A systematic review and meta-analysis of complication rates following carotid procedures performed by different specialties

Short title Specialty and outcomes following carotid revascularization

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ARTICLE HIGHLIGHTS

Type of Research: Systematic review and meta-analysis

Key Findings: In pooled analysis of unadjusted risk estimates, vascular surgeons had lower procedural complications compared to neurosurgeons and general surgeons after CEA. Neurosurgeons had higher procedural complications compared to cardiothoracic surgeons. For CAS, no differences in procedural outcomes were found by operator specialty.

Take home Message: Studies were at high risk of bias mainly due to potential confounding by patient selection for CEA and CAS. Current evidence is insufficient to restrict CEA or CAS to specific specialties.

Table of Contents Summary

This systematic review and meta-analysis analyzed procedural outcomes after carotid endarterectomy and carotid artery stenting performed by different specialties. There is insufficient evidence that CEA or CAS should be restricted to specific specialties.

Abstract

Objective

Different competencies and skills are required and obtained during medical specialization. However, whether or not these impact on procedural outcomes of carotid endarterectomy (CEA) or carotid artery stenting (CAS) is unclear. We assessed the reported association between operator specialization and procedural outcomes following CEA or CAS to determine whether CEA and CAS should be performed by specific specialties.

Methods

We systematically searched PubMed and EMBASE up to 21 August, 2017 for randomized clinical trials and observational studies that compared two or more specialties performing CEA or CAS for symptomatic and asymptomatic carotid artery stenosis. The composite primary outcome was procedural stroke or death (i.e., occurring within 30-days of the procedure or prior to discharge). Risk estimates were pooled with a generic inverse variance random effects model.

Results

A total of 35 studies (26 providing data on CEA; 8 on CAS; one both CEA and CAS) were included, describing 256,033 CEA and 38,605 CAS procedures. For CEA, decreased risk of procedural death or stroke for operations performed by vascular surgeons compared to neurosurgeons was found with pooled unadjusted relative risk (RR) of 0.63 (95% CI 0.46 to 0.86; 7 studies) and RR of 0.81 (95% CI 0.66 to 0.99; 6 studies) when compared to general surgeons. An increased risk of procedural death or stroke for operations performed by neurosurgeons compared to cardiothoracic surgeons was found with a pooled unadjusted RR of 1.22 (95% CI 1.02-1.46). No studies adjusted for potential confounding and no significant unadjusted associations were found in other comparisons of operator specialty for the primary outcome. For CAS, no differences in procedural outcomes were found by operator specialty.

Conclusions

Studies were at high risk of bias mainly due to potential confounding by patient selection for CEA and CAS. Current evidence is insufficient to restrict CEA or CAS to specific specialties.

Registration

This systematic review was registered (PROSPERO CRD42017071959).

Keywords

carotid endarterectomy – carotid artery stenting – specialty – carotid revascularization – quality of care – atherosclerosis - carotid stenosis

Conflicts of interest

MHF: None

ECB: None

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Introduction

Carotid endarterectomy (CEA) and carotid artery stenting (CAS) are commonly performed vascular procedures and a low procedural death and stroke rate is necessary to achieve long-term clinical benefit, because both procedures are performed as prophylaxis for future stroke.[1] Patient characteristics, such as age, smoking, coronary heart disease, chronic renal insufficiency, diabetes, type of preprocedural neurologic symptom, and contralateral carotid stenosis, are known to influence outcome after carotid revascularization.[2-6] Procedural characteristics that influence outcome are timing of intervention after the neurologic event[7, 8] and patch-use.[9] Type of anesthesia,[10, 11] shunt use during CEA,[12] and use of cerebral protection devices during CAS have not been shown to influence procedural outcomes.[13]

Operator characteristics have recently received more attention,[14] resulting in volume thresholds,[15-19] and which have driven reconfiguration of vascular centers with the creation of high-volume 'hubs'.[20]

Operator specialty has been proposed to influence patient outcomes after vascular procedures,[21] and may be particularly important for CEA and CAS, since these procedures are traditionally performed by a large variety of specialties with different training backgrounds.[22] However, reports of a relationship between specialty and outcome after carotid revascularization vary between studies and have not systematically reviewed. Consequently, there is no consensus whether carotid revascularization should be performed by specific specialties.

We aimed to systematically review and pool risk estimates on the association between operator specialty and procedural outcome after carotid revascularization with CEA or CAS.

Materials and Methods

This systematic review and meta-analysis was conducted with a predefined protocol that has been registered prospectively in the international prospective registry for systematic reviews (PROSPERO): CRD42017071959. We followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) recommendations,[23] and our study adhered to the Meta-analysis of Observational Studies in Epidemiology (MOOSE) guidelines (Appendix I).[24]

Data sources and searches

We searched PubMed and EMBASE on August 21, 2017 for studies describing (subgroup analyses of) randomized clinical trials (RCTs) and observational studies (Appendix II).

Eligibility criteria

Inclusion criteria: 1) full-text articles published in peer-reviewed journals; 2) written in English, French, German, Spanish, or Dutch; 3) presenting original data on patients undergoing either CEA or CAS for asymptomatic or symptomatic carotid stenosis; 4) comparing two or more operator specialties; 5) presenting effect estimates or providing raw data with which effect estimates could be calculated.

Study selection

Two authors (MHFP and ECB) independently screened all titles and abstracts for eligibility and subsequently assessed full-text copies for final inclusion in this study. Reasons for exclusion after full-text evaluation were recorded. Reference lists of included articles and identified reviews were crosschecked for further relevant studies. In case of disagreement, discrepancies were resolved between three authors (MHFP, ECB and GJdB).

Data extraction

The following study characteristics were extracted from the included studies by two authors (MP and EB) independently: 1) Methods: study design, design of data-collection, data source, setting study, number of study centers, number of operators, geographic area (country and continent) of study, study years, and sample size (patients/procedures); 2) Patient characteristics: A) Baseline characteristics: sex, age, cardiovascular risk factors (adhering to the definitions of the individual studies); B) Disease characteristics: symptomatic or asymptomatic status, degree of stenosis, duration of hospital stay; 3) Determinant: different specialty groups; 4) Outcome: definition of the outcome as used by the authors, specification of the timeframe of outcome measurement (e.g. 30-days or in-hospital), number of surgeons per specialty, number of patients/procedures per specialty, number of events per specialty, unadjusted relative risks (RRs) or odds ratios (ORs), adjusted RRs, ORs or hazard ratios (HRs) with corresponding 95%-confidence intervals (CI), and the adjustment factors where applicable.

Outcome measures

Primary

The primary outcome was procedural stroke or death, either in-hospital or 30-days (using authors' description of outcome).

A composite endpoint has the potential disadvantage of opposite directions of the risks of its constituents. For example, a higher risk of death and a lower risk of stroke within the same comparison. However, these two clinically relevant procedural outcomes are often reported together.

Secondary

The secondary outcomes were procedural: 1) death; 2) stroke; 3) MI; 4) combined death, stroke or MI; 5) postoperative cranial nerve deficit after CEA.

Quality assessment

Two authors (MHFP and ECB) independently used an adapted version of the Newcastle-Ottawa Scale to assess: patient selection (representativeness of study cohort and ascertainment of intervention), comparability of case-mix between specialties, and assessment of outcome and addressing of incomplete data. An overview of criteria to assign high or low risk of bias can be found in the PROSPERO protocol.

Statistical analyses

We obtained RRs, ORs and HRs with 95%-CI or we calculated RRs (using number of patients per event or the number of procedures if the number of patients was not provided). If no events occurred, we added 0.5 to the events and procedures of specialties to estimate an unadjusted RR.[25] We only used the relative risks and did not use the absolute risks per specialty in the statistical analysis, since the absolute risks might change between settings, cohorts and over time and should therefore not be compared directly.

We used the definitions of the operator specialty as provided by the original articles and compared different specialties in the following order, for CEA: vascular surgeons, neurosurgeons, general surgeons, cardiothoracic surgeons; and for CAS: cardiologists, radiologists, vascular surgeons, neurosurgeons. Cardiovascular surgeons, cardiothoracic surgeons, cardiac surgeons and thoracic surgeons were considered cardiothoracic surgeons. Interventional cardiologists were considered cardiologists. Interventional radiologists, neuroradiologists and interventional neuroradiologists were considered radiologists.

We pooled risk estimates with a random effects model to account for heterogeneity between studies. Study weights were based on the generic inverse variance method. We included only the largest study in the meta-analysis if studies described (partly) overlapping data for a specific outcome. We performed separate analyses for: 1) CEA and CAS; 2) RRs, ORs, and HRs; 3) unadjusted and adjusted risk estimates. R version 3.1.3 was used for all analyses.[26]

Heterogeneity

Heterogeneity across studies was assessed with the Cochran's Q test, I^2-statistic and prediction intervals.[27, 28] Prediction intervals were calculated if ≥3 studies were included in a meta-analysis. Prediction intervals should be interpreted as follows: there is a 95% chance that a risk estimate of a subsequent study with comparable characteristics will fall within the limits of the prediction interval. Wide prediction intervals indicate more heterogeneity than narrow prediction intervals. Heterogeneity was considered minor if I^2 <50%, Cochran's Q p>0.05, and narrow prediction intervals were found. Otherwise, the heterogeneity was considered substantial.

Publication bias

Risk of publication or reporting bias was assessed with funnel plots. Symmetric funnel plots indicate low evidence for publication or reporting bias. Potential asymmetry was assessed visually and tested by Egger's regression.[29] A p-value of <0.05 indicates asymmetry.[22] Funnel plots were constructed if ≥10 studies were included in a meta-analysis.[22]

Sensitivity analyses

Sensitivity analyses for the primary outcome were performed with studies: 1) reporting ≥80% symptomatic patients or stratified risk estimates by symptomatic patients; 2) reporting ≥80% asymptomatic patients or stratified risk estimates by asymptomatic patients; 3) based on clinical data and data from registries; 4) of high quality. High quality was assigned to studies with prospective data-collection, no patient selection, and case-mix adjustment.

Results

After screening 7,021 publications, 35 eligible studies were identified (Figure I).[5, 17, 18, 30-61] Twenty-six studies reported CEA data, eight CAS data, and one both. In total, 256,033 CEA and 38,605 CAS procedures were described. Three studies were based on data from one RCT[17, 18, 59] and 32 studies were observational studies. All studies described procedures performed in North America (Table I).

The number of patients per specialty is provided in Table II. The number of events and patients per outcome is provided in Table III.

Risk of bias assessment

Most studies applied no selection of patients based on risk factors that could have potentially affected outcomes when enrolling in the study. Few studies adjusted for patient variables in their analyses of the association between operator specialty and procedural outcomes, and seven studies adjusted for surgeon and/or hospital variables. Potential confounding due to the selection of patients by specialty could have affected the observed outcomes. Outcomes were almost never assessed blindly. Missing data in ≥20% of the patients was very uncommon. We found no study of high quality reporting on the primary outcome. (Supplemental Table I)

Operator specialty and outcome after CEA

Unadjusted analyses showed a significantly decreased risk of procedural stroke or death for vascular surgeons compared to neurosurgeons (RR 0.63 (95% CI 0.46-0.86); 7 studies) and compared to general surgeons (RR 0.81 (95% CI 0.66-0.99); 6 studies). An increased risk of procedural stroke or death was found for neurosurgeons compared to cardiothoracic surgeons (RR 1.22 (95% CI 1.02-1.46); 4 studies) (Table IV).

