ORIGINAL ARTICLE

The Impact of Neurophysiological Monitoring on Patient Outcomes in Carotid Endarterectomy: A Meta-Analysis

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ABSTRACT

The 30-day stroke rate following a Carotid Endarterectomy (CEA) range between 2-6% and is associated with a three-fold increase in mortality. Various types of Intraoperative Neurological Monitoring (IONM) modalities are available to help detect changes in cerebral blood flow during this procedure. The primary aim of this meta-analysis was to evaluate the efficacy of the different (IONM) techniques used for this surgery and compare them to multiple modality studies. We identified relevant articles on PubMed (2000-2024), EBSCOhost (2000-2024), and Science Direct (2000-2024) to identify studies to include in this meta-analysis. We included literature that consisted of adult patients who underwent a CEA procedure under general anesthesia and were monitored with the specified IONM modalities. We calculated the mean specificities and sensitivities for each IONM Modality studied and are as follows: mean EEG sensitivity 41% and specificity 90%; mean TCD sensitivity 99% and specificity 83%; mean SSEP sensitivity 64% and specificity 88%; combined SSEP+EEG sensitivity 59% and specificity 99%. Each IONM modality presents its own unique set of challenges to determine severe deficits in cerebral blood flow. Given the high specificity or sensitivity observed across virtually all modalities, additional studies are needed to assess the effectiveness of combining the strengths of two modalities to enhance their capabilities.

INTRODUCTION

The common carotid artery is a major blood vessel supplying blood to the brain, head, and neck. Each common carotid artery on either side of the neck bifurcates into the internal (ICA) and the external (ECA) carotid artery. Stenosis develops when plaque accumulates, narrowing or blocking the artery. Carotid endarterectomy (CEA) is a surgical procedure aimed at removing this plaque accumulation to reduce the risk of stroke in patients, as shown in Figures 1-3 [1,2].

Several surgical approaches can be used for this technique, all of which require a clamp to temporarily stop blood flow while removing plaque from the intimal layers of the blood vessel. This can lead to a significant reduction in blood flow to the ipsilateral side of the brain. If this change is left untreated, it can lead to neurological deficits post-operatively. This is especially dangerous for patients who do not have a complete Circle of Willis (CoW) and cannot receive contralateral blood flow [3]. The CoW serves as a compensatory mechanism in compromised blood flow, providing collateral circulation to maintain blood flow. In patients with an incomplete CoW, the absence of these collateral pathways increases the risk of ischemic injuries and neurological complications. Some surgeons perform routine shunting, diverting blood around the surgical site to maintain blood flow. While there are inherent risks to routinely performing shunts, including atheromatous or air emboli, arterial dissection, and acute arterial occlusion, several other complications have been reported. These include the risk of local complications such as nerve injury, hematoma, infection, and long-term stenosis [3]. Due to the risks involved, some surgeons choose to shunt only when necessary, using a multimodality neuromonitoring technique after clamping to assess whether the benefits of shunting outweigh the potential risks of postoperative neurological deficits [3].

