RESEARCH ARTICLE

Trends in the Utilization of Different Carotid Revascularization Modalities in the United States Over a 17-Year Period

Fadar O. Otite,[1,*] Nicholas A. Morris,[2] Ahmed Sabra,[1] Smit D. Patel,[3] Nnabuchi Anikpezie,[4] Anurag Sahoo,[1] David Landzberg,[5] Claribel D. Wee,[6] Amit Singla,[1] Julius Gene Silva Latorre,[7] Priyank Khandelwal,[1] and Seemant Chaturvedi[2,*]

Neurology® 2025;105:e214104. doi:10.1212/WNL.0000000000214104

Correspondence
Dr. Otite
Foo26@njms.rutgers.edu
or Dr. Chaturvedi
schaturvedi@som.umaryland.edu

MORE ONLINE

Supplementary Material

Abstract

Background and Objectives

In October 2023, the Centers for Medicare & Medicaid Services (CMS) in the United States expanded coverage for carotid artery stenting (CAS) to include non–high-risk patients with carotid disease. The aim of this study was to provide a 17-year snapshot of trends in carotid revascularization practices in the United States before this CMS policy change went into effect.

Methods

We conducted a serial cross-sectional study using the 2006–2022 National Inpatient Sample and a retrospective cohort study using the State Emergency and Inpatient Databases of Florida (2005–2021), Georgia (2010–2020), Maryland (2012–2021), and New York (2005–2020). Cases of carotid revascularizations in these databases were identified using International Classification of Diseases codes. We calculated age-specific and sex-specific proportions of revascularizations for CAS and combined annual CAS/carotid endarterectomy (CEA) counts with census data to determine utilization rates per 100,000 population. Joinpoint regression estimated annualized percentage change (APC) over time. Hospitalizations in the 6 months preceding revascularization defined symptomatic vs asymptomatic cases and characterized the subset with symptomatic stenosis.

Results

Of 1,779,948 weighted revascularizations, the mean patient age was 71.0 years and 40.9% were performed in women. 17.2% of procedures were CAS, and this proportion more than doubled from 14.3% to 29.0%. Transcarotid artery revascularization accounted for 9.1% in 2022. The CAS proportion increased across age groups, including in those aged older than 70 years and in women, even after excluding mechanical thrombectomy admission. Carotid revascularization usage per 100,000 population declined (APC −3.9%, 95% CI −4.1% to −3.3%) but plateaued after 2015. Although CEA utilization declined from 2006 to 2022 (APC −5.5%, 95% CI −5.9% to −5.1%), CAS use declined from 2006 to 2016 (APC −3.2%, 95% CI −4.6% to −2.1%) but increased from 2016 to 2022 (APC 12.0%, 95% CI 10.1%–14.1%). Only 25.7% of revascularizations in the 4 states were performed for symptomatic disease, with 75.3% of hospitalizations in women for asymptomatic disease.

Discussion

Despite uncertain benefit in selected age and sex groups, including those older than 70 years and with asymptomatic carotid disease, CAS use increased across groups over the past decade and now accounts for >25% of carotid revascularizations in the United States.

*These authors contributed equally as co-corresponding authors.

[1]Department of Neurosurgery, Rutgers the State University of New Jersey, Newark; [2]Department of Neurology, University of Maryland School of Medicine, Baltimore; [3]Department of Neurosurgery, Saint Francis Health System, Tulsa, OK; [4]Department of Population Medicine, University of Mississippi Medical Center, Jackson; [5]Department of Neurology, Rutgers the State University of New Jersey, Newark; [6]Department of Veteran Affairs, National Telestroke Program; and [7]Department of Neurology, State University of New York Upstate Medical University, Syracuse.

Glossary

AAPC = average annualized percentage change; **ACAS** = Asymptomatic Carotid Atherosclerosis Trial; **ACST** = Asymptomatic Carotid Surgery Trial; **APC** = annualized percentage change; **ARR** = absolute risk reduction; **BMT** = best medical therapy; **CAS** = carotid artery stenting; **CEA** = carotid endarterectomy; **CMS** = Centers for Medicare & Medicaid Services; **CREST** = Carotid Revascularization Endarterectomy versus Stenting Trial; **ECST** = European Carotid Surgery Trial; **HCUP** = Healthcare Cost and Utilization Project; **ICD** = International Classification of Diseases; **LOS** = length of stay; **MT** = mechanical thrombectomy; **NASCET** = North American Symptomatic Carotid Endarterectomy Trial; **NIS** = National Inpatient Sample; **SID** = State Inpatient Database; **TCAR** = transcarotid artery revascularization.

Introduction

Carotid endarterectomy (CEA) has historically been the standard surgical revascularization option for patients with high-grade stenosis of the extracranial carotid arteries, but since the 1990s, carotid artery stenting (CAS) has emerged as a less invasive alternative to CEA. Pooled analysis of randomized controlled clinical trial data suggests that CAS may be comparable to CEA in terms of ipsilateral stroke in the postprocedural period, but there may be a significant interaction between age and treatment effect, with patients aged 70 years or older having superior outcomes with CEA.[1,2] However, importantly, whether certain asymptomatic patients with high-grade stenosis benefit from surgical revascularization is still questionable because there are particular demographic subgroups, including women and the elderly, in whom the superiority of revascularization over intensive medical therapy is yet to be proven.

Data supporting the efficacy of revascularization over medical therapy for symptomatic disease come from the North American Symptomatic Carotid Endarterectomy Trial (NASCET)[3] and European Carotid Surgery Trial (ECST).[4] Compared with medical therapy, pooled analysis of these trials demonstrated that CEA offered an 11% absolute risk reduction (ARR) in 5-year stroke risk in men (ARR 11.0%, 95% CI 7.6 to 14.4).[5] A reduced benefit was seen in women (ARR 2.8%, 95% CI −2.2 to 7.8).[5] In patients with asymptomatic carotid stenosis, the Asymptomatic Carotid Atherosclerosis Trial (ACAS) and the Asymptomatic Carotid Surgery Trial (ACST) showed 50%–54% lower odds of stroke or periprocedural death with CEA in men.[6] However, there was no significant difference in outcome between revascularization and medical therapy in women.[6]

Furthermore, age-stratified pooled analysis of the NASCET and ECST demonstrated that CEA may be more beneficial in individuals older than 75 years and slightly less beneficial, albeit significantly so, in younger age groups.[5] Whether patients older than 75 years with asymptomatic disease benefit from revascularization is uncertain because ACAS excluded patients aged 80 years[7] or older and the ACST showed no difference in outcome between CEA and medical treatment in patients older than 75 years.[8] However, the ACST was not powered to evaluate this outcome.

After the publication of the pivotal mechanical thrombectomy (MT) trials in 2015,[9] MT use in the United States has increased exponentially.[10] It is likely that this increase may have been accompanied by increased CAS utilization over time as cases with tandem occlusion may also be treated with CAS at the time of MT, therefore obviating the need for future CEA. How revascularization practice in the United States has changed over time with changing MT utilization is yet to be studied systematically.

In October 2023, the Centers for Medicare & Medicaid Services expanded CAS coverage to individuals with standard surgical risk by removing the limitation of coverage to only individuals with high surgical risk.[11] This change may also lead to more CAS procedures in the United States.