Unadjusted analyses showed a decreased risk of procedural death for vascular surgeons compared to general surgeons (RR 0.70 (95% CI 0.58-0.85); 11 studies), and an increased risk of procedural death was found for neurosurgeons compared to general surgeons (RR 1.50 (95% CI 1.04-2.15); 9 studies), compared to cardiothoracic surgeons (RR 1.80 (95% CI 1.16-2.79); 7 studies (Supplemental Table II).

Unadjusted analyses showed a decreased risk of procedural stroke for vascular surgeons compared to neurosurgeons (RR 0.57 (95% CI 0.46-0.72); 11 studies), to general surgeons (RR 0.69 (95% CI 0.60-0.79); 10 studies) and to cardiothoracic surgeons (RR 0.70 (95 CI 0.58-0.86); 8 studies). The risk of procedural stroke for vascular surgeons compared to general surgeons remained significant in the meta-analysis of adjusted risk estimates (RR 0.70 (95% CI 0.58-0.83); 5 studies) (Supplemental Table II).

The (pooled) estimates for the outcomes procedural MI, procedural death, stroke or MI combined, and cranial nerve deficit are provided in Supplemental Table II. Heterogeneity was minor in most pooled analyses.

Operator specialty and outcome after CAS

We found no associations between operator specialty and procedural stroke or death (Table V), or death and stroke separately (Supplemental Table III).

The (pooled) estimates for the outcomes procedural MI, and procedural death, stroke or MI combined are provided in Supplemental Table III. No substantial heterogeneity was found in the meta-analyses.

Publication bias

None of the four constructed funnel plots showed statistical evidence for asymmetry indicating that there is no statistical evidence for publication bias (Figure 2).

Sensitivity analyses

Two studies reported on the primary outcome by symptomatic status,[31, 32] five studies were based on clinical data[31, 32, 36, 37, 45] and three studies used administrative data.[40, 42, 46] In these sensitivity analyses, the associations between operator specialty and the primary outcome were comparable to the main analyses with regard to magnitude and direction of the association. (Supplemental Table IV). No studies of high quality reported on the primary outcome.

Discussion

Our study showed that vascular surgeons had a lower unadjusted risk of stroke and death after CEA compared to neurosurgeons and general surgeons. Neurosurgeons had a higher unadjusted risk of stroke and death after CEA compared to cardiothoracic surgeons. Studies did not adjust for selection of patients for CEA by speciality. We found no associations for procedural outcomes after CAS.

Several explanations have been suggested for the relationship between operator specialty and procedural outcomes that might explain why we found that vascular surgeons had a lower procedural risk after CEA compared to neurosurgeons and general surgeons: the effect of higher volume for more specialized surgeons, different patient selection, and experience of the healthcare team.[62] These and other possible confounding factors were, however, not addressed in the included studies.

In a recent study, operator specialization has been associated with a lower risk of death after CEA.[63] However, the approach of this study was criticized because operator specialization was defined as the percentage CEAs of all procedures performed by an operator, but did not account for the absolute number of CEAs performed. As a result, a surgeon with a lower number of CEAs could be considered more specialized than a surgeon with a higher number of CEAs. Specialization should instead be understood as the relative number of CEAs supplemented by the total number of CEAs, since operator volume and learning curve have been shown to be associated with lower procedural risks.[14]

In the Carotid Revascularization Endarterectomy versus Stenting Trial (CREST), CEA and CAS performed by vascular surgeons were compared. A lower risk of periprocedural stroke was found after CEA and a lower risk of periprocedural MI after CAS, but no significant difference was found for the composite periprocedural outcome of stroke, MI, or death.[59]

Our literature search was extensive and we used predefined selection criteria for inclusion. We report the first systematic review and meta-analysis that quantified the association between operator specialty and procedural outcomes for CEA and CAS by pooling risk estimates from different studies. The current literature has several limitations. First, the definition of operator specialty differed between studies, ranging from practice designations, training level of operators, and self-reporting of specialty. Furthermore, specialty training can differ between programs among countries and the training of surgeons developed separately over the years. However, we decided not to restrict our search to more recent articles with lower procedural risks, as a consequence of improved medical therapy, because we did not use absolute numbers but risk ratios. This seems justified since we found no evidence for differential improvement over time across specialties. Second, operator or hospital experience and the 'learning curve' are not included as determined in this study. Also, patient and disease characteristics that are known to influence outcome after carotid revascularization, such as symptomatic status, were not used as adjustment factors in most included studies and the published data did not allow for stratification of these characteristics. The same holds for operator-specific characteristics that have been found to be associated with mortality for surgery in general, for example age and sex of the operator.[64, 65] Third, assessment of the outcome measures was not standardized between studies and often not performed, or reported to be performed, by an (independent) neurologist in case of procedural stroke. Fourth, some studies used administrative databases that might be of inferior reporting quality and most studies used retrospective data-collection. Fifth, we tried to exclude overlapping datasets from meta-analyses to prevent double counting of patients, but some meta-analyses could potentially still have included overlapping patient groups. Sixth, generalizability of our findings might be limited since only studies from North America were available. Finally, we may have missed publications in which operator specialty was assessed but buried in a few words within the body of the text.

In future research, prospective, long-term evaluations of operator experience, including any learning-curve, operator and hospital volumes are needed. In addition, identification of specialty-specific skills and competencies which may reduce the risk of adverse procedural outcomes need to be explored.

In conclusion, vascular surgeons showed a lower unadjusted risk of stroke and death after CEA compared to neurosurgeons and general surgeons. Neurosurgeons showed a higher unadjusted risk of stroke and death after CEA compared to cardiothoracic surgeons. No associations between specialty and procedural outcomes after CAS were found. There is insufficient evidence that CEA or CAS should be performed by specific specialties, since most studies did not adjust for case-mix differences and were therefore at high risk of bias mainly due to confounding by indication.

Author contributions

MHFP, ECB, GJdB conceived the original idea for the study. All authors were involved in acquisition, analysis, or interpretation of data. MHFP and ECB performed the statistical analysis. The manuscript was drafted by MHFP, ECB, and GJdB with input from all co-authors. Critical revision of the manuscript for important intellectual content was done by all authors. Study supervision was done by GJdB. GJdB is guarantor for this article.

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A systematic review and meta-analysis of complication rates following carotid procedures performed by different specialties

Short title Specialty and outcomes following carotid revascularization

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ARTICLE HIGHLIGHTS

Type of Research: Systematic review and meta-analysis

Key Findings: In pooled analysis of unadjusted risk estimates, vascular surgeons had lower procedural complications compared to neurosurgeons and general surgeons after CEA. Neurosurgeons had higher procedural complications compared to cardiothoracic surgeons. For CAS, no differences in procedural outcomes were found by operator specialty.

Take home Message: Studies were at high risk of bias mainly due to potential confounding by patient selection for CEA and CAS. Current evidence is insufficient to restrict CEA or CAS to specific specialties.

Table of Contents Summary

This systematic review and meta-analysis analyzed procedural outcomes after carotid endarterectomy and carotid artery stenting performed by different specialties. There is insufficient evidence that CEA or CAS should be restricted to specific specialties.

Abstract

Objective

Different competencies and skills are required and obtained during medical specialization. However, whether or not these impact on procedural outcomes of carotid endarterectomy (CEA) or carotid artery stenting (CAS) is unclear. We assessed the reported association between operator specialization and procedural outcomes following CEA or CAS to determine whether CEA and CAS should be performed by specific specialties.

Methods

We systematically searched PubMed and EMBASE up to 21 August, 2017 for randomized clinical trials and observational studies that compared two or more specialties performing CEA or CAS for symptomatic and asymptomatic carotid artery stenosis. The composite primary outcome was procedural stroke or death (i.e., occurring within 30-days of the procedure or prior to discharge). Risk estimates were pooled with a generic inverse variance random effects model.

Results

A total of 35 studies (26 providing data on CEA; 8 on CAS; one both CEA and CAS) were included, describing 256,033 CEA and 38,605 CAS procedures. For CEA, decreased risk of procedural death or stroke for operations performed by vascular surgeons compared to neurosurgeons was found with pooled unadjusted relative risk (RR) of 0.63 (95% CI 0.46 to 0.86; 7 studies) and RR of 0.81 (95% CI 0.66 to 0.99; 6 studies) when compared to general surgeons. An increased risk of procedural death or stroke for operations performed by neurosurgeons compared to cardiothoracic surgeons was found with a pooled unadjusted RR of 1.22 (95% CI 1.02-1.46). No studies adjusted for potential confounding and no significant

unadjusted associations were found in other comparisons of operator specialty for the primary outcome. For CAS, no differences in procedural outcomes were found by operator specialty.

Conclusions

Studies were at high risk of bias mainly due to potential confounding by patient selection for CEA and CAS. Current evidence is insufficient to restrict CEA or CAS to specific specialties.

Registration

This systematic review was registered (PROSPERO CRD42017071959).

Keywords

carotid endarterectomy – carotid artery stenting – specialty – carotid revascularization – quality of care – atherosclerosis - carotid stenosis

Conflicts of interest

MHF: None

ECB: None

AH: None

RB: None

MB: None

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Introduction

Carotid endarterectomy (CEA) and carotid artery stenting (CAS) are commonly performed vascular procedures and a low procedural death and stroke rate is necessary to achieve long-term clinical benefit, because both procedures are performed as prophylaxis for future stroke.[1] Patient characteristics, such as age, smoking, coronary heart disease, chronic renal insufficiency, diabetes, type of preprocedural neurologic symptom, and contralateral carotid stenosis, are known to influence outcome after carotid revascularization.[2-6] Procedural characteristics that influence outcome are timing of intervention after the neurologic event[7, 8] and patch-use.[9] Type of anesthesia,[10, 11] shunt use during CEA,[12] and use of cerebral protection devices during CAS have not been shown to influence procedural outcomes.[13]

Operator characteristics have recently received more attention,[14] resulting in volume thresholds,[15-19] and which have driven reconfiguration of vascular centers with the creation of high-volume 'hubs'.[20]

Operator specialty has been proposed to influence patient outcomes after vascular procedures,[21] and may be particularly important for CEA and CAS, since these procedures are traditionally performed by a large variety of specialties with different training backgrounds.[22] However, reports of a relationship between specialty and outcome after carotid revascularization vary between studies and have not systematically reviewed. Consequently, there is no consensus whether carotid revascularization should be performed by specific specialties.

We aimed to systematically review and pool risk estimates on the association between operator specialty and procedural outcome after carotid revascularization with CEA or CAS.

Materials and Methods

This systematic review and meta-analysis was conducted with a predefined protocol that has been registered prospectively in the international prospective registry for systematic reviews (PROSPERO): CRD42017071959. We followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) recommendations,[23] and our study adhered to the Meta-analysis of Observational Studies in Epidemiology (MOOSE) guidelines (Appendix I).[24]

Data sources and searches

We searched PubMed and EMBASE on August 21, 2017 for studies describing (subgroup analyses of) randomized clinical trials (RCTs) and observational studies (Appendix II).