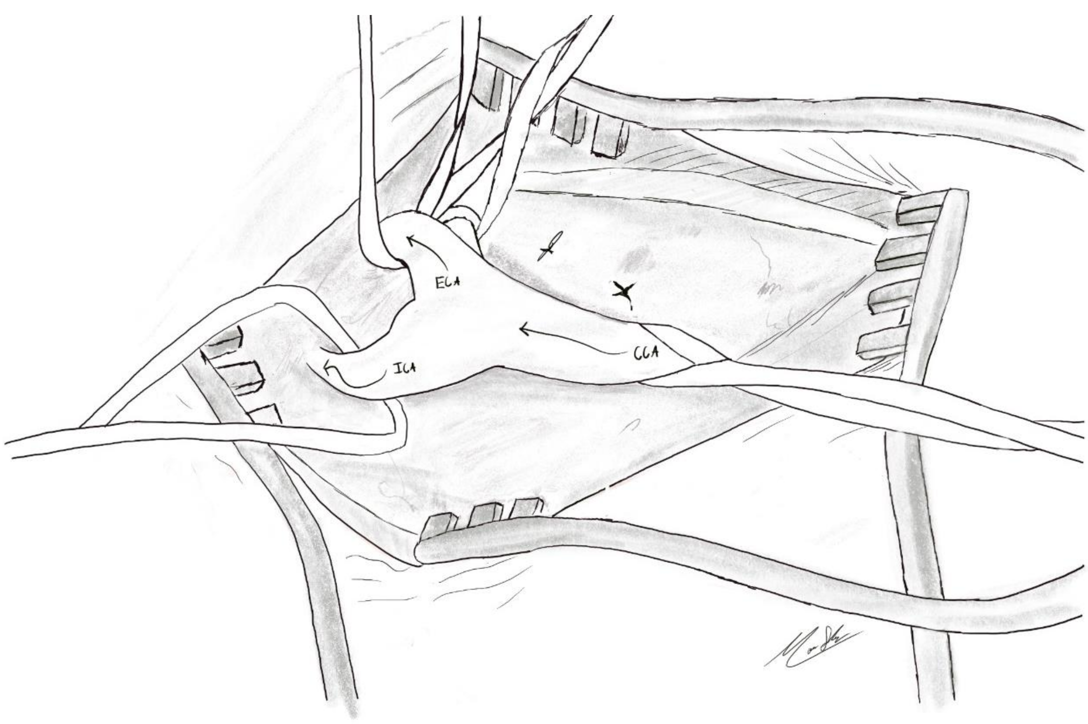

Figure 1. Normal anatomy of the carotid arteries being cross-clamped during carotid endarterectomy procedure. ICA: internal carotid artery, ECA: external carotid artery, CCA: common carotid artery (*Illustration by Mark Salazar*).