This study provides a 17-year comprehensive description of trends in revascularization practices in the United States before the Centers for Medicare & Medicaid Services (CMS)–proposed expansion went into effect. More specifically, we describe age-specific and sex-specific trends in the utilization of CEA and CAS in the United States over time, in light of what is known about the effectiveness of revascularization in various demographic subgroups and the changing practice of MT over time.

Methods

Standard Protocol Approvals and Data Availability

We conducted this study using the National Inpatient Sample (NIS), the State Inpatient Databases (SID), and State Emergency Department Databases (SEDD) of Florida, GA, NY. These databases are released by the Agency for Healthcare Research and Quality as part of the Healthcare Cost and Utilization Project (HCUP). The portion of this study performed using the SID and SEDD was approved by HCUP after the agency reviewed this project to be consistent with HCUP data use agreement. Utilization of the deidentified NIS does not require an institutional review board review according to the HCUP. The authors are bound by HCUP data use agreement and cannot share these data sets, but all data sets used in this study are publicly available for purchase directly from HCUP. This study was written to comply with

STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guidelines. Data analyses codes used in this study can be shared on reasonable request. FOO was responsible for data stewardship.

Data Sources

Overall Specific Trends in Revascularization

To evaluate overall national revascularization trends, we used the 2006–2022 NIS to conduct a serial cross-sectional study. The NIS is a 20% stratified random sample of all hospitalizations in the United States. Weights provided in the NIS allow for estimation of treatment patterns for the entire country based on the 20% of admissions contained in the sample.

Study Population for Evaluating Symptomatic vs Asymptomatic Stenosis Hospitalizations

To comprehensively differentiate symptomatic vs asymptomatic carotid disease, we used the SEDD and SID of FL (2005–2021), GA (2010–2020), MD (2012–2021), and NY (2005–2020) to conduct a retrospective cohort study. The selected states are large, demographically diverse states that together account for >17% of the total US population. These databases contain all the inpatient and emergency department visits in these states and contain unique "visitlink" variables that allow for the identification of individual patients across hospitalizations over years. The variation in start dates between states reflects when unique patient identifiers became available in various states.

We identified all cases of CAS and CEA from the NIS or state databases as appropriate using previously validated International Classification of Diseases (ICD) Ninth Revision procedural codes "3812" and "0063," respectively, for hospitalizations before September 2015,[12] and a constellation of ICD-10 codes is provided in eTables 1 and 2 in the online supplement afterward. ICD codes for transcarotid artery revascularization (TCAR) were established beginning October 2020, and patients/hospitalizations were classified under the TCAR group if they had code X2AH336 or X2AJ336 for the cerebral embolic filtration and extracorporeal flow reversal circuit, required for TCAR. We excluded n = 92 hospitalizations in patients younger than 18 years, n = 1 hospitalization with missing age, n = 75 hospitalizations with missing information on sex, and n = 752 hospitalizations with concomitant codes for CEA and CAS.

Definition of Symptomatic and Asymptomatic Stenosis

Admissions for symptomatic stenosis were defined using ICD-9 and ICD-10 codes corresponding to ischemic stroke, TIA, or retinal ischemic events as provided in eTable 1. Admissions were further classified under the symptomatic acute ischemic stroke (AIS) group if they had diagnosis-related group codes 061–063 corresponding to AIS with thrombolytic agents with or without comorbidities/conditions or major complications/comorbidities or if they had concomitant ICD procedural codes for IV thrombolysis or MT. We further classified hospitalizations under the symptomatic group if they had codes for long-term sequelae of stroke such as hemiplegia or aphasia as has been described previously by others.[13]

In the state administrative databases, all hospitalizations in revascularized patients in the preceding 6 months were reviewed and patients were classified under the symptomatic group if they had codes corresponding to AIS, TIA, or retinal events. Patients with codes for IV thrombolysis or MT in current hospitalizations or in hospitalizations in the preceding 6 months as well as those with late effects of stroke such as hemiplegia or aphasia during this time frame were also categorized as symptomatic.

In these state administrative databases, for hospitalizations with concomitant symptomatic and carotid revascularization procedures, we defined the time to revascularization as the day of revascularization during hospitalization. For cases where revascularization was performed during a follow-up hospitalization, we calculated the difference in days between both hospitalizations using the HCUP "DaysToEvent" variable and added this to the day of revascularization in the index CEA or CAS hospitalization to obtain the day of revascularization. The Current American Heart Association secondary stroke prevention guidelines recommend that revascularizations be performed within 14 days of qualifying symptomatic event because they may be most beneficial during this time frame.[14] Therefore, we defined early revascularization as revascularization performed within 14 days of qualifying symptomatic event.

Population Data

Counts of the annual total adult (≥18 years) US population were obtained from tables available on the US Census Bureau website (Census.gov).

Definition of In-Hospital Complications

Acute myocardial infarction during revascularization hospitalization was defined using a constellation of ICD-9 and ICD-10 codes as given in eTable 1. In-hospital mortality was defined using the HCUP variable named "DIED" and in-hospital length-of-stay (LOS) defined using the variable "LOS."

Statistical Analysis

Baseline characteristics of study participants were summarized using descriptive statistics. We used weights provided in the NIS to compute the weighted number and weighted proportion of revascularizations performed. Weighted numbers were combined with adult census data to compute revascularization proportions per 100,000 population. Joinpoint regression with first-order autocorrelation was used to evaluate trends in the proportion of hospitalizations for CAS and to evaluate utilization over time.

The proportion of hospitalizations with Medicare or Medicaid as the primary payer was also identified. LOS in various revascularization subgroups was summarized using the median and interquartile range, and differences in LOS between revascularization subtypes were evaluated using the Kruskal-Wallis test.

We used multilevel multivariable mixed-effect generalized linear regression models (with a binomial family and logit link) clustered by state and adjusted for age, sex, race, year, Elixhauser comorbidity score, insurance status, smoking, MT status, and qualifying symptomatic event type to compare odds of early revascularization between various categories of revascularizations.

Generalized linear models with year as the independent variable and with Medicare + Medicaid payer (logit link and binomial family) or LOS (identity link and gamma family) as the dependent variable were used to evaluate trends in the prevalence of Medicare/Medicaid-associated hospitalizations and LOS, respectively, over time. Significant difference in trend over time was evaluated using the Wald test. Additional multivariable generalized linear models adjusted for age, sex, race and ethnicity, Elixhauser score, hospital region, hospital location/teaching status and hospitalization year, smoking, and dyslipidemia were used to evaluate the association of carotid revascularization subtypes with LOS, myocardial infarction, and in-hospital mortality according to symptomatic disease status.

Statistical significance required a 2-tailed α level of <0.05. All analyses were performed by FOO using Stata, version 16 (StataCorp LP). We considered the complex NIS survey design in all analyses through use of relevant primary sampling units and weights.

Missing Data

Data on primary payer for hospitalization were missing in 0.1% of hospitalizations and on LOS were missing in 0.02% of hospitalizations. Hospitalizations with missing primary payer were categorized into the unknown/other category, whereas hospitalizations with missing LOS were excluded when evaluating LOS as outcome.