Eligibility criteria

Inclusion criteria: 1) full-text articles published in peer-reviewed journals; 2) written in English, French, German, Spanish, or Dutch; 3) presenting original data on patients undergoing either CEA or CAS for asymptomatic or symptomatic carotid stenosis; 4) comparing two or more operator specialties; 5) presenting effect estimates or providing raw data with which effect estimates could be calculated.

Study selection

Two authors (MHFP and ECB) independently screened all titles and abstracts for eligibility and subsequently assessed full-text copies for final inclusion in this study. Reasons for exclusion after full-text evaluation were recorded~~(Data available upon request)~~. Reference lists of included articles and identified reviews were crosschecked for further relevant studies. In case of disagreement, discrepancies were resolved between three authors (MHFP, ECB and GJdB).

Data extraction

The following study characteristics were extracted from the included studies by two authors (MP and EB) independently: 1) Methods: study design, design of data-collection, data source, setting study, number of study centers, number of operators, geographic area (country and continent) of study, study years, and sample size (patients/procedures); 2) Patient characteristics: A) Baseline characteristics: sex, age, cardiovascular risk factors (adhering to the definitions of the individual studies); B) Disease characteristics: symptomatic or asymptomatic status, degree of stenosis, duration of hospital stay; 3) Determinant: different specialty groups; 4) Outcome: definition of the outcome as used by the authors, specification of the timeframe of outcome measurement (e.g. 30-days or in-hospital), number of surgeons per specialty, number of patients/procedures per specialty, number of events per specialty, unadjusted relative risks (RRs) or odds ratios (ORs), adjusted RRs, ORs or hazard ratios (HRs) with corresponding 95%-confidence intervals (CI), and the adjustment factors where applicable.

Outcome measures

Primary

The primary outcome was procedural stroke or death, either in-hospital or 30-days (using authors’ description of outcome).

A composite endpoint has the potential disadvantage of opposite directions of the risks of its constituents. For example, a higher risk of death and a lower risk of stroke within the same comparison. However, these two clinically relevant procedural outcomes are often reported together.

Secondary

The secondary outcomes were procedural: 1) death; 2) stroke; 3) MI; 4) combined death, stroke or MI; 5) postoperative cranial nerve deficit after CEA.

Quality assessment

Two authors (MHFP and ECB) independently used an adapted version of the Newcastle-Ottawa Scale to assess: patient selection (representativeness of study cohort and ascertainment of intervention), comparability of case-mix between specialties, and assessment of outcome and addressing of incomplete data. An overview of criteria to assign high or low risk of bias can be found in the PROSPERO protocol.

Statistical analyses

We obtained RRs, ORs and HRs with 95%-CI or we calculated RRs (using number of patients per event or the number of procedures if the number of patients was not provided). If no events occurred, we added 0.5 to the events and procedures of specialties to estimate an unadjusted RR.[25] We only used the relative risks and did not use the absolute risks per specialty in the statistical analysis, since the absolute risks might change between settings, cohorts and over time and should therefore not be compared directly.

We used the definitions of the operator specialty as provided by the original articles and compared different specialties in the following order, for CEA: vascular surgeons, neurosurgeons, general surgeons, cardiothoracic surgeons; and for CAS: cardiologists, radiologists, vascular surgeons, neurosurgeons. Cardiovascular surgeons, cardiothoracic surgeons, cardiac surgeons and thoracic surgeons were considered cardiothoracic surgeons. Interventional cardiologists were considered cardiologists. Interventional radiologists, neuroradiologists and interventional neuroradiologists were considered radiologists.

We pooled risk estimates with a random effects model to account for heterogeneity between studies. Study weights were based on the generic inverse variance method. We included only the largest study in the meta-analysis if studies described (partly) overlapping data for a specific outcome. We performed separate analyses for: 1) CEA and CAS; 2) RRs, ORs, and HRs; 3) unadjusted and adjusted risk estimates. R version 3.1.3 was used for all analyses.[26]

Heterogeneity

Heterogeneity across studies was assessed with the Cochran's Q test, I^2-statistic and prediction intervals.[27, 28] Prediction intervals were calculated if ≥3 studies were included in a meta-analysis. Prediction intervals should be interpreted as follows: there is a 95% chance that a risk estimate of a subsequent study with comparable characteristics will fall within the limits of the prediction interval. Wide prediction intervals indicate more heterogeneity than narrow prediction intervals. Heterogeneity was considered minor if $I^2 < 50\%$, Cochran's Q $p > 0.05$, and narrow prediction intervals were found. Otherwise, the heterogeneity was considered substantial.

Publication bias

Risk of publication or reporting bias was assessed with funnel plots. Symmetric funnel plots indicate low evidence for publication or reporting bias. Potential asymmetry was assessed visually and tested by Egger's regression.[29] A p-value of <0.05 indicates asymmetry.[22] Funnel plots were constructed if ≥10 studies were included in a meta-analysis.[22]

Sensitivity analyses

Sensitivity analyses for the primary outcome were performed with studies: 1) reporting ≥80% symptomatic patients or stratified risk estimates by symptomatic patients; 2) reporting ≥80% asymptomatic patients or stratified risk estimates by asymptomatic patients; 3) based on clinical data and data from registries; 4) of high quality. High quality was assigned to studies with prospective data-collection, no patient selection, and case-mix adjustment.

Results

After screening 7,021 publications, 35 eligible studies were identified (Figure I).[5, 17, 18, 30-61] Twenty-six studies reported CEA data, eight CAS data, and one both. In total, 256,033 CEA and 38,605 CAS procedures were described. Three studies were based on data from one RCT[17, 18, 59] and 32 studies were observational studies. All studies described procedures performed in North America (Table I).

The number of patients per specialty is provided in Table II. The number of events and patients per outcome is provided in Table III.

Risk of bias assessment

Most studies applied no selection of patients based on risk factors that could have potentially affected outcomes when enrolling in the study. Few studies adjusted for patient variables in their analyses of the association between operator specialty and procedural outcomes, and seven studies adjusted for surgeon and/or hospital variables. Potential confounding due to the selection of patients by specialty could have affected the observed outcomes. Outcomes were almost never assessed blindly. Missing data in ≥20% of the patients was very uncommon. We found no study of high quality reporting on the primary outcome. (Supplemental Table I)

Operator specialty and outcome after CEA

Unadjusted analyses showed a significantly decreased risk of procedural stroke or death for vascular surgeons compared to neurosurgeons (RR 0.63 (95% CI 0.46-0.86); 7 studies) and compared to general surgeons (RR 0.81 (95% CI 0.66-0.99); 6 studies). An increased risk of procedural stroke or death was found for neurosurgeons compared to cardiothoracic surgeons (RR 1.22 (95% CI 1.02-1.46); 4 studies) (Table IV).

Unadjusted analyses showed a decreased risk of procedural death for vascular surgeons compared to general surgeons (RR 0.70 (95% CI 0.58-0.85); 11 studies), and an increased risk of procedural death was found for neurosurgeons compared to general surgeons (RR 1.50 (95% CI 1.04-2.15); 9 studies), compared to cardiothoracic surgeons (RR 1.80 (95% CI 1.16-2.79); 7 studies (Supplemental Table II).

Unadjusted analyses showed a decreased risk of procedural stroke for vascular surgeons compared to neurosurgeons (RR 0.57 (95% CI 0.46-0.72); 11 studies), to general surgeons (RR 0.69 (95% CI 0.60-0.79); 10 studies) and to cardiothoracic surgeons (RR 0.70 (95 CI 0.58-0.86); 8 studies). The risk of procedural stroke for vascular surgeons compared to general surgeons remained significant in the meta-analysis of adjusted risk estimates (RR 0.70 (95% CI 0.58-0.83); 5 studies) ~~(Data available upon request).~~ (Supplemental Table II).

The (pooled) estimates for the outcomes procedural MI, procedural death, stroke or MI combined, and cranial nerve deficit are provided in ~~are available upon request~~ Supplemental Table II. Heterogeneity was minor in most pooled analyses.

Operator specialty and outcome after CAS

We found no associations between operator specialty and procedural stroke or death (Table V), or death and stroke separately (~~data available upon request~~Supplemental Table III).

The (pooled) estimates for the outcomes procedural MI, and procedural death, stroke or MI combined are provided in ~~are available upon request~~ Supplemental Table III. No substantial heterogeneity was found in the meta-analyses.

Publication bias

None of the four constructed funnel plots showed statistical evidence for asymmetry indicating that there is no statistical evidence for publication bias (Figure 2).

Sensitivity analyses

Two studies reported on the primary outcome by symptomatic status,[31, 32] five studies were based on clinical data[31, 32, 36, 37, 45] and three studies used administrative data.[40, 42, 46] In these sensitivity analyses, the associations between operator specialty and the primary outcome were comparable to the main analyses with regard to magnitude and direction of the association. (Supplemental Table IV~~I~~). No studies of high quality reported on the primary outcome.

Discussion

Our study showed that vascular surgeons had a lower unadjusted risk of stroke and death after CEA compared to neurosurgeons and general surgeons. Neurosurgeons had a higher unadjusted risk of stroke and death after CEA compared to cardiothoracic surgeons. Studies did not adjust for selection of patients for CEA by speciality. We found no associations for procedural outcomes after CAS.

Several explanations have been suggested for the relationship between operator specialty and procedural outcomes that might explain why we found that vascular surgeons had a lower procedural risk after CEA compared to neurosurgeons and general surgeons: the effect of higher volume for more specialized surgeons, different patient selection, and experience of the healthcare team.[62] These and other possible confounding factors were, however, not addressed in the included studies.

In a recent study, operator specialization has been associated with a lower risk of death after CEA.[63] However, the approach of this study was criticized because operator specialization was defined as the percentage CEAs of all procedures performed by an operator, but did not account for the absolute number of CEAs performed. As a result, a surgeon with a lower number of CEAs could be considered more specialized than a surgeon with a higher number of CEAs. Specialization should instead be understood as the relative number of CEAs supplemented by the total number of CEAs, since operator volume and learning curve have been shown to be associated with lower procedural risks.[14]

In the Carotid Revascularization Endarterectomy versus Stenting Trial (CREST), CEA and CAS performed by vascular surgeons were compared. A lower risk of periprocedural stroke was found after CEA and a lower risk of periprocedural MI after CAS, but no significant difference was found for the composite periprocedural outcome of stroke, MI, or death.[59]

Our literature search was extensive and we used predefined selection criteria for inclusion. We report the first systematic review and meta-analysis that quantified the association between operator specialty and procedural outcomes for CEA and CAS by pooling risk estimates from different studies. The current literature has several limitations. First, the definition of operator specialty differed between studies, ranging from practice designations, training level of operators, and self-reporting of specialty. Furthermore, specialty training can differ between programs among countries and the training of surgeons developed separately over the years. However, we decided not to restrict our search to more recent articles with lower procedural risks, as a consequence of improved medical therapy, because we did not use absolute numbers but risk ratios. This seems justified since we found no evidence for differential improvement over time across specialties. Second, operator or hospital experience and the 'learning curve' are not included as determined in this study. Also, patient and disease characteristics that are known to influence outcome after carotid revascularization, such as symptomatic status, were not used as adjustment factors in most included studies and the published data did not allow for stratification of these characteristics. The same holds for operator-specific characteristics that have been found to be associated with mortality for surgery in general, for example age and sex of the operator.[64, 65] Third, assessment of the outcome measures was not standardized between studies and often not performed, or reported to be performed, by an (independent) neurologist in case of procedural stroke. Fourth, some studies used administrative databases that might be of inferior reporting quality and most studies used retrospective data-collection. Fifth, we tried to exclude overlapping datasets from meta-analyses to prevent double counting of patients, but some meta-analyses could potentially still have included overlapping patient groups. Sixth, generalizability of our findings might be limited since only studies from North America were available. Finally, we may have missed publications in which operator specialty was assessed but buried in a few words within the body of the text.