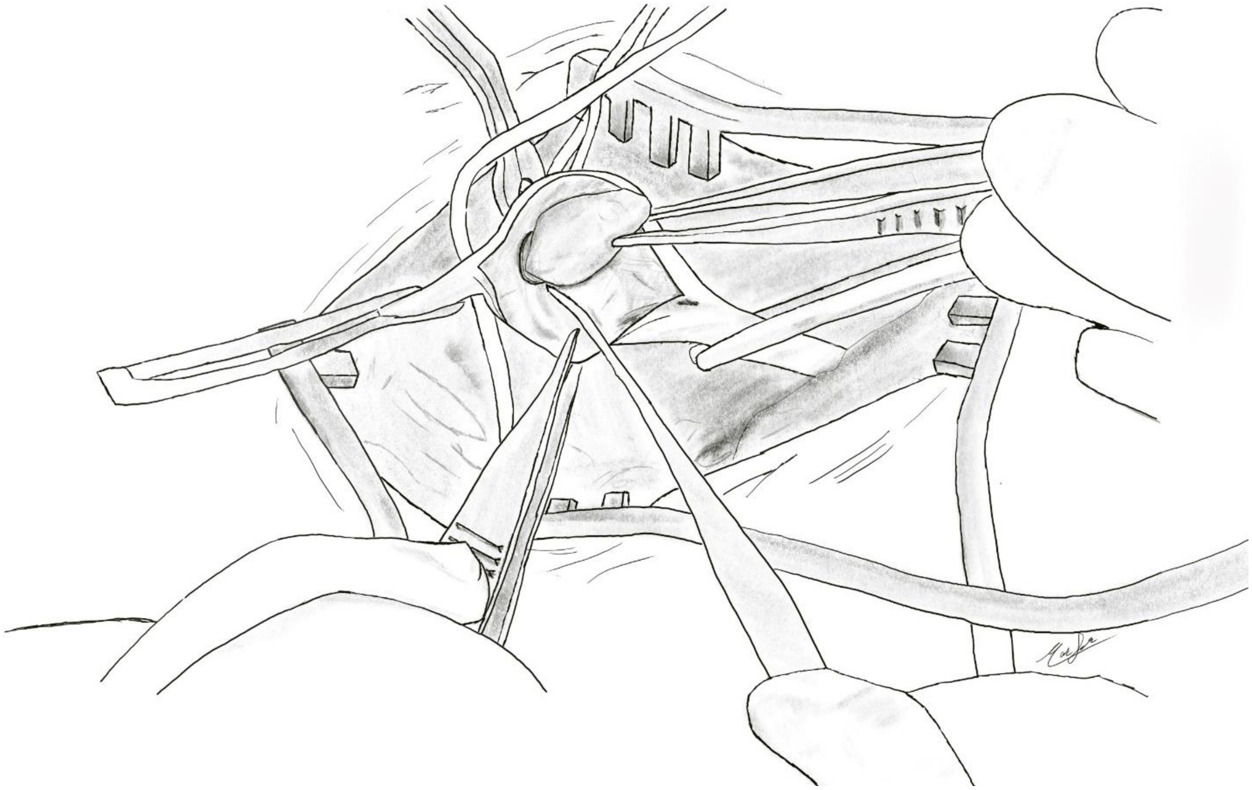

Figure 2. Plaque removal during carotid endarterectomy procedure after cross-clamping internal carotid (ICA), external carotid (ECA), and common carotid arteries (CCA) (*Illustration by Mark Salazar*).

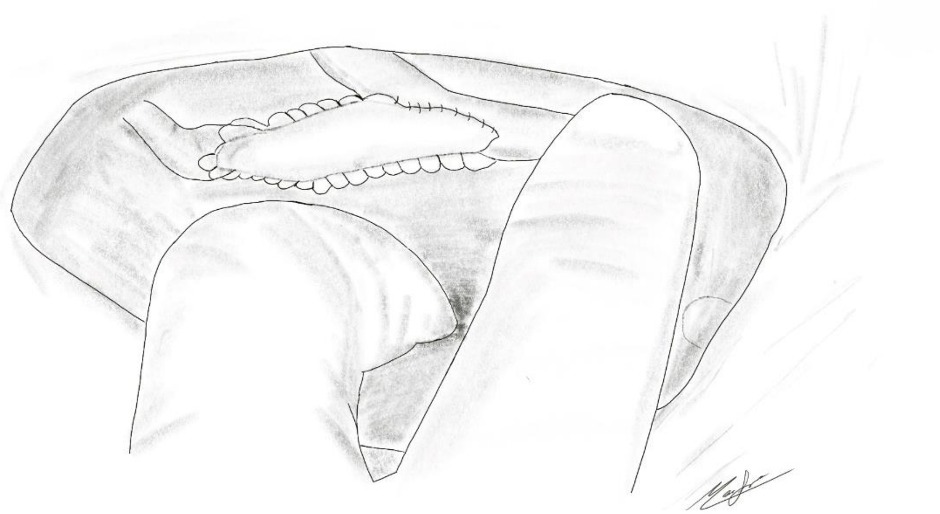

Figure 3. Skin closure after a carotid endarterectomy procedure (*Illustration by Mark Salazar*).

Multiple Intraoperative Neurophysiological Monitoring (IONM) modalities are available to monitor the integrity of the nervous system. Some of the most common methods used for CEA procedures were Somatosensory Evoked Potentials (SSEPs), Electroencephalography (EEG), and Transcranial Doppler (TCD). The function of the SSEP is to monitor the integrity of the somatosensory pathways of the nervous system. Stimulating electrodes, such as adhesive surface electrodes, can be placed at the wrist to stimulate the median nerve. Subdermal needle recording electrodes are strategically placed to record the propagating signal course through the nervous system until it reaches the primary somatosensory cortex. This same protocol can also be adapted to stimulate the posterior tibial nerve at the medial malleolus in the lower limbs and is helpful for surgical procedures that may damage a nerve in the thoracic or lumbar region. Each has a set of obligatory potentials that must be recorded. A median nerve SSEP protocol must contain a potential for the Brachial Plexus (N9), Nucleus Cuneatus (N13), Medial Lemniscus (P14), Brainstem/Thalamus (N18), and the Primary Somatosensory Cortex (N20) [4]. The alert criteria include an amplitude reduction of at least 50% or more in the N20/P25 peaks and an increased latency in the Central Conduction Time (CCT) by greater than 20% [5,6].