Results

Carotid Revascularization Volumes

There were 1,779,948 weighted carotid revascularization hospitalizations in the United States from 2006 to 2022, averaging out to 104,702.8 revascularizations annually. However, annual volumes have remained consistently <100,000 since 2014 (Figure 1). CEA was the most common revascularization procedure accounting for 82.0% of all cases. TCAR accounted for 5.8% and 9.1% of all revascularizations in 2021 and 2022, respectively (Figure 1). Medicare (72.8%) and Medicaid (4.0%) hospitalizations accounted for over three-fourths of all revascularization hospitalizations, and the proportion of combined Medicare/Medicaid hospitalizations increased in most subgroups of CEA and CAS hospitalizations over time, except for symptomatic CAS hospitalizations (eFigure 1).

Age and Gender Distribution

The mean age at all revascularizations was 71.0 years. 58.3% of all CEA procedures and 55.7% of all CAS procedures were performed in patients aged 70 years or older (Figure 2). 40.9% of procedures were performed in women. The proportion of revascularizations performed in women declined relatively by 3.0% in CEA and by 3.6% in CAS hospitalizations when comparing rates in 2006 vs 2022 (p for trend <0.001) (Figure 3).

Symptomatic and Asymptomatic Revascularizations

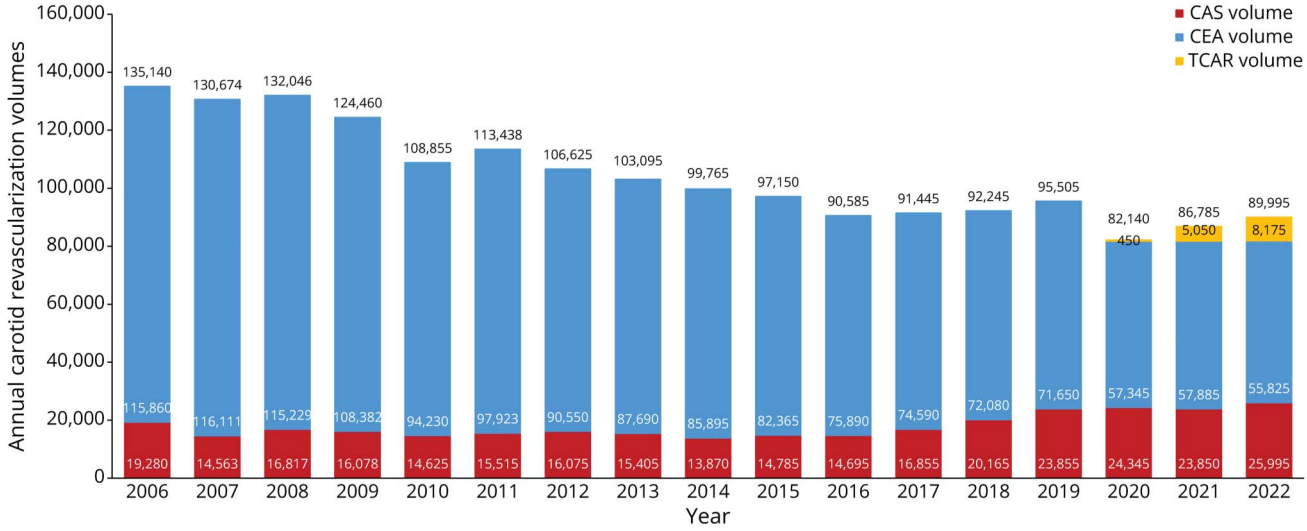
Nationally, the age-standardized and sex-standardized proportion of revascularizations that were concurrently symptomatic was 19.9%, but this differed significantly by revascularization type (Figure 4). Almost 1-in-3 CAS revascularizations (30.1%) were performed in concurrently symptomatic hospitalizations. 1.1% of all revascularizations had codes for MT, with a significantly higher frequency in CAS hospitalizations (5.5%) compared with CEA (0.1%) (p value for comparison <0.001) (eTable 3). When concurrent MT hospitalizations (which capture most tandem occlusion hospitalizations) were excluded, just over 1-in-4 CAS revascularizations (28.1%) were performed in concurrent symptomatic hospitalizations (Figure 4). Less than one-third of all types of revascularizations in women were performed for symptomatic disease, and more than one-third of all asymptomatic revascularizations were performed in individuals aged 75 years or older (Figure 4).

Of the 237,520 revascularizations performed in the states of Florida, GA, Maryland, and New York with available data over the study period, the age-standardized and sex-standardized proportions of hospitalizations with concomitant revascularization and symptomatic stenosis codes were similar to those in the NIS (20.2%) (eTable 3). However, review of all previous hospitalizations in these patients over the preceding 6 months revealed a total symptomatic stenosis proportion of 25.7%, indicating that most revascularizations for symptomatic disease (78.3%) were performed during the index symptomatic stenosis hospitalization as opposed to a follow-up hospitalization (eTable 3).

Just as was the case nationally, a disproportionately greater percentage of CAS procedures were performed in symptomatic patients when compared with CEA and TCAR (Figure 4), but these percentages were higher than the national estimates because they take into account all previous hospitalizations for qualifying cerebrovascular events in the 6 months preceding revascularization hospitalization.

Ischemic stroke was the qualifying index event in 82.1% of symptomatic cases, followed by TIA (9.8%) and then retinal

Figure 1 Annual Volumes of Carotid Revascularizations in the United States From 2006 to 2022 According to Revascularization Type



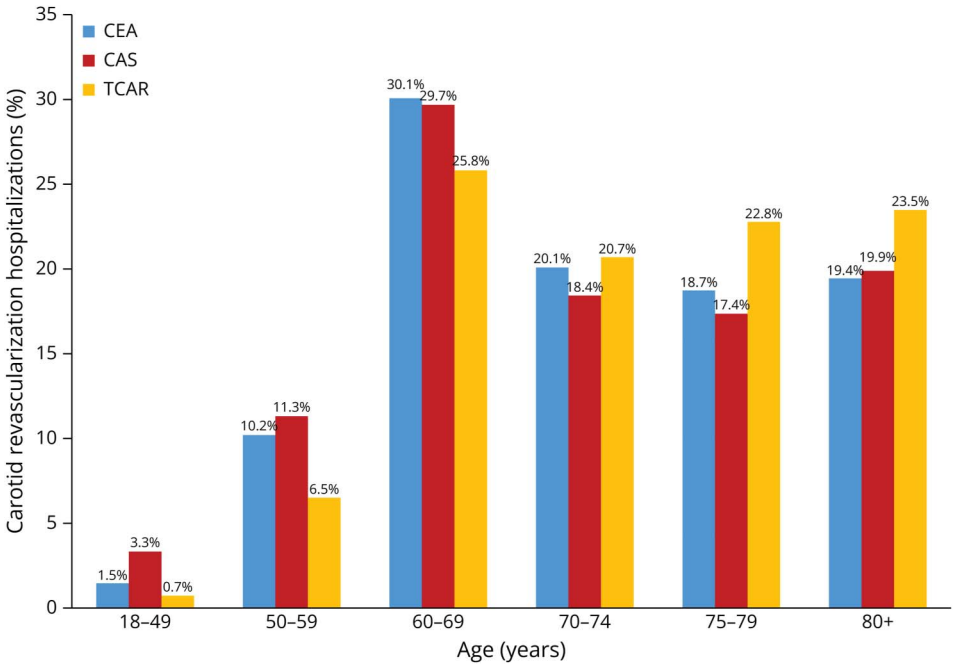
TCAR estimates are for the period October 2020–December 2023. CAS = carotid artery stenting; CEA = carotid endarterectomy; TCAR = transcarotid artery revascularization.

events (8.1%) in the 4 states. Only 1-in-4 revascularizations in women (24.7%) were being performed for symptomatic disease, but this proportion approached 40% in CAS (Figure 4).

