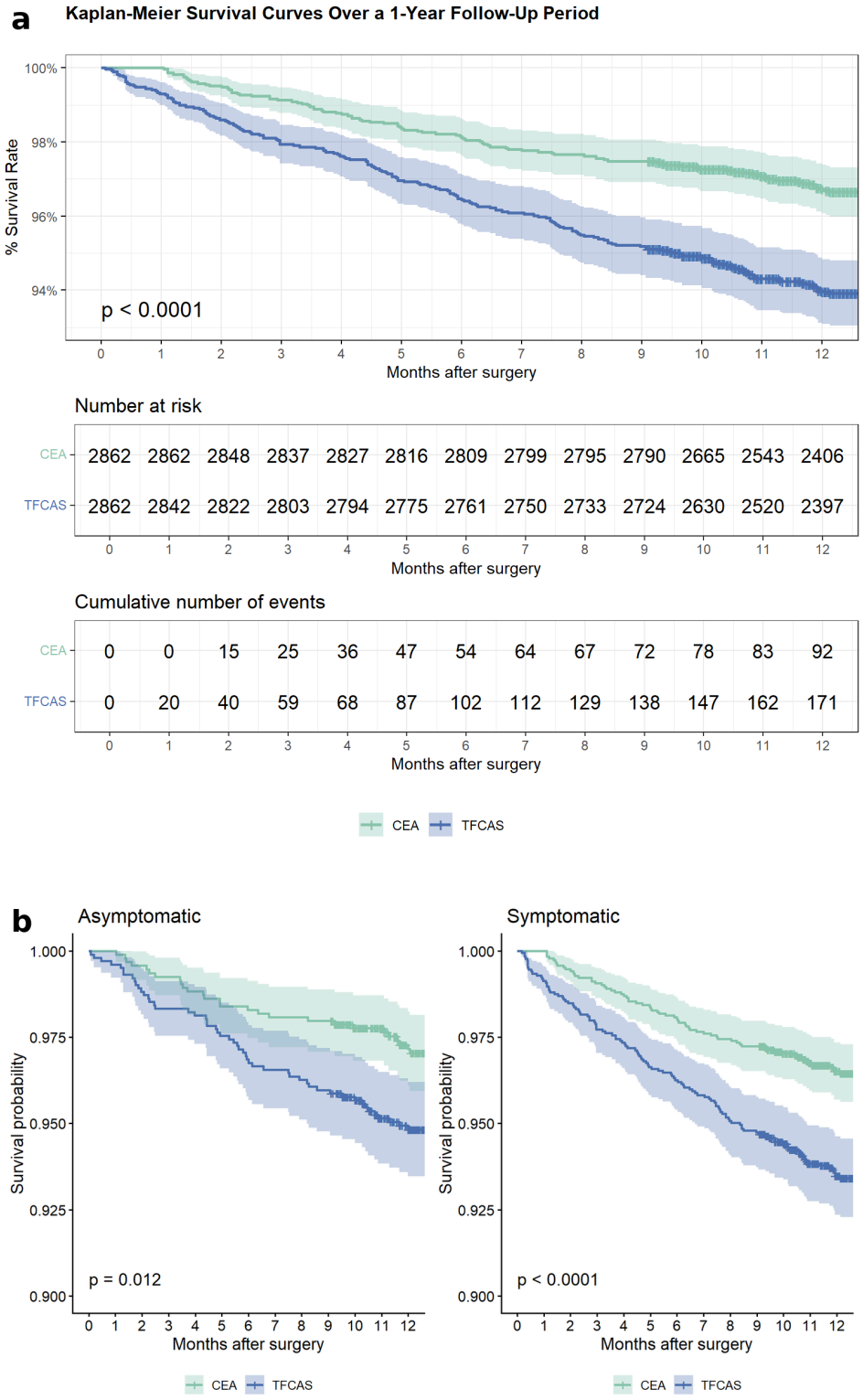


Figure 3

One-year survival after CEA versus TFCAS in the propensity score-matched cohort.