In future research, prospective, long-term evaluations of operator experience, including any learning-curve, operator and hospital volumes are needed. In addition, identification of specialty-specific skills and competencies which may reduce the risk of adverse procedural outcomes need to be explored.

In conclusion, vascular surgeons showed a lower unadjusted risk of stroke and death after CEA compared to neurosurgeons and general surgeons. Neurosurgeons showed a higher unadjusted risk of stroke and death after CEA compared to cardiothoracic surgeons. No associations between specialty and procedural outcomes after CAS were found. There is insufficient evidence that CEA or CAS should be performed by specific specialties, since most studies did not adjust for case-mix differences and were therefore at high risk of bias mainly due to confounding by indication.

Author contributions

MHFP, ECB, GJdB conceived the original idea for the study. All authors were involved in acquisition, analysis, or interpretation of data. MHFP and ECB performed the statistical analysis. The manuscript was drafted by MHFP, ECB, and GJdB with input from all co-authors. Critical revision of the manuscript for important intellectual content was done by all authors. Study supervision was done by GJdB. GJdB is guarantor for this article.

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Table I. Overview of study characteristics

	CEA (27 studies) No. of studies (%)	**CAS (9 studies)** No. of studies (%)
Study characteristics		
Study approach		
Cohort	26 (96.3%)	6 (66.7%)
Subgroup of RCT	1 (3.7%)	3 (33.3%)
Population-based	9 (33.3%)	2 (22.2%)
Multicenter	22 (81.5%)	8 (88.9%)
Data-collection		
Prospective	4 (14.8%)	6 (66.7%)
Retrospective	22 (81.5%)	3 (33.3%)
Unknown	1 (3.7%)	0
Data source		
Clinical	12 (44.4%)	5 (55.6%)
Administrative	15 (55.6%)	4 (44.4%)
Continent		
North-America	27 (100%)	9 (100%)
Number of operators		
≥100 operators	7 (25.9%)	6 (66.7%)
<100 operators	13 (48.1%)	0
Unknown	7 (25.9%)	3 (33.3%)
Patient characteristics		
Sex		
Reported	23 (85.2%)	7 (77.8%)
≥66% male	4 (17.4%)	1 (14.3%)
Age		
Reported	15 (55.6%)	8 (88.9%)
Mean or median ≥70 years	7 (46.7%)	4 (50.0%)
Disease characteristics		
Reported symptomatic status	18 (66.7%)	7 (77.7%)
≥50% symptomatic patients	8 (44.4%)	0 (NA)
Reported degree of stenosis	6 (22.2%)	2 (22.2%)
Reported duration of hospital stay	8 (29.6%)	3 (33.3%)

CAS, carotid stenting; *CEA*, carotid endarterectomy; *RCT*, randomized clinical trial

Table II. Overview of procedures per specialty

	CEA	CAS
	Procedures (%)	**Procedures (%)**
Vascular surgeons	129 282 (50.5)	2973 (7.7)
Neurosurgeons	12 388 (4.8)	170 (0.4)
General surgeons	45 083 (17.6)	N/A
Cardiothoracic surgeons	29 630 (11.6)	N/A
Cardiologists	N/A	9019 (23.4)
Radiologists	N/A	1952 (5.1)
Specialties combined[a]	39 650 (15.5)	24 491 (63.4)
Total	**256 033**	**38 605**

CAS, carotid artery stenting; *CEA*, carotid endarterectomy; *N/A*, not available.

[a] Different specialties were combined in one group for the analyses in the original studies.

Table III. Overview of number of events, patients, and studies per outcome

	CEA		CAS	
	Events / patients (%)	**No. of studies**	**Events / patients (%)**	**No. of studies**
Procedural outcomes				
Stroke or death	1749 / 45 135 (3.88%)	14	>175‡ / 11 143 (N/A)	4
Death	>1036* / 197 814 (N/A)	14	236 / 28 041 (0.84%)	3
Stroke	>1997† / 186 541 (N/A)	16	1029 / 28 666 (3.59%)	4
MI	1040 / 104 573 (0.99%)	6	463 / 24 665 (1.88%)	3
Death, stroke or MI	4558 / 96 345 (4.80%)	4	>253§ / 12 289 (N/A)	5
Cranial nerve deficit	124 / 43 840 (0.28%)	3	NA	NA

CAS, carotid artery stenting; *CEA*, carotid endarterectomy; *MI*, myocardial infarction; *NA*, not applicable; *N/A*, not available.
* The number of patients with procedural death after CEA was not provided in two studies. † The number of patients with procedural stroke after CEA was not provided in one study. ‡ The number of patients with procedural stroke after CAS was not provided in one study. § The number of patients with procedural death, stroke or myocardial infarction combined after CAS was not provided in one study.

Table IV. Pooled risk estimates for the relation between specialties and procedural stroke or death after CEA

Index specialty		Reference specialty	Unadjusted RR (95% CI)	No. of studies	Cochran's Q	I^2	Prediction interval[a]
Vascular surgeons	vs	Neurosurgeons	**0.63 (0.46-0.86)**	[7 studies][31, 36, 37, 40, 42, 45, 46]	df: 6; Q: 11.832; p=0.07	54.3%	0.27-1.48
	vs	General surgeons	**0.81 (0.66-0.99)**	[6 studies][31, 32, 37, 40, 42, 45]	df: 5; Q: 6.560; p=0.26	0.0%	0.61-1.07
	vs	Cardiothoracic surgeons	0.87 (0.63-1.19)	[5 studies][31, 32, 40, 42, 45]	df: 4; Q: 5.280; p=0.26	25.8%	0.39-1.94
Neurosurgeons	vs	General surgeons	1.53 (0.85-2.74)	[5 studies][31, 37, 40, 42, 45]	df: 4; Q: 11.682; p=0.02	63.2%	0.24-9.77
	vs	Cardiothoracic surgeons	**1.22 (1.02-1.46)**	[4 studies][31, 40, 42, 45]	df: 3; Q: 2.150; p=0.54	0.0%	0.82-1.81
General surgeons	vs	Cardiothoracic surgeons	1.16 (0.85-1.57)	[5 studies][31, 32, 40, 42, 45]	df: 4; Q: 3.660; p=0.45	12.5%	0.58-2.31

CI, confidence interval; *df*, degrees of freedom; *RR*, relative risk.

The risk estimates in a **bold font** are considered statistically significant. Data on risk estimates for comparisons with specialty groups combined or "other" specialties as reference category are provided in Supplemental Table II.

[a] Only estimated if ≥3 studies were included in the meta-analyses.

Table V. Risk estimates for the relation between operator specialty and procedural stroke or death after CAS

Index specialty		Reference specialty	Unadjusted RR (95% CI)	No. of studies
Cardiologists	vs	Radiologists	0.95 (0.47-1.90)	[1 study][41]
	vs	Vascular surgeons	0.81 (0.49-1.32)	[1 study][41]
	vs	Neurosurgeons	0.64 (0.16-2.56)	[1 study][41]
Radiologists	vs	Vascular surgeons	0.85 (0.39-1.82)	[1 study][41]
	vs	Neurosurgeons	0.68 (0.15-3.03)	[1 study][41]
Vascular surgeons	vs	Neurosurgeons	1.27 (0.30-5.26)	[1 study][41]

CI, confidence interval; RR relative risk.

Data on risk estimates for comparisons with specialty groups combined or "other" specialties as reference category are provided in Supplemental Table III.

Figure I. Flowchart

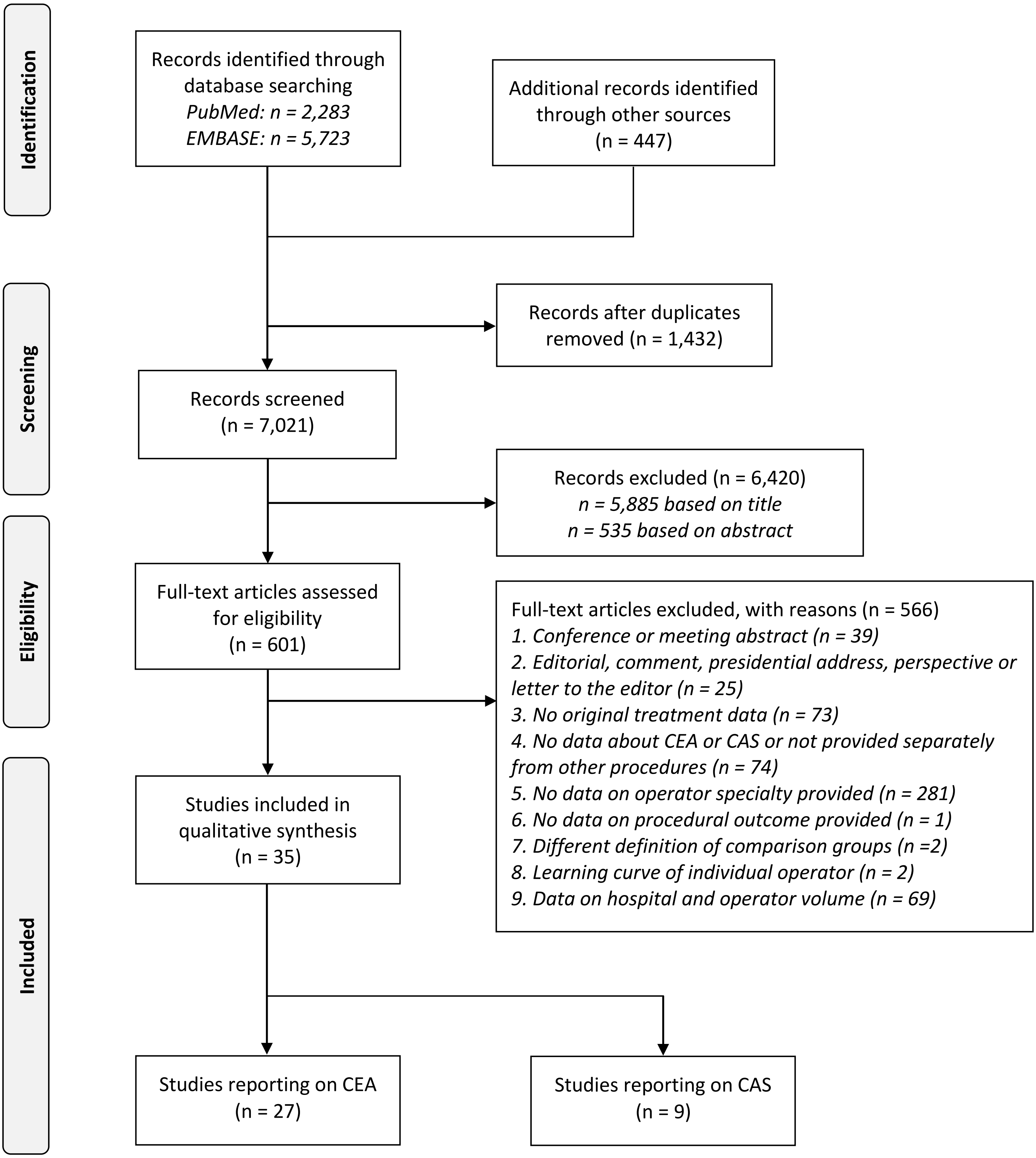

Figure II

Figure II. Publication bias.