Continuous EEG monitoring is used intraoperatively to assess cerebral perfusion during this procedure and help determine the need for a shunt [6]. The benefit of using the EEG is that it allows for direct monitoring of cerebral perfusion, as opposed to Transcranial Doppler (TCD) or stump pressure, which measures brain function indirectly [7]. The CEA procedure should use a minimum of eight channels. Various montages can be used; Table 1 shows one of the most common montages, the modified double-banana [7]. This is a kind of bipolar montage that uses active electrodes referenced to one another to increase the specificity of ischemic changes [7]. We could not find a set of widely agreed-upon EEG criteria used to indicate ischemic changes. The criteria had slight variations between authors but commonly included looking at a 50% or greater amplitude reduction associated with slowing [7].

Left	Right
FP1 - CP3	FP2 - CP4
CP3 - O1	CP4 - O2
FP1 - T3	FP2 - T4
T3 - O1	T4 - O2

Table 1. Modified double banana electrode placement.

TCD can also be used during a CEA to monitor the blood flow velocity of the middle cerebral artery (MCA) [8]. An Ultrasound Doppler device is used to monitor the MCA at a depth of around 45-50 mm [8]. The probe can be secured using a headband that wraps around the patient’s head, maintaining a consistent reading. A mean blood flow velocity of the MCA (Vm) is obtained as a baseline after induction, and blood pressure has been stabilized. The Vm is continuously monitored during the procedure, including peak systolic velocity, end-diastolic velocity, and pulsatility index. Once the ICA is clamped, the Vm is carefully monitored to help identify whether a shunt is needed. A decrease of MCA Vm >50% of the baseline was a common criterion for identifying hypoperfusion [8-9].