The median time from index symptomatic admission to revascularization was 5.0 days (IQR 1.0–27.0). The proportion of early revascularizations was 68.5%, and this proportion increased over time in both CAS and CEA (both p value for trend <0.001) (eFigure 2).

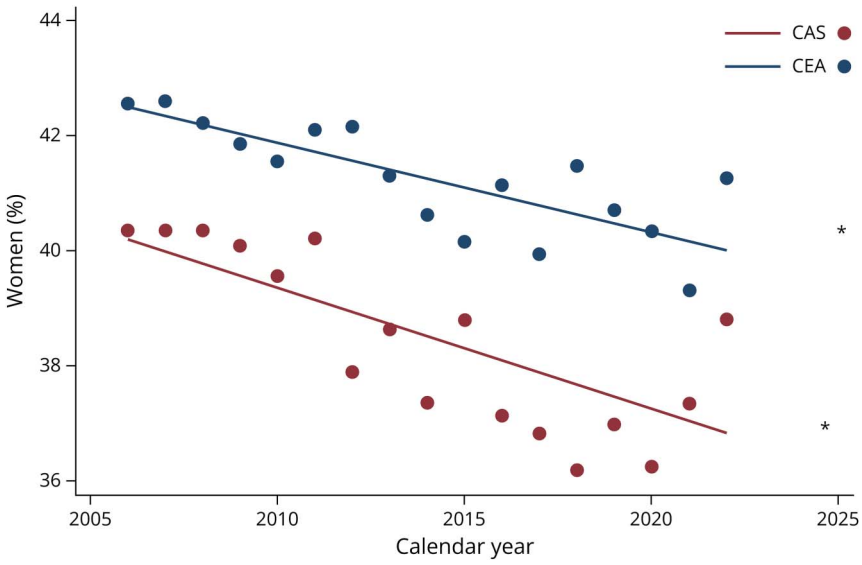
After multivariable adjustment, women had 5% lower odds of early revascularization compared with men. Hispanic patients had 20% greater odds of early revascularization compared with White patients, but there was no difference in odds of

Figure 2 Age Distribution of Carotid Revascularization Hospitalizations in the United States From 2006 to 2022 According to Revascularization Type



TCAR estimates are for the period October 2020–December 2023. CAS = carotid artery stenting; CEA = carotid endarterectomy; TCAR = transcarotid artery revascularization.

Figure 3 Trends in Proportion of Carotid Revascularizations Performed in Women in the United States According to Revascularization Type



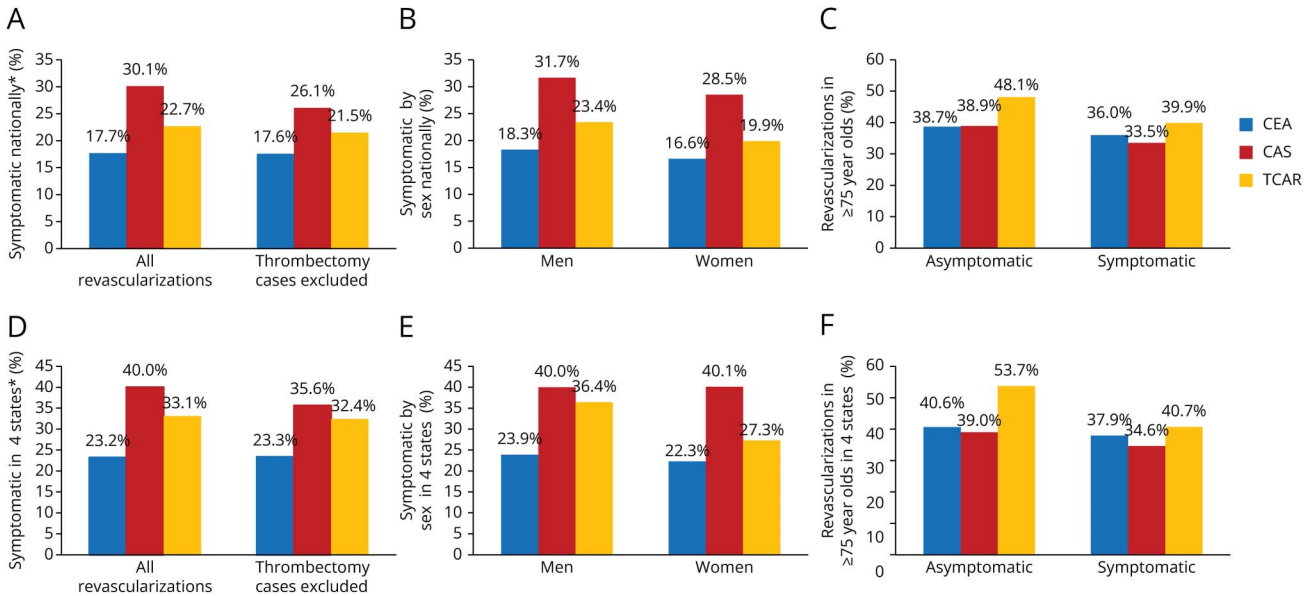
*p Value for trend <0.001. CAS = carotid artery stenting; CEA = carotid endarterectomy.

early revascularization in Black compared with White patients. Patients with retinal events or with TIA had significantly greater odds of early revascularization compared with those with ischemic stroke, whereas those undergoing CAS had 18% greater odds of early revascularization compared with those undergoing CEA, after multivariable adjustment including adjustment for differences in MT (Table 1).

Trends in In-Hospital Indices

Nationally, the mean and the median LOS after asymptomatic hospitalizations were 2.3 and 1.0 days, respectively, while

Figure 4 Percentage of Carotid Revascularizations in the United States That Are Symptomatic in All Patients, by Sex and in Individuals Aged 75 Years or Older



Top row (A–C) represents the entire country, and symptomatic hospitalizations are defined using index hospitalizations alone. Bottom row (D–F) represents cases in the states of Florida, GA, Maryland, and NY. Symptomatic cases are defined more comprehensively using all emergency and inpatient encounters for stroke, TIA, or retinal events in the 6 months preceding revascularization hospitalization. TCAR estimates are for the period October 2020–December 2023. *Estimates are age-standardized and sex-standardized proportions. CAS = carotid artery stenting; CEA = carotid endarterectomy; TCAR = transcarotid artery revascularization.