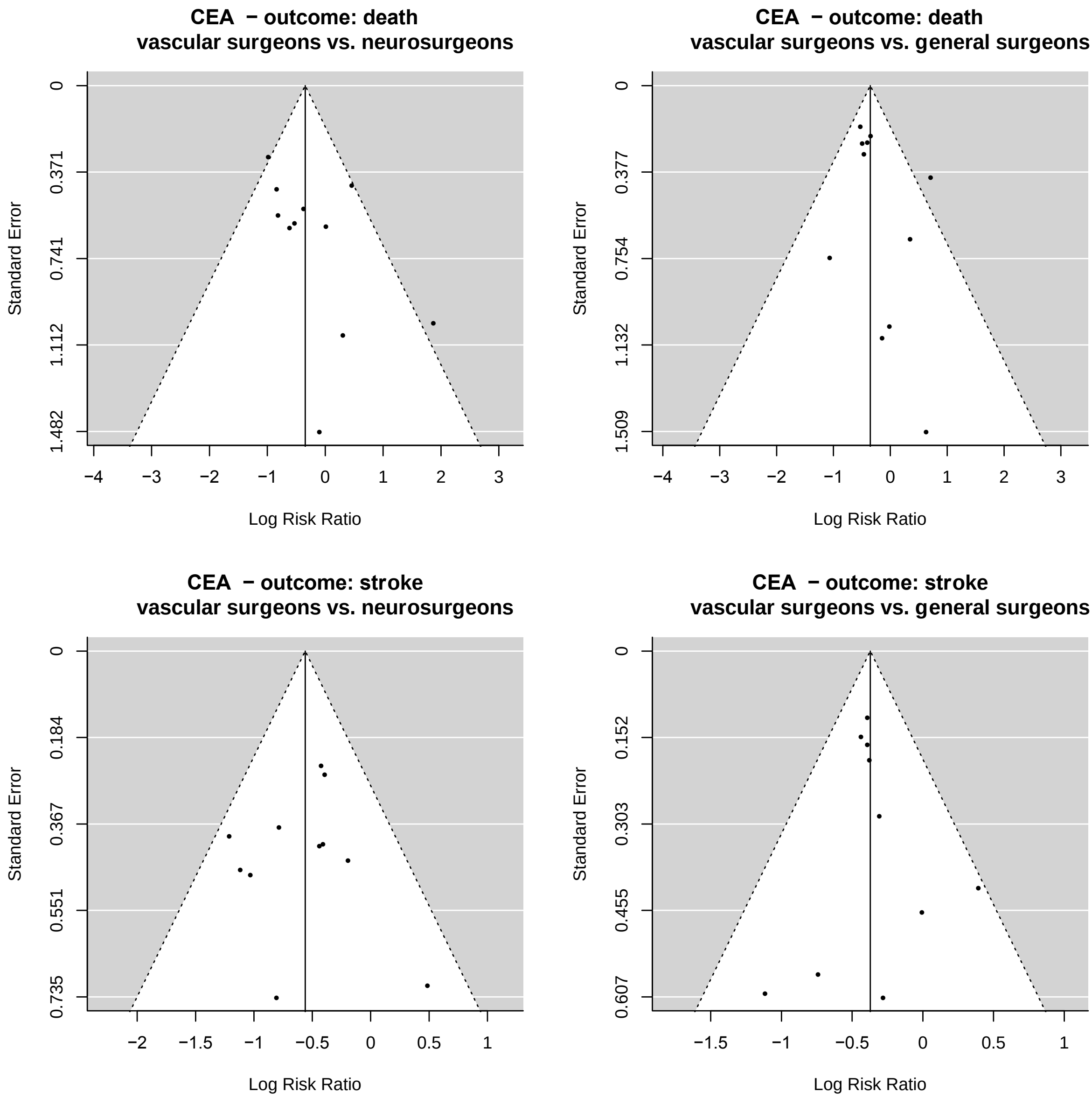

Figure I: Flowchart

Flowchart detailing the numbers of studies excluded and included at each step of the literature search.

Figure II: Publication bias

Funnel plots showing Egger's regression p-values. From left to right and top to bottom: p=0.081; p=0.179; p=0.709; p=0.706. An Egger's regression p-value <0.05 indicates potential publication bias.

Appendices

Table of contents

Appendix I. Checklists for reporting standards

PRISMA Checklist [1]

Section/topic	#	Checklist item	Reported
TITLE			
Title	1	Identification as a systematic review, meta-analysis, or both.	✓
ABSTRACT			
Structured summary	2	Structured abstract including background, objectives, data sources, study eligibility criteria, methodological assessment, synthesis method, results, conclusions and implications of key findings.	✓
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	✓
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, outcomes (PICO design).	✓
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, and where it can be accessed.	✓
Eligibility criteria	6	Specify study characteristics and report characteristics (such as years considered, language, publication status) used as criteria for eligibility.	✓
Information sources	7	Describe all information sources (such as databases with dates of coverage, contact with study authors, experts) in the search, and the date of last search.	✓
Search	8	Present full electronic search strategy, including limits used, such that it could be repeated.	✓
Study selection	9	State the process for selecting studies (i.e., screening, eligibility) and make sure that this is done by 2 authors.	✓
Data collection	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	✓
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	✓
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	✓
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	✓
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	✓
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	✓
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	✓

RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, illustrated with a flow diagram.	✓
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	✓
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment.	✓
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	✓
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	✓
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies.	✓
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression).	✓
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	✓
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	✓
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	✓
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	✓

MOOSE Checklist for Meta-analyses of Observational Studies [2]

Item No	Recommendation	Reported
Reporting of background should include		
1	Problem definition	✓
2	Hypothesis statement	✓
3	Description of study outcome(s)	✓
4	Type of exposure or intervention used	✓
5	Type of study designs used	✓
6	Study population	✓
Reporting of search strategy should include		
7	Qualifications of searchers (eg, librarians and investigators)	✓
8	Search strategy, including time period included in the synthesis and key words	✓
9	Effort to include all available studies, including contact with authors	✓
10	Databases and registries searched	✓
11	Search software used, name and version, including special features used (eg, explosion)	✓
12	Use of hand searching (eg, reference lists of obtained articles)	✓
13	List of citations located and those excluded, including justification	✓
14	Method of addressing articles published in languages other than English	✓
15	Method of handling abstracts and unpublished studies	✓
16	Description of any contact with authors	Not applicable
Reporting of methods should include		
17	Description of relevance or appropriateness of studies assembled for assessing the hypothesis to be tested	✓
18	Rationale for the selection and coding of data (eg, sound clinical principles or convenience)	✓
19	Documentation of how data were classified and coded (eg, multiple raters, blinding and interrater reliability)	✓, no inter-rater reliability has been calculated
20	Assessment of confounding (eg, comparability of cases and controls in studies where appropriate)	✓
21	Assessment of study quality, including blinding of quality assessors, stratification or regression on possible predictors of study results	✓
22	Assessment of heterogeneity	✓
23	Description of statistical methods (eg, complete description of fixed or random effects models, justification of whether the chosen models account for predictors of study results, dose-response models, or cumulative meta-analysis) in sufficient detail to be replicated	✓
24	Provision of appropriate tables and graphics	✓
Reporting of results should include		
25	Graphic summarizing individual study estimates and overall estimate	No graphs used
26	Table giving descriptive information for each study included	✓

27	Results of sensitivity testing (eg, subgroup analysis)	✓
28	Indication of statistical uncertainty of findings	✓
Reporting of discussion should include		
29	Quantitative assessment of bias (eg, publication bias)	✓
30	Justification for exclusion (eg, exclusion of non-English language citations)	✓
31	Assessment of quality of included studies	✓
Reporting of conclusions should include		
32	Consideration of alternative explanations for observed results	✓
33	Generalization of the conclusions (ie, appropriate for the data presented and within the domain of the literature review)	✓
34	Guidelines for future research	✓
35	Disclosure of funding source	✓

Appendix II. Search strategies

PubMed search

1. "Hospitals, Low-Volume"[Mesh] OR "Hospitals, High-Volume"[Mesh]
2. "Health Facility Size"[Mesh]
3. "Hospitals/statistics and numerical data"[Mesh]
4. Hospital[tiab] OR hospitals[tiab] OR "Health facility"[tiab] OR "health facilities"[tiab] OR Provider[tiab] OR providers[tiab]
5. Size[tiab] OR sizes[tiab] OR Volume[tiab] OR volumes[tiab] OR capacity [tiab] OR capacities[tiab] OR load[tiab] OR loads[tiab] OR loading[tiab]
6. #4 AND #5
7. #1 OR #2 OR #3 OR #6
8. Workload[Mesh] OR workload[tiab] OR workloads[tiab]
9. Caseload[tiab] OR caseloads[tiab]
10. Work[tiab] OR Case[tiab] OR cases[tiab] OR Patient[tiab] OR patients[tiab] OR operator[tiab] OR operators[tiab] OR physician[tiab] OR physicians[tiab] OR surgeon[tiab] OR surgeons[tiab] OR surgeon's[tiab] OR surgical[tiab] OR surgery[tiab] OR surgeries[tiab]
11. Load[tiab] OR loads[tiab] OR loading[tiab] OR Volume[tiab] OR volumes[tiab]
12. #10 AND #11
13. #8 OR #9 OR #12
14. "Specialties, Surgical"[Mesh]
15. Operator[tiab] OR operators[tiab] OR physician[tiab] OR physicians[tiab] OR Surgeon[tiab] OR surgeons[tiab] OR surgeon's[tiab] OR surgical[tiab] OR surgery[tiab] OR surgeries[tiab]
16. Specialty[tiab] OR specialties[tiab] OR Specialization[tiab] OR specializations[tiab] OR specializing [tiab] OR specialize[tiab] OR specializes[tiab] OR specialized[tiab] OR Specialisation[tiab] OR specialisations[tiab] OR specializing[tiab] OR specialise[tiab] OR specialises[tiab] OR specialised[tiab] OR Specialism[tiab] OR specialisms[tiab]
17. #15 AND #16
18. #14 OR #17
19. #7 OR #13 OR #18
20. "Endarterectomy, Carotid"[Mesh] OR "Endarterectomy"[Mesh] OR Endarterectomy[tiab] OR endarterectomies[tiab]
21. "Carotid Arteries"[Mesh] OR Carotid[tiab] OR Carotids[tiab] OR Carotis[tiab]
22. "Surgical Procedures, Operative"[Mesh] OR "Surgery"[Subheading] OR Surgery[tiab] OR Surgeries[tiab] OR Surgical[tiab] OR Operation[tiab] OR Operations[tiab] OR Operative[tiab] OR "Stents"[Mesh] OR Stent[tiab] OR Stents[tiab] OR Stenting[tiab] OR "Angioplasty"[Mesh] OR "Angioplasty, balloon"[Mesh] OR "Catheterization"[Mesh] OR Angioplasty[tiab] OR Angioplasties[tiab]
23. #21 AND #22
24. #20 OR #23
25. #19 AND #24

This search strategy was used for a project on quality of care in carotid revascularization.[3] For this reason, the search strategy also contains terms referring to volume.