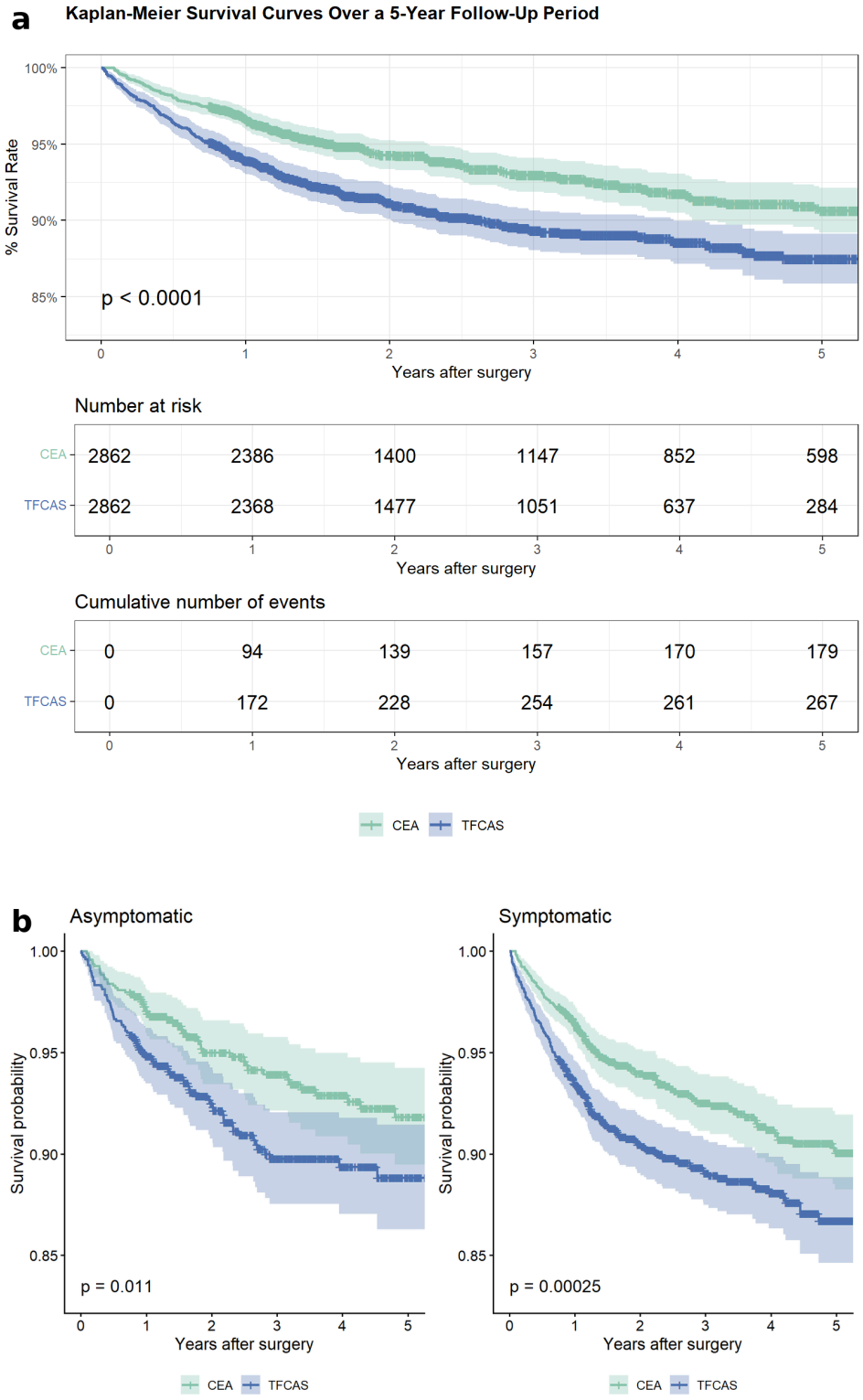


Figure 4

Five-year survival after CEA versus TFCAS in the propensity score-matched cohort.