Table 1 Multivariable Association of Various Demographic and Hospitalization Factors With Odds of Early Revascularization in 4 States

Variable	Odds ratio	95% CI	*p* Value
Women vs men	0.95	0.91–0.98	0.007
Age			
50–59 y vs 18–49	0.78	0.69–0.87	<0.001
60–69 y vs 18–49 y	0.91	0.81–1.02	0.102
70–74 y vs 18–49 y	1.01	0.90–1.15	0.815
75–79 y vs 18–49 y	1.10	0.97–1.25	0.137
Race			
Black vs White	1.02	0.96–1.09	0.465
Hispanic vs White	1.20	1.11–1.29	<0.001
Asian/Pacific Islander vs White	1.06	0.90–1.24	0.527
Other/unknown vs White	1.26	1.15–1.38	<0.001
Insurance status			
Medicaid vs Medicare	0.96	0.89–1.04	0.357
Private vs Medicare	1.32	1.25–1.40	<0.001
Self-pay vs Medicare	1.55	1.36–1.75	<0.001
No charge vs Medicare	1.52	1.21–1.92	<0.001
Other vs Medicare	1.19	1.05–1.37	0.006
Year	1.02	1.01–1.02	<0.001
Elixhauser comorbidity score	1.17	1.16–1.18	<0.001
Smoking status	1.58	1.51–1.66	<0.001
Qualifying symptom category			
TIA vs stroke	1.11	1.04–1.17	<0.001
Retinal event vs stroke	7.54	6.78–8.38	<0.001
Mechanical thrombectomy	8.08	6.66–9.80	<0.001
Revascularization type			
CAS vs CEA	1.18	1.13–1.24	<0.001
TCAR vs CEA	0.91	0.64–1.31	0.623

Abbreviations: CAS = carotid artery stenting; CEA = carotid endarterectomy; TCAR = transcarotid artery revascularization.
Estimates obtained from mixed-effect generalized linear models with random effects by hospital states.

those after symptomatic hospitalizations were 4.0 and 6.0 days, respectively (eTable 4). Among asymptomatic hospitalizations, the LOS was on average 0.07 days shorter in CAS admissions compared with CEA admissions (eTable 5) after multivariable adjustment, but there was a divergent trend in mean LOS after asymptomatic and symptomatic hospitalizations over time. Although LOS increased over time in CAS and CEA symptomatic hospitalizations (p for trend <0.001), LOS in asymptomatic CEA hospitalizations declined over time while that in asymptomatic CAS hospitalizations remained unchanged over time (eFigure 3). The age-adjusted and sex-adjusted prevalence of myocardial infarction in CEA and CAS hospitalizations was 1.5% and 1.4%, respectively, but CAS hospitalizations had 31% greater odds of reporting myocardial infarction compared with CEA hospitalizations (eTable 5). The in-hospital mortality was <1% in all asymptomatic hospitalizations, but mortality was variable in all asymptomatic hospitalizations ranging from 1.2% to 4.1% between the various modalities. Myocardial infarction and mortality also demonstrated heterogeneous trends across various revascularization subtypes and symptomatic disease status (eFigures 4–6).

Trends in Revascularization Volumes Over Time

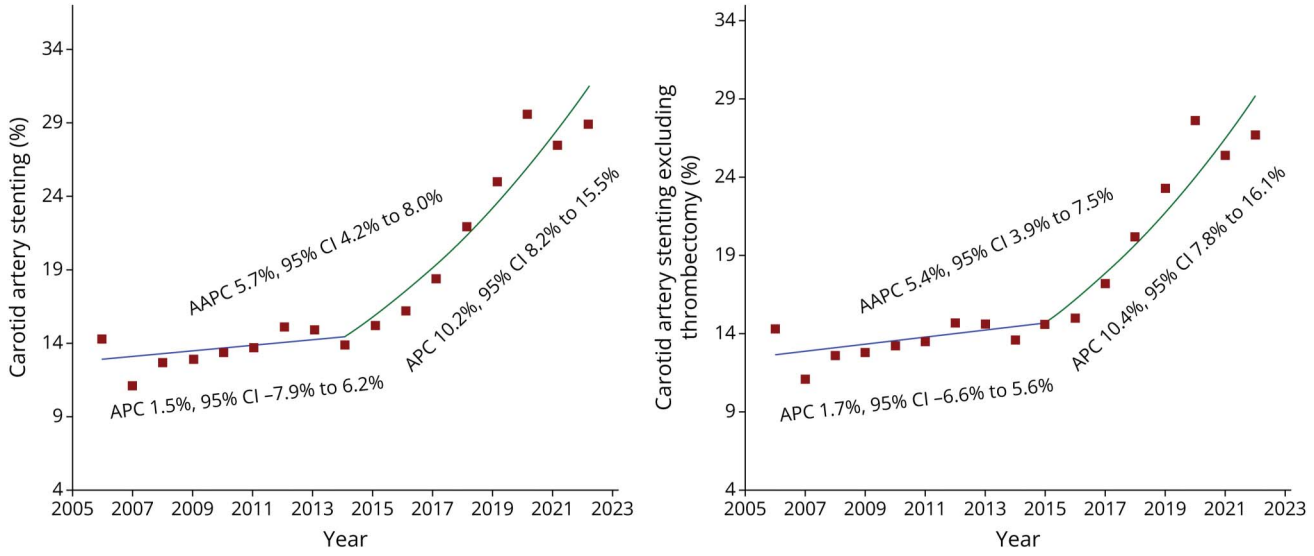
After joinpoint regression, the age-standardized and sex-standardized proportion of revascularizations for CAS increased by 5.7% (average annualized percentage change [AAPC] 4.2%–8.0%) across the study period. However, this increase was mainly seen in the period 2014–2022 (Figure 5A). Although there was no significant change in the annual proportion of CAS procedures over 2006–2014, the proportion of CAS revascularizations increased by 10% annually (annualized percentage change [APC] 10.2% [95% CI 8.2%–15.5%]) over the period 2014–2022. This increase in CAS proportion was still pronounced after 2015, even after all cases with concomitant MT codes were excluded (Figure 5B). The increase in CAS proportion occurred in all age groups and in both sexes, even among women with symptomatic or asymptomatic disease (eFigures 7 and 8). The proportion of concurrent CAS and MT hospitalizations also increased markedly after 2015 (eFigure 9).

Using the total adult US population as the denominator, the overall carotid revascularization utilization per 100,000 population declined by 3.7% annually across the study period (AAPC −3.7%, 95% CI −4.1% to −3.3%) but decline plateaued after 2015 (Figure 6). Although CEA utilization per total population declined by −5.5% over the entire study period, CAS utilization declined by 3.8% annually from 2006 to 2014 and increased by 7.8% annually from 2014 to 2022, resulting in a net total increase in CAS utilization per total adult population of 1.8% annually over the entire study period (Figure 6). CAS utilization volume per population increased nationally even after all MT cases were excluded (Figure 6).

Discussion

In this assessment of multiple administrative health care databases, we provide a population-level descriptive summary of carotid revascularization practices and trends in the United States over the period 2006–2022. Consistent with previous studies,[15] we show that the average annual volume of carotid revascularizations in the United States was just over 100,000 during the study period but revascularization usage

Figure 5 Joinpoint Regression of the Age-Adjusted and Sex-Adjusted Proportions of All Revascularizations That Are Carotid Artery Stenting in the United States From 2006 to 2022



APC represents annualized percentage change. AAPC represents the average weighted annualized percentage change across the entire study period when more than 1 joinpoint trend is observed.