EMBASE search

1. 'Low volume hospital'/exp
2. 'High volume hospital'/exp
3. 'Hospital bed capacity'/exp
4. 'Hospital'/de
5. Hospital:ab,ti OR hospitals:ab,ti OR 'Health facility':ab,ti OR 'health facilities':ab,ti OR Provider:ab,ti OR providers:ab,ti
6. Size:ab,ti OR sizes:ab,ti OR Volume:ab,ti OR volumes:ab,ti OR capacity:ab,ti OR capacities:ab,ti OR load:ab,ti OR loads:ab,ti OR loading:ab,ti
7. #5 AND #6
8. #1 OR #2 OR #3 OR #4 OR #7
9. 'Workload'/exp
10. Workload:ab,ti OR workloads:ab,ti
11. Caseload:ab,ti OR caseloads:ab,ti
12. Work:ab,ti OR case:ab,ti OR cases:ab,ti OR patient:ab,ti OR patients:ab,ti OR operator:ab,ti OR operators:ab,ti OR physician:ab,ti OR physicians:ab,ti OR surgeon:ab,ti OR surgeons:ab,ti OR 'surgeon/s':ab,ti OR surgical:ab,ti OR surgery:ab,ti OR surgeries:ab,ti
13. Load:ab,ti OR loads:ab,ti OR loading:ab,ti OR Volume:ab,ti OR volumes:ab,ti
14. #12 AND #13
15. #9 OR #10 OR #11 OR #14
16. 'Surgeon'/exp
17. 'Medical specialist'/exp
18. Operator:ab,ti OR operators:ab,ti OR physician:ab,ti OR physicians:ab,ti OR surgeon:ab,ti OR surgeons:ab,ti OR 'surgeon/s':ab,ti OR surgical:ab,ti OR surgery:ab,ti OR surgeries:ab,ti
19. Specialty:ab,ti OR specialties:ab,ti OR Specialization:ab,ti OR specializations:ab,ti OR specializing:ab,ti OR specialize:ab,ti OR specializes:ab,ti OR specialized:ab,ti OR Specialisation:ab,ti OR specialisations:ab,ti OR specialising:ab,ti OR specialise:ab,ti OR specialises:ab,ti OR specialised:ab,ti OR Specialism:ab,ti OR specialisms:ab,ti
20. #18 AND #19
21. #16 OR #17 OR #20
22. #8 OR #15 OR #21
23. 'Carotid artery surgery'/exp
24. 'Carotid artery stent'/exp
25. 'Cerebral revascularization'/exp
26. 'Endarterectomy'/exp OR Endarterectomy:ab,ti OR endarterectomies:ab,ti
27. 'Carotid artery'/exp OR Carotid:ab,ti OR carotids:ab,ti OR carotis:ab,ti
28. 'Surgery'/exp OR 'Stent'/exp OR Surgery:ab,ti OR surgeries:ab,ti OR surgical:ab,ti OR Operation:ab,ti OR operations:ab,ti OR operative:ab,ti OR Stent:ab,ti OR stents:ab,ti OR stenting:ab,ti OR Angioplasty:ab,ti OR angioplasties:ab,ti
29. #27 AND #28
30. #23 OR #24 OR #25 OR #26 OR #29
31. #22 AND #30

Supplemental Table I. Risk of bias summary

		Representativeness of study cohort	Ascertainment of intervention	Comparability of intervention and comparison group	Assessments of outcomes	Addressing incomplete data <20%	**Total**
1.	AbuRahma, 1988[4]	+	+	-	-	+	**3**
2.	AbuRahma, 2013[5]	+	+	-	-	+	**3**
3.	AbuRahma, 2014[6]	+	+	-	-	+	**3**
4.	AbuRahma, 2017[7]	+	+	+	-	+	**4**
5.	Asaph, 1991[8]	+	+	-	-	+	**3**
6.	Bennett, 2015[9]	+	-	-	-	+	**2**
7.	Brott, 1984[10]	+	+	-	-	+	**3**
8.	Cafferata, 1986[11]	+	+	-	-	+	**3**
9.	Cowan, 2002[12]	+	-	-	-	-	**1**
10.	Enomoto, 2014[13]	-	-	+	-	+	**2**
11.	Feasby, 2002[14]	-	-	+	-	+	**2**
12.	Gray, 2011[15]	-	+	-	-	+	**2**
13.	Halm, 2005[16]	+	-	-	-	+	**2**
14.	Hannan, 2001[17]	+	+	-	-	+	**3**
15.	Hobson, 2004[18]	+	+	-	-	+	**3**
16.	Hollenbeak, 2010[19]	+	-	-	-	+	**2**
17.	Hopkins, 2010[20]	+	+	+	-	+	**4**
18.	Kempczinski, 1986[21]	+	+	-	-	+	**3**
19.	Kucey, 1998[22]	+	-	-	-	+	**2**
20.	Lieber, 2017[23]	+	+	+	-	+	**4**
21.	Mattos, 1995[24]	-	+	-	-	+	**2**
22.	Meltzer, 2017[25]	+	-	+	-	+	**3**
23.	O'Neill, 2000[26]	+	-	-	-	+	**2**
24.	Pearce, 1999[27]	+	-	+	-	+	**3**
25.	Rigdon, 1998[28]	+	+	-	-	+	**3**
26.	Ruby, 1996[29]	+	-	-	-	+	**2**
27.	Sgroi, 2015[30]	+	-	+	-	+	**3**
28.	Shah, 2004[31]	+	-	-	-	?	**1**
29.	Shishehbor, 2014[32]	-	+	+	-	+	**3**
30.	Steppacher, 2009[33]	+	-	-	-	+	**2**
31.	Stoner, 2006[34]	+	-	-	-	+	**2**
32.	Teso, 2004[35]	+	-	+	-	+	**3**
33.	Timaran, 2013[36]	-	+	+	+	+	**4**
34.	Vogel, 2009[37]	+	-	-	-	+	**2**
35.	Wong, 1997[38]	+	+	-	-	+	**3**

- indicates high risk of bias; + indicates low risk of bias; ? indicates unclear risk of bias.

Supplemental Table II. Overview of risk estimates assessing operator specialization and CEA

Table A. Procedural outcomes after CEA (Adjusted risk estimates)

Outcomes	Index specialty	Reference specialty	Adjusted OR (95% CI)	No. of studies	Cochran's Q	I^2	Prediction interval[a]
Procedural death or stroke	*Vascular surgeons*	*Other specialties (not specified)*	***0.32 (0.14-0.72)***	*[1 study][36]*	-	-	-
Procedural death	Vascular surgeons	Neurosurgeons	0.59 (0.18-1.92)	[1 study][25 ,b]	-	-	-
		General surgeons	0.71 (0.44-1.18)	[1 study][25 ,b]	-	-	-
		Cardiothoracic surgeons	0.87 (0.34-2.17)	[1 study][25]	-	-	-
		General, neuro-, cardiothoracic surgeons	*2.04 (0.97-4.17)*	*[1 study][35]*	-	-	-
Procedural stroke	Vascular surgeons	Neurosurgeons	1.05 (0.59-1.84)	[3 study][23, 25, 35]	df: 2; Q: 0.339; p=0.84	0.0%	0.03-40.79
		General surgeons	**0.70 (0.58-0.83)**	[5 studies][5, 13, 23, 25, 35]	df: 4; Q: 1.720; p=0.79	0.0%	0.51-0.94
		Cardiothoracic surgeons	0.93 (0.59-1.45)	[4 studies][5, 23, 25, 35]	df: 3; Q: 2.949; p=0.40	0.0%	0.34-2.49
		General & Cardiothoracic surgeons	*0.50 (0.18-1.38)*	*[1 study][5]*	-	-	-
Procedural MI	Vascular surgeons	Neurosurgeons	**0.24 (0.11-0.53)**	[1 study][35]	-	-	-
		General surgeons	0.80 (0.07-9.65)	[2 studies][13, 35]	df: 1; Q: 18.162; p<0.005	94.5%	NA
		Cardiothoracic surgeons	**0.44 (0.23-0.85)**	[1 study][35]	-	-	-
Procedural death, stroke or MI	Vascular surgeons	General surgeons	0.80 (0.61-1.05)	[1 study][13]	-	-	-
		Not vascular certified	0.85 (0.77-0.94)	[1 study][27]	-	-	-
		Other specialties (not-specified)	*HR 0.73 (0.42-1.27)*	*[1 study][36]*	-	-	-

CI, confidence interval; *HR*, hazard ratio; *MI*, myocardial infarction; *NA*, not applicable; *OR*, odds ratio.
The risk estimate in a **bold** font is considered statistically significant. Combined groups of specializations or not clearly specified reference groups are in *italics*.
[a]Only estimated when ≥3 studies are within the meta-analyses. [b] The risk estimate of one study was omitted in this table, because the risk estimate did not fall within the confidence interval.

Table B. Procedural outcomes after CEA (Unadjusted risk estimates)

Outcomes	Index specialty	Reference specialty	*Unadjusted RR (95% CI)*	No. of studies	Cochran's Q	I^2	Prediction interval[a]
Procedural death or stroke	*Vascular surgeons*	*General & Cardiothoracic surgeons*	*0.42 (0.16-1.05)*	*[1 study][6]*	-	-	-
		Non-vascular surgeons	*0.86 (0.43-1.75)*	*[1 study][9]*	-	-	-
		Other specialties (not specified)	*0.88 (0.60-1.29)*	*[1 study][34]*	-	-	-
		Other specialties (not specified)	***0.31 (0.14-0.69)***	*[1 study][36]*	**-**	-	-
		General, neuro-, cardiothoracic surgeons	***0.47 (0.30-0.72)***	*[1 study][24]*	-	-	-
	Neurosurgeons	*Vascular & General surgeons*	*0.69 (0.24-1.98)*	*[1 study][38]*	**-**	-	-
Procedural death	Vascular surgeons	Neurosurgeons	0.71 (0.47-1.07)	[11 studies][4, 10-12, 17, 21-23, 25, 26, 35]	df: 10; Q: 15.391; p=0.12	34.4%	0.26-1.96
		General surgeons	**0.70 (0.58-0.85)**	[11 studies][4, 5, 11-13, 17, 21, 23, 25, 26, 35]	df: 10; Q: 11.192; p=0.34	0.0%	0.57-0.87
		Cardiothoracic surgeons	0.86 (0.66-1.13)	[8 studies][4, 5, 12, 21, 23, 25, 26, 35]	df: 7; Q: 5.230; p=0.63	0.0%	0.62-1.21
		General, neuro-, cardiothoracic surgeons	*1.55 (0.76-3.16)*	*[1 study][35]*	-	-	-
		General & Cardiothoracic surgeons	*1.69 (0.28-10.07)*	*[1 study][5]*	-	-	-
		Other specialties (not specified)	*0.88 (0.41-1.91)*	*[1 study][26]*	-	-	-
		Other specialties (not specified)	*0.95 (0.57-1.59)*	*[1 study][34]*	-	-	-
		Other specialties (not specified)	*1.04 (0.06-17.78)*	*[1 study][35]*	-	-	-
	Neurosurgeons	General surgeons	**1.50 (1.04-2.15)**	[9 studies][4, 11, 12, 17, 21, 23, 25, 26, 35]	df: 8; Q: 9.565; p=0.30	0.0%	0.97-2.32
		Cardiothoracic surgeons	**1.80 (1.16-2.79)**	[7 studies][4, 12, 21, 23, 25, 26, 35]	df: 6; Q: 8.815; p=0.18	2.97%	1.01-3.20
		Other specialties (not specified)	*0.13 (0.02-1.07)*	*[1 study][26]*	-	-	-