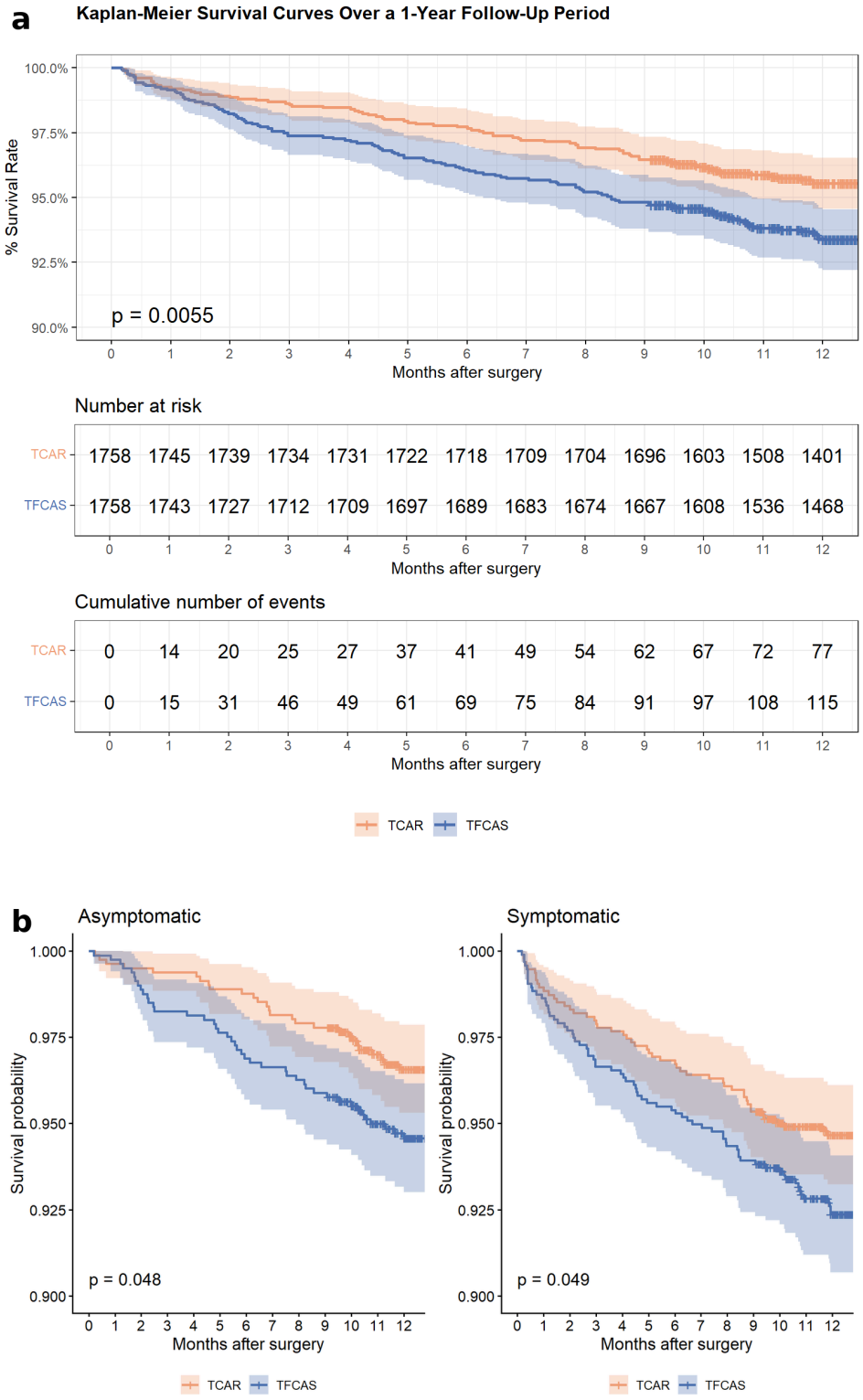


Figure 5

One-year survival after TCAR versus TFCAS in the propensity score-matched cohort. Kaplan–Meier survival estimates over 1 year of follow-up in the matched TCAR–TFCAS cohort (1,758 pairs). (a) Overall survival, with the number of patients at risk and the cumulative number of events shown below the curves; (b) survival stratified by asymptomatic and symptomatic presentation. Shaded areas represent

95% confidence intervals; p-values are from the log-rank test. TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