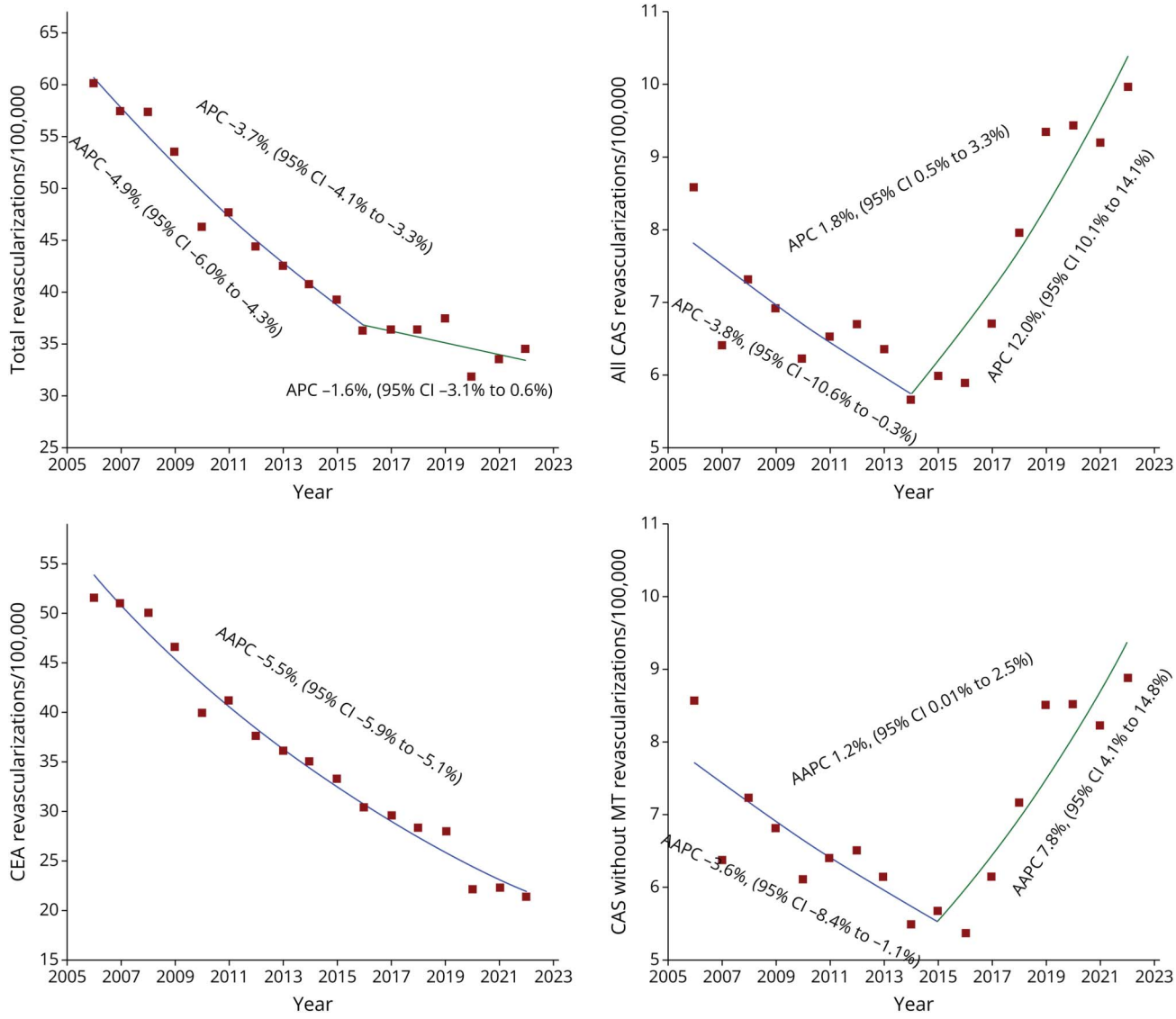
per total population has declined over time. Most of this decline occurred before 2015 and has plateaued afterward due in part to increasing CAS utilization even after MT cases were excluded. TCAR accounted for almost 10% of all revascularizations in 2022. These data are important for health care resource allocation and for clinical or research planning.

From a clinical viewpoint, this study suggests that national carotid revascularization practices over the past 2 decades may not have been totally concordant with the evidence from major revascularization trials. The percentage of revascularization procedures performed in women is substantial, given the uncertain benefit of revascularization in this group of individuals who may potentially have a less inflammatory and more stable profile of carotid disease compared with men.[16,17] Almost 3-in-4 revascularizations are being performed for asymptomatic disease, including in women, for whom there is no clear benefit of revascularization. Although the benefit of revascularization over medical therapy in individuals aged 75 years or older has only been clearly established for patients with symptomatic disease, over one-third of all asymptomatic revascularizations nationally were performed in this age group. Despite known reduced efficacy of revascularization for stroke prevention in patients with isolated retinal events,[14,16] patients presenting with retinal events as qualifying symptomatic event had >7 times higher odds of early revascularization compared with those with stroke.

Furthermore, other than the Carotid Revascularization Endarterectomy versus Stenting Trial (CREST),[2] there is a preponderance of level 1 evidence data that CAS may be associated with more risk compared with CEA in individuals older than 70 years. In pooled analysis of the CREST, Endarterectomy versus Angioplasty in Patients with Symptomatic Severe Carotid Stenosis (EVA-3S), International Carotid Stenting Study, and the Stent-Protected Angioplasty versus Carotid Endarterectomy trial, the hazard ratio for periprocedural stroke or death after CAS in symptomatic individuals aged 70–74 years was 2 times that of CEA.[1] No such difference was noted in younger individuals. Despite these reported findings, over half of CAS procedures were performed in patients older than 70 years and the proportion of CAS revascularizations in older individuals has continued to increase over time even after excluding all concurrent MT hospitalizations.

Exact reasons underlying this dissonance are not very clear, but multiple factors may be contributing at least to the excess CAS utilization over time. First, leading neuroendovascular experts argue that age in itself is not a marker of elevated CAS risk and that the higher risk of complications in older patients is due to this population's anatomical features.[18] They maintain that common reasons for increased stroke risk after CAS include aortic arch disease including calcification, which increases with age, manipulation through type III aortic arches, and aortic ostial disease, and subsequently, CAS risk should be evaluated in the context of these variables as opposed to stratifying treatment choices based on age.[18] Moreover, CAS technology has improved over time to include transradial and transbrachial approaches, which can bypass the aortic arch completely in right-sided CAS or bovine-type aortic arch configuration in left-sided CAS, therefore potentially reducing complication risks. Other

Figure 6 Joinpoint Regression of the Volume of Carotid Revascularizations per 100,000 Population in the United States According to Revascularization Type



APC represents annualized percentage change. AAPC represents the average weighted annualized percentage change across the entire study period when more than 1 joinpoint trend is observed.