		Other specialties (not specified)	*1.42 (0.08-25.26)*	*[1 study][35]*	-	-	-
	General surgeons	Cardiothoracic surgeons	1.16 (0.90-1.50)	[8 studies][4, 5, 12, 21, 23, 25, 26, 35]	df: 7; Q: 3.77; p=0.81	0.0%	0.84-1.60
		Other specialties (not specified)	*1.38 (0.60-3.20)*	*[1 study][26]*	-	-	-
		Other specialties (not specified)	*0.45 (0.03-7.48)*	*[1 study][35]*	-	-	-
	Cardiovascular surgeons	Thoracic surgeons	1.03 (0.49-2.18)	[1 study][26]	-	-	-
		Other specialties (not specified)	*1.31 (0.58-2.96)*	*[1 study][26]*	-	-	-
	Cardiothoracic surgeons	*Other specialties (not specified)*	*0.62 (0.04-10.36)*	*[1 study][35]*	-	-	-
	Thoracic surgeons	*Other specialties (not specified)*	*1.27 (0.50-3.21)*	*[1 study][26]*	-	-	-
Procedural stroke	Vascular surgeons	Neurosurgeons	**0.57 (0.46-0.72)**	[11 studies] [4, 10-12, 16, 21-23, 25, 28, 35]	df: 10; Q: 9.464; p=0.49	0.0%	0.44-0.74
		General surgeons	**0.69 (0.60-0.79)**	[10 studies] [4, 5, 11-13, 16, 21, 23, 25, 35]	df: 9; Q: 6.303; p=0.71	0.0%	0.59-0.81
		Cardiothoracic surgeons	**0.70 (0.58-0.86)**	[8 studies] [4, 5, 12, 16, 21, 23, 25, 35]	df: 7; Q: 4.366; p=0.74	0.0%	0.55-0.91
		General & Cardiothoracic surgeons	0.42 (0.16-1.05)	[1 study][6]	-	-	-
		General, neuro-, cardiothoracic surgeons	**0.40 (0.24-0.66)**	[1 study][24]	-	-	-
		Other specialties (not specified)	0.64 (0.40-1.02)	[1 study][34]	-	-	-
		Other specialties (not specified)	1.47 (0.09-24.72)	[1 study][35]	-	-	-
	Neurosurgeons	General surgeons	1.24 (0.83-1.85)	[8 studies] [4, 11, 12, 16, 21, 23, 25, 35]	df: 7; Q: 11.505; p=0.12	37.0%	0.47-3.26
		Cardiothoracic surgeons	1.17 (0.85-1.61)	[7 studies] [4, 12, 16, 21, 23, 25, 35]	df: 6; Q: 4.592; p=0.60	0.0%	0.77-1.78
		Other specialties (not specified)	*2.30 (0.13-39.23)*	*[1 study][35]*	-	-	-
	General surgeons	Cardiothoracic surgeons	1.02 (0.86-1.21)	[8 studies] [4, 5, 12, 16, 21, 23, 25, 35]	df: 7; Q: 5.502; p=0.60	0.0%	0.83-1.26

		Other specialties (not specified)	*1.93 (0.12-31.05)*	*[1 study][35]*	-	-	-
	Cardiothoracic surgeons	*Other specialties (not specified)*	*1.64 (0.10-26.70)*	*[1 study][35]*	-	-	-
Procedural MI	Vascular surgeons	Neurosurgeons	0.40 (0.10-1.61)	[3 studies][4, 23, 35]	df: 2; Q: 4.953; p=0.08	64.08%	0.00-2120044.95
		General surgeons	0.96 (0.33-2.79)	[5 studies][4, 5, 13, 23, 35]	df: 4; Q: 23.667; p<0.005	81.6%	0.03-34.98
		Cardiothoracic surgeons	**0.52 (0.31-0.88)**	[4 studies][4, 5, 23, 35]	df: 3; Q: 0.488; p=0.92	0.0%	0.17-1.65
		General & cardiothoracic surgeons	*0.75 (0.13-4.48)*	*[1 study][5]*			
		Other specialties (not-specified)	*0.98 (0.48-1.98)*	*[1 study][34]*			
		Other specialties (not-specified)	*0.61 (0.08-4.60)*	*[1 study][35]*			
	Neurosurgeons	General surgeons	0.93 (0.59-1.46)	[3 studies][4, 23, 35]	df: 2; Q: 1.841; p=0.40	0.0%	0.05-17.33
		Cardiothoracic surgeons	1.52 (0.92-2.50)	[3 studies][4, 23, 35]	df: 2; Q: 1.729; p=0.42	0.0%	0.06-38.42
		Other specialties (not specified)	*1.96 (0.27-14.46)*	*[1 study][35]*			
	General surgeons	Cardiothoracic surgeons	1.22 (0.56-2.68)	[4 studies][4, 5, 23, 35]	df: 3; Q: 2.905; p=0.41	27.1%	0.09-17.26
		Other specialties (not specified)	*2.19 (0.31-15.38)*	*[1 study][35]*			
	Cardiothoracic surgeons	*Other specialties (not specified)*	*1.25 (0.18-8.89)*	*[1 study][35]*			
Procedural death, stroke or MI	Vascular surgeons	General surgeons	0.82 (0.63-1.07)	[1 study][13]	-	-	-
		Other specialties (not-specified)	*0.85 (0.60-1.20)*	*[1 study][34]*	-	-	-
		Other specialties (not-specified)	*0.72 (0.42-1.24)*	*[1 study][36]*	-	-	-
Procedural cranial nerve injury	Vascular surgeons	Neurosurgeons	1.27 (0.25-6.39)	[2 studies][4, 23]	df: 1; Q: 0.029; p=0.86	0.0%	NA
		General surgeons	0.87 (0.44-1.68)	[3 studies][4, 5, 23]	df: 2; Q: 1.106; p=0.58	0.0%	0.01-64.75

		Cardiothoracic surgeons	0.77 (0.36-1.62)	[3 studies][4, 5, 23]	df: 2; Q: 0.240; p=0.89	0.0%	0.01-97.92
		Cardiothoracic & general surgeons	*0.75 (0.31-1.82)*	*[1 study][5]*	-	-	-
	Neurosurgeons	General surgeons	0.58 (0.10-3.29)	[2 studies][4, 23]	df: 1; Q: 0.231; p=0.63	0.0%	NA
		Cardiothoracic surgeons	0.74 (0.07-7.83)	[1 study][4]	-	-	-
	General surgeons	Cardiothoracic surgeons	1.00 (0.36-2.81)	[3 studies][4, 5, 23]	df: 2; Q: 0.824; p=0.66	0.0%	0.00-783.69

CI, confidence interval; *MI*, myocardial infarction; *NA*, not applicable; *RR*, Risk ratio.
The risk estimate in a **bold** font is considered statistically significant. Combined groups of specializations or not clearly specified reference groups are in *italics*.
[a]Only estimated when ≥3 studies are within the meta-analyses.

Supplemental Table III. Overview of risk estimates assessing operator specialization and CAS

Table A. Procedural outcomes after CAS (adjusted risks)

Outcome	Index specialty	Reference specialty	Adjusted OR (95% CI)	N of studies	Cochran's Q	I^2	Prediction interval[a]
Procedural death or stroke	Vascular surgeons	*Other specialties (not specified)*	*HR 1.12 (0.54-2.35)*	*[1 study][36]*	-	-	-
	Cardiologists	Surgeons	0.89 (0.58-1.35)	[1 study][32]	-	-	-
	Cardiologists	*Radiologists & neurologists*	*0.85 (0.49-1.45)*	*[1 study][32]*	-	-	-
Procedural death	*Vascular surgeons*	*Cardiologists & interventional radiologists*	*1.67 (0.40-7.02)*	*[1 study][33]*	-	-	-
	Interventionalists (including cardiologists)	*Surgeons*	*1.29 (0.90-1.84)*	*[1 study][30]*	-	-	-
Procedural stroke	Vascular surgeons	*Cardiologists & interventional radiologists*	*0.61 (0.25-1.48)*	*[1 study][33]*	-	-	-
	Interventionalists (including cardiologists)	Surgeons	1.00 (0.84-1.19)	[1 study][30]	-	-	-
Procedural MI	Interventionalists (including cardiologists)	Surgeons	1.14 (0.90-1.43)	[1 study][30]	-	-	-
Procedural death, stroke or MI	Vascular surgeons	Cardiologists	**1.96 (1.19-3.24)**	[1 study][20]	-	-	-
		Interventional cardiologists & interventional radiologists & interventional vascular medicine	*1.3 (0.45-3.95)*	*[1 study][7]*	-	-	-
		Other specialties (not further specified)	*HR 0.99 (0.50-2.0)*	*[1 study][36]*	-	-	-
	Neurosurgeons	Cardiologists	1.69 (0.76-3.74)	[1 study][20]	-	-	-
	Cardiologists	Radiologists	1.14 (0.31-4.19)	[1 study][20]	-	-	-
		Radiologists & neurologists	*0.66 (0.40-1.09)*	*[1 study][32]*	-	-	-
	Surgeons	Cardiologists	1.26 (0.84-1.89)	[1 study][32]	-	-	-

CI, confidence interval; *HR*, hazard ratio; *MI*, myocardial infarction; *OR*, odds ratio.
Combined groups of specializations or not clearly specified reference groups are in *italics*.
[a]Only estimated when ≥3 studies are within the meta-analyses.