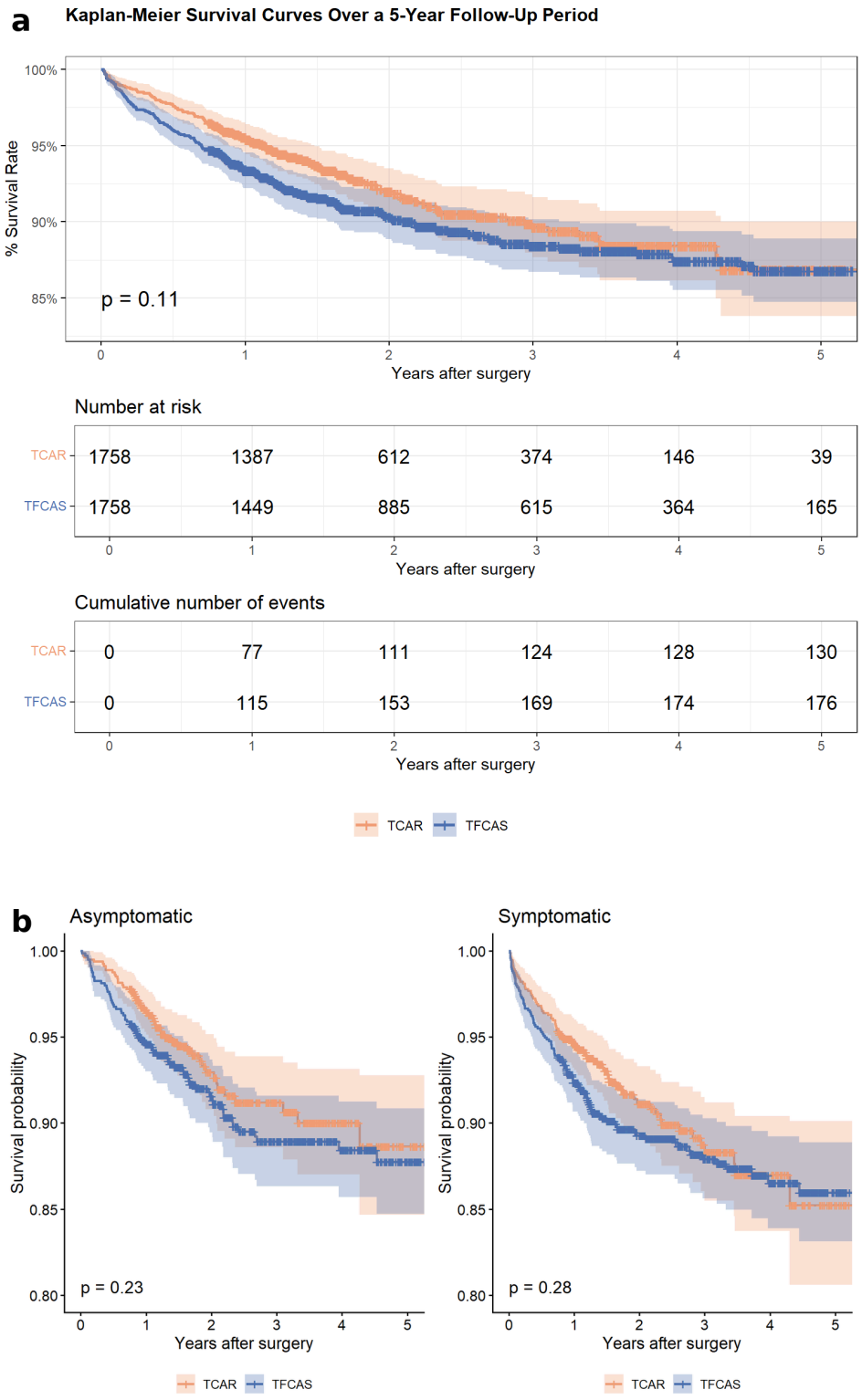


Figure 6

Five-year survival after TCAR versus TFCAS in the propensity score-matched cohort. Kaplan–Meier survival estimates over 5 years of follow-up in the matched TCAR–TFCAS cohort (1,758 pairs). (a)

Overall survival, with the number of patients at risk and the cumulative number of events shown below the curves; (b) survival stratified by asymptomatic and symptomatic presentation. Shaded areas represent 95% confidence intervals; p-values are from the log-rank test. TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting

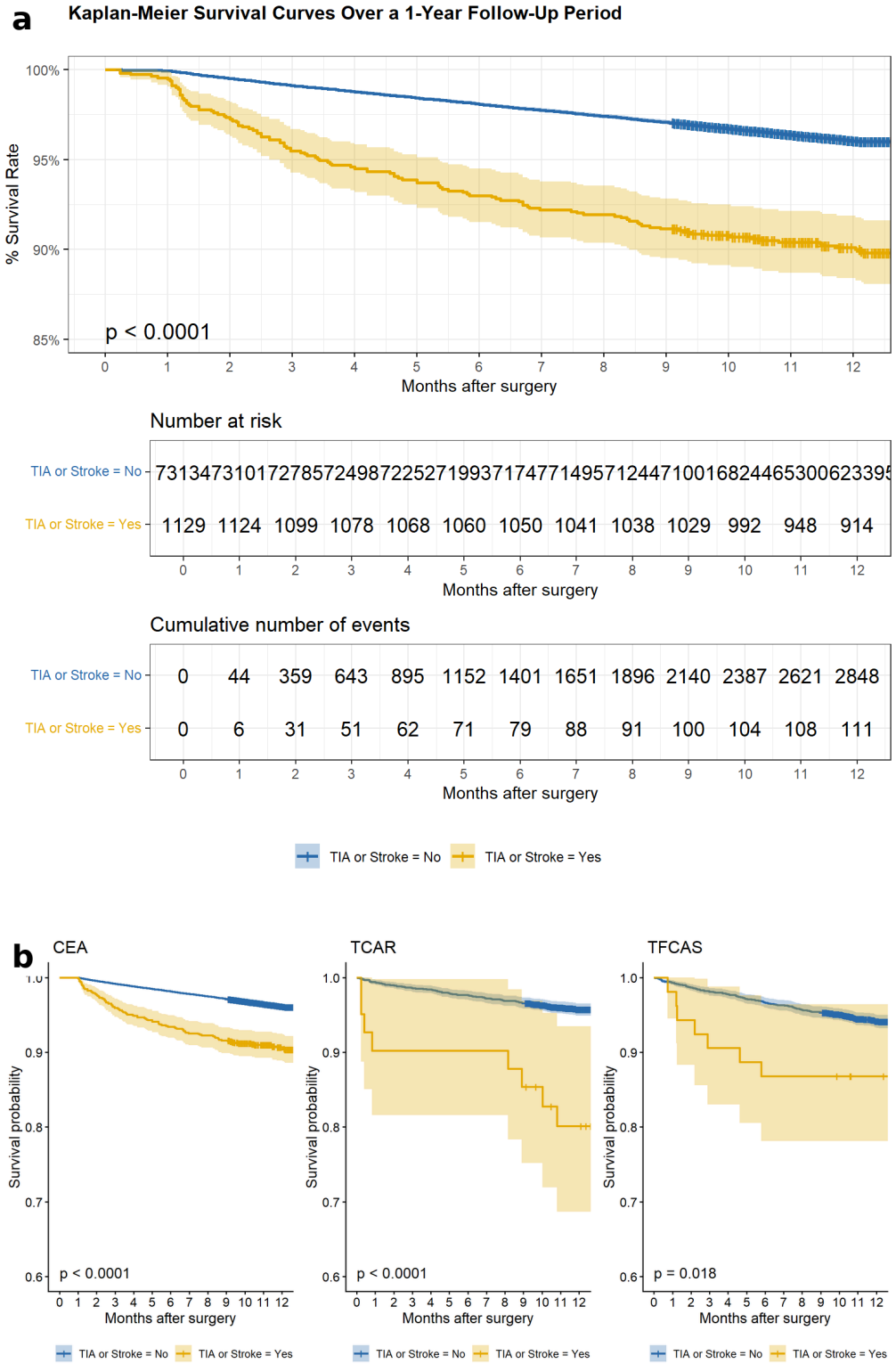
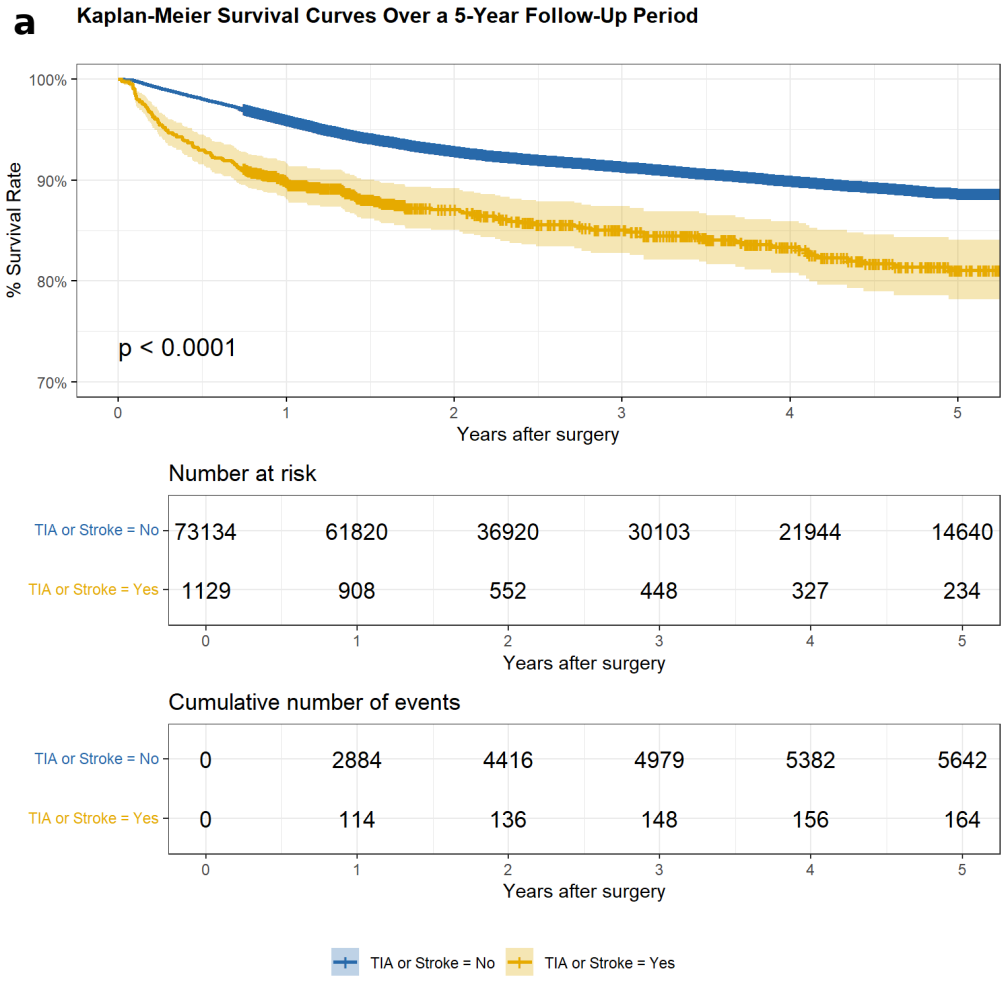