neurointerventionists argue that,+ through technological and technical advances in CAS over time, the perioperative stroke or death rate after CAS in the real world over the past decade may be comparable if not better than that reported in CEA trials or in TCAR registries.[19]

While CAS technology and even CEA procedure may have improved over time,[20] it remains critical to note that no clinical trial has established superiority of CAS over best medical therapy (BMT) in carotid disease. BMT has also evolved over time from simple aspirin monotherapy to include dual antiplatelet therapy and other treatment targets such as aggressive cholesterol management with statins, smoking cessation, and aggressive blood pressure and diabetes management, and consistent with this evolution, the ipsilateral stroke risk after BMT alone has also declined significantly over time. In a recent systematic review of 73 cohort studies and trials of medically treated patients with asymptomatic disease ≥50%, the ipsilateral stroke risk declined by 24% with each 5-year increment from 1976 to 2014.[21] Therefore, whether surgical revascularization offers any additional benefit to patients receiving contemporary BMT is uncertain.[16] In fact, the one trial comparing surgical revascularization + contemporary BMT with BMT alone in asymptomatic disease, the SPACE-2 trial,[22] found no significant difference between CEA or CAS and BMT. This trial was stopped early because of slow enrollment, so the conclusions are not definitive. Another recent trial, the ECST-2 trial, also found no benefit from revascularization in addition to BMT among 429 patients with asymptomatic or symptomatic

stenosis at low or intermediate predicted risk of stroke.[23] Hopefully, the ongoing CREST-2 trial, with close to 2,500 patients enrolled, will provide additional useful data to guide future treatment decisions.

The increase in CAS utilization after 2015 suggests that the widespread adoption of MT may have changed the carotid revascularization landscape toward more CAS even for non-MT hospitalizations. The increase in the number of thrombectomy-capable centers and comprehensive stroke centers in the United States over time may have been accompanied by changing referral patterns for patients with carotid disease that may otherwise have been referred to CEA experts (such as vascular or neurosurgeons) to neurointerventionists who predominantly perform CAS. There may also be a financial incentive for proceduralists to perform CAS. The recent change in CMS reimbursement policy for CAS will likely lead to further increase in CAS use over time.

From a resource standpoint, older studies have established that most revascularizations performed in the United States are CEA procedures. In 1 recent analysis of 108,676 patients undergoing revascularization in the Vascular Quality Initiative database from 2015 to 2019,[24] 75% of all revascularizations were CEA, with 14.3% being transfemoral CAS and 10.7% TCARs. We provide novel information highlighting exponential increase in CAS utilization after 2015. By 2022, CAS accounted for 29.0% of all revascularizations. If the increased CAS usage continues at current pace, CAS will overtake CEA as the major revascularization option in 2029. The CAS use has increased in spite of TCAR emerging as the major revascularization option in some institutions for patients at high stroke risk.[24] Another study using the Vascular Quality Initiative database has demonstrated that, as of 2022, TCAR accounted for almost 25% of all revascularizations at institutions offering all 3 procedures and was taking a proportionate share out of both CEA and CAS,[25] so with declining CEA volumes from TCAR, coupled with increased CAS usage over time, CAS will soon become the primary revascularization procedure of choice in the United States. Some have expressed concern that TCAR has not been studied in randomized trials and that it has not been vetted as thoroughly as CEA.[26]

This study should be viewed in the context of limitations. Although we relied on previously validated ICD-9 procedure codes and on CMS-recommended ICD-10 codes for most revascularization procedures, we cannot exclude errors because of coding inaccuracies. TCAR was approved as a revascularization option in the United States in 2015, but the ICD codes for TCAR only became available in 2020 so all patients undergoing TCAR during the period 2015–2020 may have been misclassified under either the CAS or CEA group during this period. Moreover, the ICD coding of TCAR still needs validation in future studies. In addition, because of the lack of TCAR-specific codes before 2020, we are unable to evaluate trends in TCAR utilization over time. Furthermore, the accuracy of ICD coding for determining the symptomatic status of patients is unknown. The reported percentage of asymptomatic patients in this study is likely an underestimate because some postprocedural strokes may have been classified under the symptomatic stenosis groups. Recent studies have demonstrated that ipsilateral stroke risk may be more than twice as high in patients with severe asymptomatic stenosis (70%–99%) compared with moderate (50%–69%),[21,27] but we are unable to report on the degree of carotid stenosis or on the approach to CAS (e.g., transradial vs transfemoral) because this information is not available in administrative databases. Overall, carotid revascularization declined over time, but we are unable to comment on whether this decline is due to population-level decline in extracranial carotid disease or to changing revascularization practices over time. Although revascularization practices described in this study are generalizable to the entire US population, the subset of this study describing symptomatic stenosis in 4 states should be viewed with caution because there may potentially be regional differences in revascularization practices between these states and others. However, given the close similarity between the characteristics of revascularized patients in these states and those nationally, we believe that any such differences may be likely small.

Although the prevalence of acute myocardial infarction and in-hospital mortality reported in this study suggest that revascularization procedures are not without morbidity and may be associated with potentially serious complications in patients with previously asymptomatic disease, no conclusion of the comparative effectiveness of these revascularization types can be derived from these estimates because of the huge potential for selection bias. Several factors that may have necessitated a particular revascularization choice such as greater baseline comorbidity burden may also have put patients in that revascularization subgroup at high risk of mortality or in-hospital complications. The reported mortality and in-hospital complication burden reported in symptomatic patients should also be viewed with extreme caution because these conditions may have been related to the underlying stroke, and not necessarily a downstream consequence of revascularization.

Over the period 2015–2022, there was a marked increase in CAS utilization for carotid revascularization even after exclusion of MT hospitalizations. This increase is despite the lack of evidence showing benefit of CAS over current BMT. If the pace of increased CAS remains constant over the next 7 years, CEA will cease to be the dominant revascularization procedure of choice in the United States before 2030. With the change in CMS reimbursement policy for CAS to include non–high-risk patients, this increase is likely to be even more sustained. CREST 2 trial results will be important to define whether the high utilization of carotid revascularization in asymptomatic patients is warranted.

Author Contributions

F.O. Otite: drafting/revision of the manuscript for content, including medical writing for content; major role in the

acquisition of data; study concept or design; analysis or interpretation of data. N.A. Morris: analysis or interpretation of data. A. Sabra: analysis or interpretation of data. S.D. Patel: analysis or interpretation of data. N. Anikpezie: analysis or interpretation of data. A. Sahoo: analysis or interpretation of data. D. Landzberg: analysis or interpretation of data. C.D. Wee: analysis or interpretation of data. A. Singla: analysis or interpretation of data. J.G.S. Latorre: analysis or interpretation of data P. Khandelwal: analysis or interpretation of data. S. Chaturvedi: drafting/revision of the manuscript for content, including medical writing for content; study concept or design; analysis or interpretation of data.

Study Funding

The authors report no targeted funding.

Disclosure

S. Chaturvedi serves on the Executive Committee of the CREST 2 trial. All other authors report no conflict of interest relevant to this manuscript. Go to Neurology.org/N for full disclosures.

Publication History

Received by *Neurology*® March 11, 2025. Accepted in final form July 7, 2025. Submitted and externally peer reviewed. The handling editor was Editor-in-Chief José Merino, MD, MPhil, FAAN.