Table B. Procedural outcomes after CAS (unadjusted risks)

Procedural outcomes	Index specialty	Reference specialty	Unadjusted RR (95% CI)	N of studies	Cochran's Q	I^2	Prediction interval[a]
Procedural death or stroke	*Vascular surgeons*	*Neurosurgeons & interventional cardiologists & interventional radiologists & interventional neuroradiologists*	*1.26 (0.78-2.04)*	*[1 study][15]*	-	-	-
		Other specialties (not specified)	*0.85 (0.42-1.73)*	*[1 study][36]*	-	-	-
	Vascular surgeons and neurosurgeons	*Other specialties (not specified)*	*1.21 (0.54-2.71)*	*[1 study][18]*	-	-	-
Procedural death	Vascular surgeons	Neurosurgeons	1.45 (0.08-24.93)	[1 study][15]	-	-	-
		Cardiologists	1.96 (0.85-4.54)	[2 studies][15, 33]	df: 1; Q: 0.013; p=0.91	0.0%	NA
		Radiologists	1.60 (0.74-3.50)	[2 studies][15, 33]	df: 1; Q: 0.003; p=0.96	0.0%	NA
		Cardiologists & interventional radiologists	*1.81 (0.83-3.96)*	*[1 study][33]*	-	-	-
	Neurosurgeons	Cardiologists	1.45 (0.09-24.21)	[1 study][15]	-	-	-
		Radiologist	0.94 (0.05-18.29)	[1 study][15]	-	-	-
		Interventional radiologists	1.35 (0.05-33.13)	[1 study][15]	-	-	-
		Interventional neuroradiologists	0.51 (0.02-10.72)	[1 study][15]	-	-	-
	Cardiologists	Radiologists	0.81 (0.36-1.83)	[2 studies][15, 33]	df:1; Q:0.032; p=0.86	0.0%	NA
	Interventionalists (including cardiologists)	Surgeons	1.22 (0.89-1.67)	[1 study][30]	-	-	-
Procedural stroke	Vascular surgeons	Neurosurgeons	0.68 (0.16-2.85)	[1 study][15]			
		Cardiologists	1.19 (0.80-1.76)	[3 studies][15, 33, 37]	df: 2; Q: 1.520; p=0.47	0.0%	0.09-14.96
		Radiologists	0.93 (0.48-1.77)	[3 studies][15, 33, 37]	df:2; Q: 2.033; p=0.36	26.48%	0.00-288.69
		Cardiologists & interventional radiologists	*0.91 (0.52-1.58)*	*[1 study][33]*			
	Neurosurgeons	Cardiologists	2.01 (0.50-8.08)	[1 study][15]			
		Radiologist	2.22 (0.46-10.71)	[1 study][15]			

	Cardiologists	Radiologist	0.78 (0.44-1.41)	[3 studies][15, 33, 37]	df:2; Q: 1.964; p=0.37	18.66%	0.01-99.78
	Interventionalists (including cardiologists)	Surgeons	0.96 (0.83-1.11)	[1 study][30]			
Procedural MI	Vascular surgeons	Neurosurgeons	0.38 (0.02-7.95)	[1 study][15]	-	-	-
		Cardiologist	0.93 (0.27-3.24)	[2 studies][15, 37]	df: 1; Q: 0.211; p=0.65	0.0%	NA
		Radiologists	1.24 (0.26-6.01)	[2 studies][15, 37]	df: 1; Q: 0.049; p=0.82	0.0%	NA
	Neurosurgeons	Cardiologists	2.36 (0.14-40.61)	[1 study][15]	-	-	-
		Radiologists	2.20 (0.09-54.10)	[1 study][15]	-	-	-
	Cardiologists	Radiologists	1.16 (0.27-4.97)	[2 studies][15, 37]	df:1; Q: 0.030; p =0.86	0.0%	NA
	Interventionalists (including cardiologists)	*Surgeons*	*1.01 (0.82-1.25)*	*[1 study][30]*	-	-	-
Procedural death, stroke or MI	Vascular surgeons	Neurosurgeons	1.07 (0.54-2.10)	[2 studies][15, 20]	df: 1; Q: 0.156; p=0.69	0.0%	-
		Cardiologists	**1.57 (1.06-2.33)**	[3 studies][7, 15, 39]	df: 2; Q: 2.151; p=0.34	22.1%	0.06-43.70
		Radiologists	1.43 (0.92-2.23)	[3 studies][7, 15, 20]	df: 2; Q: 1.132; p=0.57	0.0%	0.08-25.11
		Interventional vascular medicine	0.94 (0.22-4.02)	[1 study][7]	-	-	-
		Interventional cardiologists & interventional radiologists & interventional vascular medicine	*1.65 (0.70-3.90)*	*[1 study][7]*	-	-	-
		Interventional cardiologists & interventional radiologists & interventional neuroradiologists & neurosurgeons	*1.18 (0.74-1.88)*	*[1 study][15]*	-	-	-
		Other specialties (not further specified)	*0.79 (0.41-1.54)*	*[1 study][36]*	-	-	-
	Neurosurgeons	Cardiologists	1.71 (0.79-3.71)	[1 study][20]	-	-	-
		Interventional cardiologists	1.44 (0.36-5.72)	[1 study][15]	-	-	-
		Radiologists	1.47 (0.73-2.94)	[2 studies][15, 20]	df: 1; Q: 0.022; p=0.88	0.0%	-

	Cardiologists	Radiologists	0.87 (0.57-1.34)	[3 studies][7, 15, 20]	df: 2; Q: 0.512; p=0.77	0.0%	0.05-14.04
		Radiologists & neurologists	***0.62 (0.43-0.90)***	*[1 study][32]*	-	-	-
		Interventional vascular medicine	0.46 (0.10-2.19)	[1 study][7]	-	-	-
	Radiologists	Interventional vascular medicine	1.07 (0.11-10.85)	[1 study][7]	-	-	-
	Surgeons	Cardiologists	1.11 (0.82-1.49)	[1 study][32]	-	-	-
		Radiologists & neurologists	*0.69 (0.45-1.05)*	*[1 study][32]*	-	-	-

CI, confidence interval; *HR*, hazard ratio; *MI*, myocardial infarction; *NA*, not applicable; *RR*, relative risk.
Combined groups of specializations or not clearly specified reference groups are in *italics*.
[a]Only estimated when ≥3 studies are within the meta-analyses.

Supplemental Table IV. Sensitivity analyses for CEA

A. Sensitivity analysis for the primary outcome with studies reporting ≥80% symptomatic patients and with studies reporting ≥80% asymptomatic patients

		All studies		***Studies with ≥80% symptomatic patients***		***Studies with ≥80% asymptomatic patients***	
Index specialty	**Reference specialty**	**Unadjusted RR (95% CI)**	**No. of studies**	**Unadjusted RR (95% CI)**	**No. of studies**	**Unadjusted RR (95% CI)**	**No. of studies**
Vascular surgeons	Neurosurgeons	**0.63 (0.46-0.86)**	[7 studies][4, 10, 11, 14, 16, 21, 22]	0.69 (0.16-2.98)	[1 study][4]		No studies
	General surgeons	**0.81 (0.66-0.99)**	[6 studies][4, 6, 11, 14, 16, 21]	0.77 (0.25-2.30) *df: 1; Q: 1.00; p=0.32;I^2=0.4%*	[2 studies][4, 6]	**0.12 (0.03-0.45)** *df: 1; Q: 0.61; p=0.43;I^2=0%*	[2 studies][4, 6]
	Cardiothoracic surgeons	0.87 (0.63-1.19)	[5 studies][4, 6, 14, 16, 21]	0.83 (0.27-2.51) *df: 1; Q: 0.06; p=0.81;I^2=0%*	[2 studies][4, 6]	**0.16 (0.05-0.52)** *df: 1; Q: 0.54; p=0.46;I^2=0%*	[2 studies][4, 6]
Neurosurgeons	General surgeons	1.53 (0.85-2.74)	[5 studies][4, 11, 14, 16, 21]	1.84 (0.27-12.42)	[1 study][4]		No studies
	Cardiothoracic surgeons	1.22 (1.02-1.46)	[4 studies][4, 14, 16, 21]	1.06 (0.16-7.10)	[1 study][4]		No studies
General surgeons	Cardiothoracic surgeons	1.16 (0.85-1.57)	[5 studies][4, 6, 14, 16, 21]	1.16 (0.29-4.66) *df: 1; Q: 1.06; p=0.30;I^2=5.8%*	[2 studies][4, 6]	1.31 (0.46-3.70) *df: 1; Q: 0.02; p=0.89;I^2=0%*	[2 studies] [4, 6]

CI, confidence interval; *RR*, relative risk.
The risk estimates in a **bold** font are considered statistically significant.
Cochran's Q and I^2 values can only be estimated for meta-analyses included >1 study. Prediction intervals can only be estimated for meta-analyses including >2 studies, therefore no prediction intervals are depicted in the sensitivity analyses.

B. Sensitivity analysis for the primary outcome with studies based on clinical data and studies based on data from registries

		All studies		*Studies based on clinical data*		*Studies based on administrative data*	
Index specialty	**Reference specialty**	**Unadjusted RR (95% CI)**	**No. of studies**	**Unadjusted RR (95% CI)**	**No. of studies**	**Unadjusted RR (95% CI)**	**No. of studies**
Vascular surgeons	Neurosurgeons	**0.63 (0.46-0.86)**	[7 studies][4, 10, 11, 14, 16, 21, 22]	**0.52 (0.36-0.77)** *df: 3; Q: 2.03; p=0.57;I^2=0%; prediction interval: 0.23-1.21*	[4 studies][4, 10, 11, 21]	0.71 (0.45-1.13) *df: 2; Q: 5.38; p=0.07;I^2=72.6%; prediction interval: 0.0-137.6*	[3 studies][14, 16, 22]
	General surgeons	**0.81 (0.66-0.99)**	[6 studies][4, 6, 11, 14, 16, 21]	0.72 (0.41-1.24) *df: 3; Q: 3.76; p=0.29;I^2=22.9%; prediction interval: 0.13-3.82*	[4 studies][4, 6, 11, 21]	0.98 (0.53-1.79) *df: 1; Q: 2.65; p=0.10;I^2=62.3%*	[2 studies][14, 16]
	Cardiothoracic surgeons	0.87 (0.63-1.19)	[5 studies][4, 6, 14, 16, 21]	0.63 (0.34-1.18) *df: 2; Q: 2.77; p=0.25;I^2=32.8%; prediction interval: 0.0-194.8*	[3 studies][4, 6, 21]	1.02 (0.85-1.23) *df: 1; Q: 0.14; p=0.71; I^2=0.0%*	[2 studies][14, 16]
Neurosurgeons	General surgeons	1.53 (0.85-2.74)	[5 studies][4, 11, 14, 16, 21]	1.53 (0.86-2.73) *df: 2; Q: 0.24; p=0.89;I^2=0%; prediction interval: 0.04-64.33*	[3 studies][4, 11, 21]	1.85 (0.39-8.71) *df: 1; Q: 9.43; p<0.001;I^2=89.4%*	[2 studies][14, 16]
	Cardiothoracic surgeons	1.22 (1.02-1.46)	[4 studies][4, 14, 16, 21]	1.23 (0.61-2.46) *df: 1; Q: 0.44; p=0.51;I^2=0%*	[2 studies][4, 21]	1.41 (0.76-2.61) *df: 1; Q: 1.71; p=0.19;I^2=41.5%*	[2 studies][14, 16]
General surgeons	Cardiothoracic surgeons	1.16 (0.85-1.57)	[5 studies][4, 6, 14, 16, 21]	1.00 (0.56-1.80) *df: 2; Q: 0.96; p=0.62;I^2=0%; prediction interval: 0.02-45.27*	[3 studies][4, 6, 21]	1.04 (0.49-2.18) *df: 1; Q: 2.13; p=0.14;I^2=53.0%*	[2 studies][14, 16]

CI, confidence interval; *RR*, relative risk.
The risk estimates in a **bold** font are considered statistically significant.
Cochran's Q and I^2 values can only be estimated for meta-analyses included >1 study. Prediction intervals can only be estimated for meta-analyses including >2 studies.

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