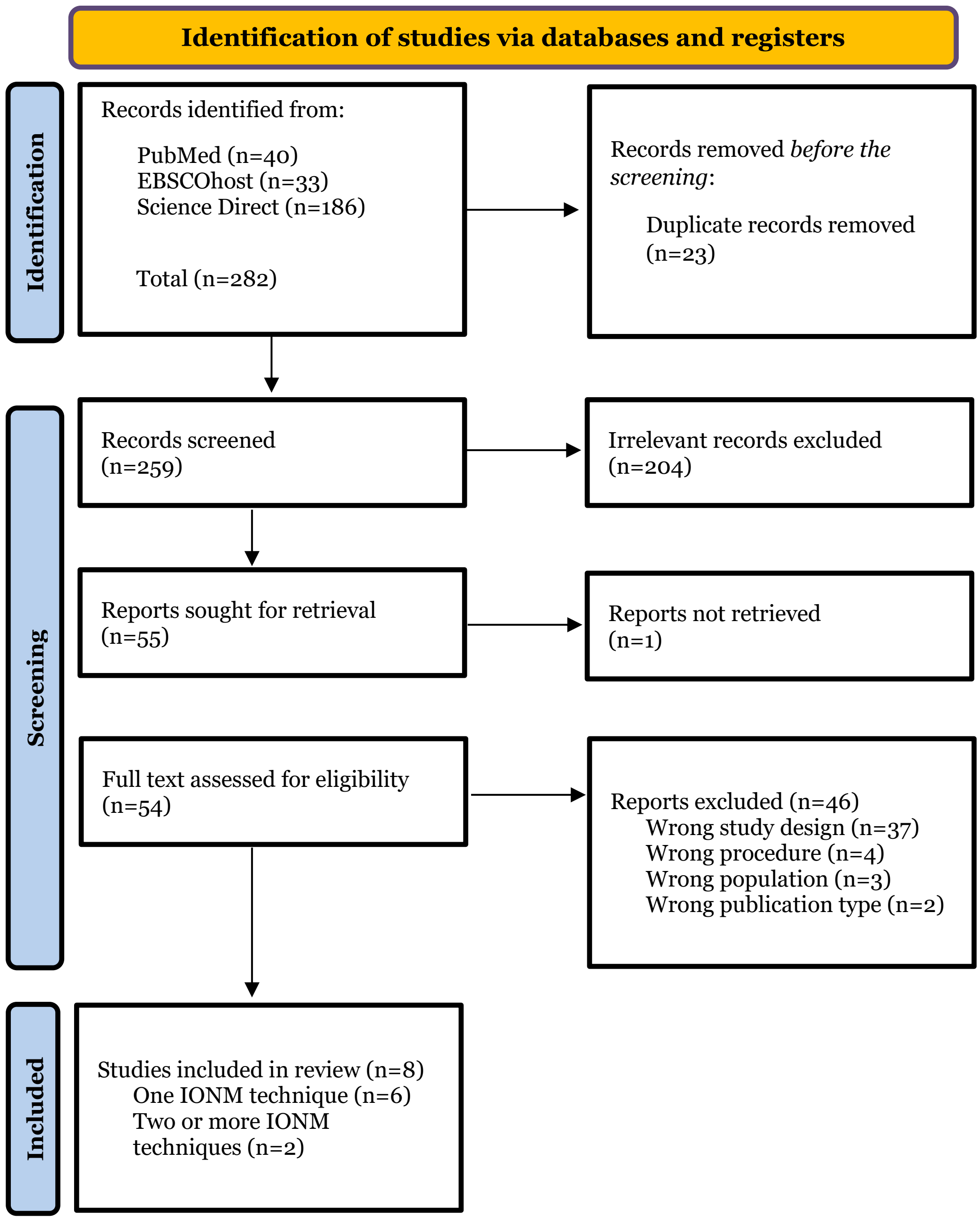

Figure 4. PRISMA Flow Diagram.

METHODS

Protocol

This meta-analysis utilized the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) procedure. The flow diagram for the PRISMA procedure is included above (Figure 4).

Study Search and Eligibility

PubMed, EBSCOhost, and Science Direct were searched using the keywords "Carotid endarterectomy" OR "CEA," AND "neurophysiological monitoring" OR "intraoperative monitoring" OR "cerebral monitoring" AND "patient outcomes" OR "stroke prevention" OR "complications." The inclusion criteria are as follows: (1) articles were written in the English Language, (2) only general anesthesia was used, (3) EEG, SSEP, and/or TCD were the only IONM techniques used, and (4) articles published from 2000-2024.

Study Selection

Rayyan AI, a platform used to conduct systematic literature reviews and meta-analyses, was used to manage the research papers extracted from databases. Duplicate articles were removed, and all the articles were screened with their title and abstracts to exclude those that failed to meet the inclusion criteria. The final list of studies that met the inclusion criteria is accepted to be relevant in investigating the specificity and sensitivity of each IONM modality in their ability to detect cerebral ischemia after clamping of the ICA.

Data Extraction and Analysis

The included studies were reviewed for the specificities and sensitivities reported for the respective IONM modality studied. The data from the articles was collected and included in Table 2. The data was then extrapolated, and the 95% Confidence Interval (CI) contained in the studies was used to determine the error bars in the graphs. For the studies that did not include a 95% Confidence Interval, the error was determined using 5% plus or minus the mean. The specificities and sensitivities were averaged to each IONM modality studied and plotted in Figure 6. The 95% Confidence Interval for the mean of each modality was determined by using online software and adding the patient population in each study to reflect the total sample size. This process was repeated for all IONM modalities with data from two or more studies (EEG, TCD, and SSEP).