Figure 7

One-year survival according to perioperative stroke or TIA. Kaplan–Meier survival estimates over 1 year of follow-up according to the occurrence of a perioperative stroke or TIA. (a) All patients undergoing CEA, TCAR, or TFCAS, with the number of patients at risk and the cumulative number of events shown below the curves; (b) survival stratified by index procedure (CEA, TCAR, and TFCAS). Shaded areas represent 95% confidence intervals; p-values are from the log-rank test. CEA, carotid endarterectomy; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack



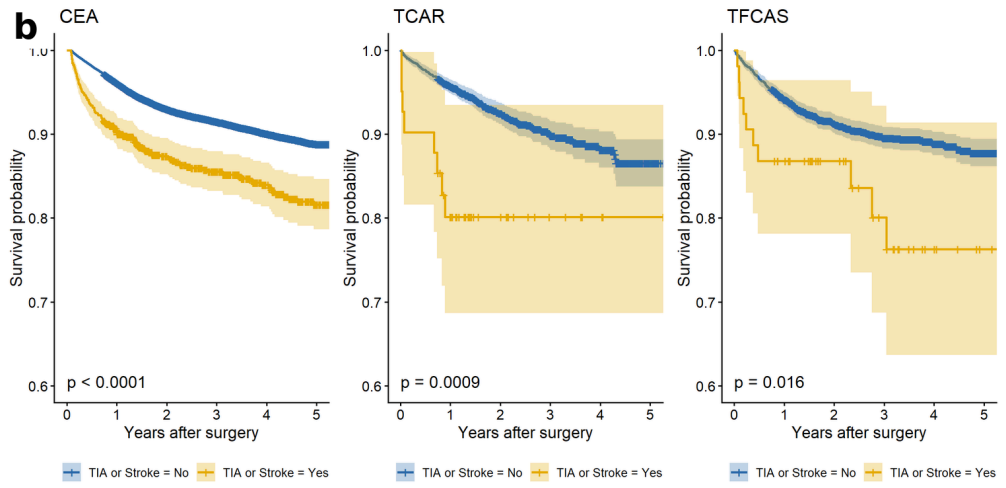


Figure 8

Five-year survival according to perioperative stroke or TIA. Kaplan–Meier survival estimates over 5 years of follow-up according to the occurrence of a perioperative stroke or TIA. (a) All patients undergoing CEA, TCAR, or TFCAS, with the number of patients at risk and the cumulative number of events shown below the curves; (b) survival stratified by index procedure (CEA, TCAR, and TFCAS). Shaded areas represent 95% confidence intervals; p-values are from the log-rank test. CEA, carotid endarterectomy; TCAR, transcarotid artery revascularization; TFCAS, transfemoral carotid artery stenting; TIA, transient ischemic attack

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- BMCSurgeryTables111.docx