References

1. Howard G, Roubin GS, Jansen O, 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(10025):1305-1311. doi:10.1016/S0140-6736(15)01309-4
2. Howard VJ, Lutsep HL, Mackey A, et al. Influence of sex on outcomes of stenting versus endarterectomy: a subgroup analysis of the carotid revascularization endarterectomy versus stenting trial (CREST). *Lancet Neurol*. 2011;10(6):530-537. doi:10.1016/S1474-4422(11)70080-1
3. North American Symptomatic Carotid Endarterectomy Trial Collaborators, Barnett HJM, Taylor DW, et al. Beneficial effect of carotid endarterectomy in symptomatic patients with high-grade carotid stenosis. *N Engl J Med*. 1991;325(7):445-453. doi:10.1056/NEJM199108153250701
4. Randomised trial of endarterectomy for recently symptomatic carotid stenosis: final results of the MRC European Carotid Surgery Trial (ECST). *Lancet*. 1998;351:1379-1387. doi:10.1016/S0140-6736(97)09342-6
5. 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(9413):915-924. doi:10.1016/S0140-6736(04)15785-1
6. Rothwell PM, Goldstein LB. Carotid endarterectomy for asymptomatic carotid stenosis: asymptomatic carotid surgery trial. *Stroke*. 2004;35(10):2425-2427. doi:10.1161/01.STR.0000141706.50170.a7
7. Walker MD. Endarterectomy for asymptomatic carotid artery stenosis. *JAMA*. 1995;273(18):1421-1428. doi:10.1001/jama.1995.03520420037035
8. Halliday A, Mansfield A, Marro J, et al. Prevention of disabling and fatal strokes by successful carotid endarterectomy in patients without recent neurological symptoms: randomised controlled trial. *Lancet*. 2004;363(9420):1491-1502. doi:10.1016/S0140-6736(04)16146-1
9. Goyal M, Menon BK, van Zwam WH, et al. Endovascular thrombectomy after large-vessel ischaemic stroke: a meta-analysis of individual patient data from five randomised trials. *Lancet*. 2016;387(10029):1723-1731. doi:10.1016/S0140-6736(16)00163-X
10. Atchaneeyasakul K, Liaw N, Lee RH, Liebeskind DS, Saver JL. Patterns of mechanical thrombectomy for stroke before and after the 2015 pivotal trials and US national guideline update. *J Stroke Cerebrovasc Dis*. 2020;29(12):105292. doi:10.1016/j.jstrokecerebrovasdis.2020.105292
11. Paraskevas KI, Zeebregts CJ, AbuRahma AF, Perler BA. Implications of the centers for medicare and medicaid services decision to expand indications for carotid artery stenting. *J Vasc Surg*. 2024;80(3):599-603. doi:10.1016/j.jvs.2024.03.008
12. Reznik M, Kamel H, Gialdini G, Pandya A, Navi BB, Gupta A. Timing of carotid revascularization procedures after ischemic stroke. *Stroke*. 2017;48(1):225-228. doi:10.1161/STROKEAHA.116.015766
13. Cole TS, Mezher AW, Catapano JS, et al. Nationwide trends in carotid endarterectomy and carotid artery stenting in the Post-CREST era. *Stroke*. 2020;51(2):579-587. doi:10.1161/STROKEAHA.119.027388
14. Kleindorfer DO, Towfighi A, Chaturvedi S, et al. 2021 guideline for the prevention of stroke in patients with stroke and transient ischemic attack: a guideline from the American Heart Association/American Stroke Association. *Stroke*. 2021;52(7):e364-e467. doi:10.1161/STR.0000000000000375
15. Martin SS, Aday AW, Allen NB, et al. 2025 heart disease and stroke statistics: a report of US and global data from the American Heart Association. *Circulation*. 2025;151(8):e524. doi:10.1161/cir.0000000000001303
16. Chaturvedi S. Diagnosis and management of large artery atherosclerosis. *Continuum (Minneap Minn)*. 2023;29(2):486-500. doi:10.1212/CON.0000000000001212
17. Hellings WE, Pasterkamp G, Verhoeven BA, et al. Gender-associated differences in plaque phenotype of patients undergoing carotid endarterectomy. *J Vasc Surg*. 2007;45(2):289-297. doi:10.1016/j.jvs.2006.09.051
18. Rangel-Castilla L, Nakaji P, Siddiqui AH, Spetzler RF, Levy EI. *Decision Making in Neurovascular Disease*. Thieme; 2018.
19. Ezzeldin M, Hassan AE, Kerro A, et al. Carotid artery stenting outcomes by neurointerventional surgeons (CASONI). *Stroke Vasc Interv Neurol*. 2025;5(1):e001459. doi:10.1161/svin.124.001459
20. White CJ, Brott TG, Gray WA, et al. Carotid artery stenting: JACC state-of-the-art review. *J Am Coll Cardiol*. 2022;80(2):155-170. doi:10.1016/j.jacc.2022.05.007
21. Poorthuis MH, Solomon Y, Herings RA, et al. Temporal trends and determinants of stroke risk in patients with medically treated asymptomatic carotid stenosis. *Stroke*. 2023;54(7):1735-1749. doi:10.1161/STROKEAHA.122.041921
22. Reiff T, Eckstein HH, Mansmann U, et al. Carotid endarterectomy or stenting or best medical treatment alone for moderate-to-severe asymptomatic carotid artery stenosis: 5-year results of a multicentre, randomised controlled trial. *Lancet Neurol*. 2022;21(10):877-888. doi:10.1016/S1474-4422(22)00290-3
23. Donners SJ, van Velzen TJ, Cheng SF, et al. Optimised medical therapy alone versus optimised medical therapy plus revascularisation for asymptomatic or low-to-intermediate risk symptomatic carotid stenosis (ECST-2): 2-year interim results of a multicentre randomised trial. *Lancet Neurol*. 2025;24(5):389-399. doi:10.1016/S1474-4422(25)00107-3
24. Stonko DP, Goldsborough E, Kibrik P, Zhang G, Holscher CM, Hicks CW. Use of transcarotid artery revascularization, transfemoral carotid artery stenting, and carotid endarterectomy in the US from 2015 to 2019. *JAMA Netw Open*. 2022;5(9):e2231944. doi:10.1001/jamanetworkopen.2022.31944
25. Columbo JA, Stone DH, Martinez-Camblor P, Goodney PP, O'Malley AJ. Adoption and diffusion of transcarotid artery revascularization in contemporary practice. *Circ Cardiovasc Interv*. 2023;16(9):e012805. doi:10.1161/CIRCINTERVENTIONS.122.012805
26. Chaturvedi S. Transcarotid artery revascularization for stroke prevention-multiple elephants in the room. *JAMA Neurol*. 2023;80(5):435-436. doi:10.1001/jamaneurol.2023.0293
27. Howard DP, Gaziano L, Rothwell PM.; Oxford Vascular Study. Risk of stroke in relation to degree of asymptomatic carotid stenosis: a population-based cohort study, systematic review, and meta-analysis. *Lancet Neurol*. 2021;20(3):193-202. doi:10.1016/S1474-4422(20)30484-1