Authors	Year	Title	Modalities	Sensitivity and Specificity
		Single Modality		
Thirumala PD, Thiagarajan K, Gedela S, Crammond DJ, Balzer, JR.	2015	Diagnostic accuracy of EEG changes during carotid endarterectomy in predicting perioperative strokes (1)	EEG	Sensitivity 52%; (95% CI, 43-61%) Specificity 84%; (95% CI, 81-86%)
Chang R, Reddy RP, Sudadi S, Balzer J, Crammond DJ, Anetakis K, Thirumala PD.	2020	Diagnostic accuracy of various EEG changes during carotid endarterectomy to detect 30-day perioperative stroke: A systematic review (12)	EEG	Sensitivity 46% (95% CI, 38-54%) Specificity 86% (95% CI, 83-88%)
Pugliese F, Ruberto F, Tosi A, Martelli S, Bruno K, Summonti D, D'Alio A, Diana B, Anile M, Panico A, Speziale F, Pietropaoli P.	2009	Regional cerebral saturation versus transcranial Doppler during carotid endarterectomy under regional anesthesia (15)	TCD	Sensitivity 100% (95% CI not reported Specificity 80% (95% CI not reported)
Woo-Sung Yun	2017	Cerebral monitoring during carotid endarterectomy by transcranial Doppler ultrasonography (16)	TCD	Sensitivity 100% (95% CI not reported) Specificity 86% (95% CI not reported)
Fielmuth S, Uhlig T.	2008	The role of somatosensory evoked potentials in detecting cerebral ischemia during carotid endarterectomy (5)	SSEP	Sensitivity 87% (95 CI% not reported) Specificity 66% (95 CI% not reported)
Reddy RP, Brahme IS, Karnati T, Balzer JR, Crammond DJ, Anetakis KM, Thirumala PD.	2018	Diagnostic value of somatosensory evoked potential changes during carotid endarterectomy for 30-day perioperative stroke (13)	SSEP	Sensitivity 61% (95 CI% not reported) Specificity 94% (95 CI% not reported)
		Dual-Modality		
Florence G, Guerit JM, Gueguen B.	2004	Electroencephalography (EEG) and somatosensory evoked potentials (SEP) to prevent cerebral ischemia in the operating room (14)	EEG SSEP	**EEG:** Sensitivity 20% (95 CI% not reported) Specificity 95% (95 CI% not reported) **SSEP:** Sensitivity 60% (95% CI not reported) Specificity 97% (95% CI not reported)
Thiagarajan K, Cheng HL, Huang JE, Natarajan P, Crammond DJ, Balzer JR, Thirumala PD.	2015	Is Two Really Better Than One? Examining the Superiority of Dual Modality Neurophysiological Monitoring During Carotid Endarterectomy: A Meta-Analysis (10)	EEG SSEP	**EEG:** Sensitivity 44.5% (95% CI, 23.9-67.2%) Specificity 96.5% (95% CI, 91.1-98.7%) **SSEP:** Sensitivity 46.7% (95%, 31.1-63.0%) Specificity 94.8% (95% CI, 87.5-97.9%) **SSEP + EEG:** Sensitivity 58.9% (95% CI, 41.2-74.4%) Specificity 98.6% (95% CI, 90.3-98.4%)

Table 2: Summary of the studies included in Meta-analysis.

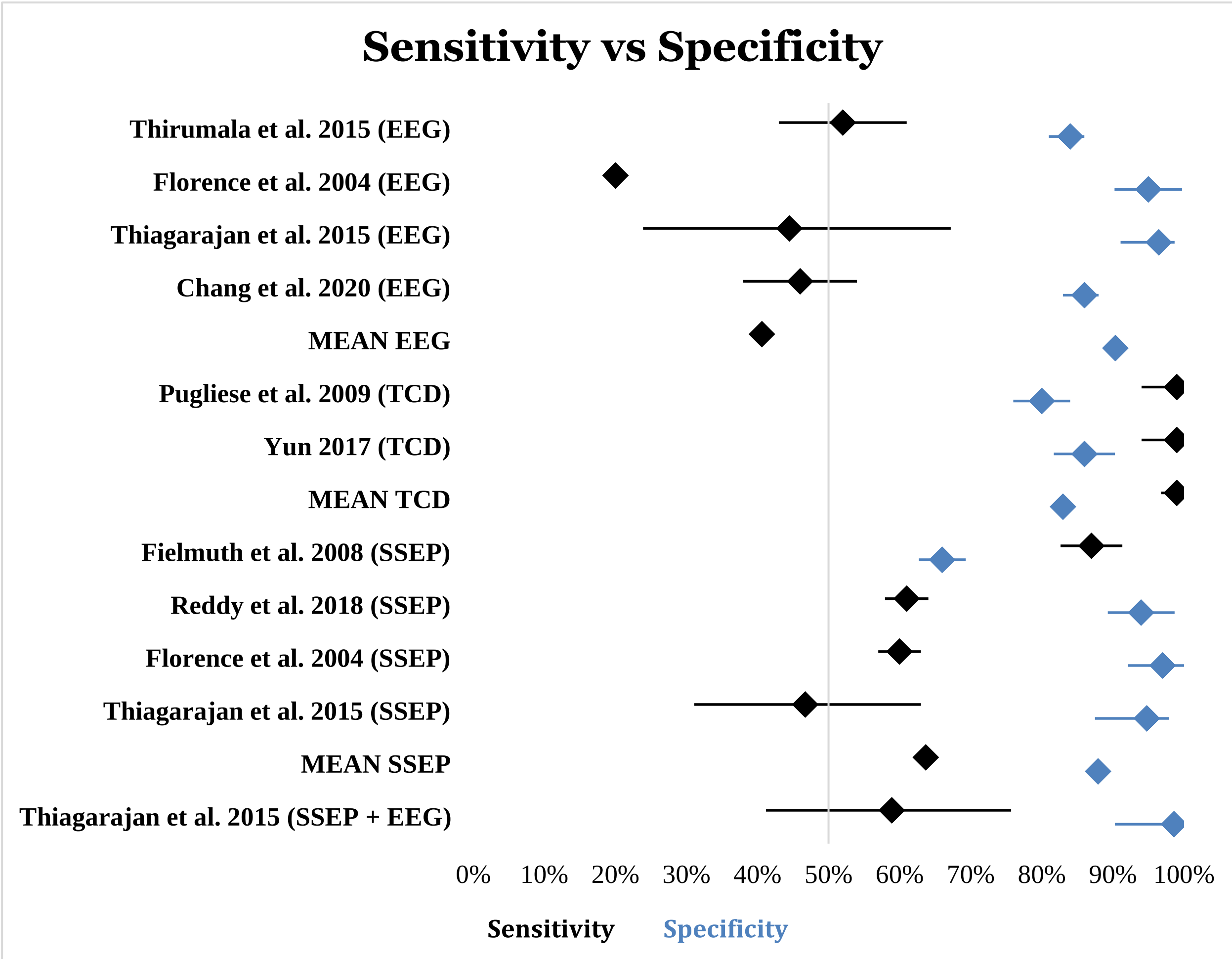

Figure 5. Forest Plot comparing IONM modality specificities and sensitivities

RESULTS

We reviewed each study in Table 2 and included a forest plot (Figure 5) to compare the specificities and sensitivities for each IONM modality studied. A vertical line was placed at the 50% mark to visually compare if the reported sensitivity and specificity values fall above or below. The studies were organized in this plot based on the modality studied (EEG, TCD, SSEP, and EEG+SSEP), and a mean was calculated for the modalities studied by two or more articles (EEG, TCD, and SSEP). The mean sensitivities and specificities are mean EEG sensitivity of 41% and specificity of 90%; mean TCD sensitivity of 99% and specificity of 83%; mean SSEP sensitivity of 64% and specificity of 88%. Due to only one article reporting the specificities of SSEP + EEG, a mean was not calculated. This study reported that the specificities and sensitivity of using

SSEP and EEG simultaneously increased relative to the computed value when using each modality independently [10]. The study reported that dual-modality monitoring (EEG + SSEP) was 1.32 times more sensitive than exclusive EEG monitoring and 1.26 times more sensitive than exclusive SSEP monitoring [10]. Changes in specificity were reported to be nearly identical compared to using each modality independently [10].

DISCUSSION

CEA is designed to improve blood supply to the brain and remove any plaque accumulation, but it carries a risk of stroke both during and after the procedure. These risks could arise due to changes in perfusion during the procedure or a plaque embolism. Shunting during the procedure is at the surgeon's discretion and is performed as needed. The use of electroencephalography (EEG), transcranial Doppler ultrasound (TCD), and somatosensory evoked potentials (SSEP) with intraoperative neurophysiological monitoring (IONM) is vital due to the risk of stroke that can arise from high-risk procedures like CEA. The intraoperative multimodality IONM approach can allow timely intervention and mitigate the risk of neurological complications. Multiple monitoring methods provide the most effective strategy for accurately assessing all stroke-related factors during CEA [10]. Many studies have evaluated various modalities and highlighted the importance of assessing sensitivity and specificity to determine the reliability and accuracy of these techniques. Sensitivity measures how well a test can correctly identify those with a specific condition, also known as true positives [11]. Therefore, an IONM modality with high sensitivity would be an excellent tool for ruling out intraoperative ischemia in CEA cases. Specificity measures how well a test can correctly identify those without the specific condition, also known as true negatives[11]. Highly specific tests are helpful to determine the risk of a stroke when changes are present while monitoring.

EEG allows for direct monitoring of cerebral perfusion and may help predict strokes. The studies investigating EEG during the CEA procedure reported a high specificity and a low sensitivity [1,0,12,13]. The high specificity associated with this modality is particularly useful when EEG changes occur intraoperatively. However, this modality cannot definitively assess the presence of a stroke when there aren't any changes in EEG waveforms during the procedure. EEG can detect strokes even in individuals who have never experienced one before, which enables prompt intervention to address neurological damage.

SSEP allows direct monitoring of the integrity of somatosensory pathways of the nervous system. This modality is vital to preserve neurological function during the procedure. The studies investigating the use of SSEP demonstrated a high specificity but a low sensitivity [5,10.13,14]. Its high specificity, like the EEG, is very useful in predicting the incidence of a stroke when there are changes in data during the procedure.

However, its low sensitivity would not strongly indicate the absence of a stroke when no changes in intraoperative data are shown.

TCD monitors the blood flow velocity of the middle cerebral artery and helps ensure blood flow during surgery. Studies investigating the use of TCD showed a high sensitivity and a lower specificity [15,16]. Its high sensitivity helps ensure that a stroke does not occur when the intraoperative changes do not meet the criteria. Although high, its specificity lowers the probability of accurately diagnosing a perioperative stroke when there are changes in TCD data.

Additional studies are needed to include papers without monitoring, but near-infrared spectroscopy (NIRS) and regional cerebral oxygenation (rSO2) could be used for future monitoring. Near-infrared spectroscopy is a noninvasive technique that measures changes in the concentration of deoxygenated and oxygenated hemoglobin in tissue. rSO2 uses NIRS to provide real-time information about cerebral oxygenation.

CONCLUSION

Integrating various intraoperative neurophysiological monitoring (IONM) techniques such as SSEPs, EEG, and TCD has significantly improved the detection and prevention of brain ischemia during carotid surgeries. Research indicates that combining these methods can lead to higher sensitivities and specificities, underscoring the effectiveness of a multimodal approach compared to single-modality monitoring. Future studies should focus on exploring strategic combinations of modalities that demonstrate high specificity and sensitivity in identifying perioperative strokes, such as EEG and TCD. While EEG exhibits high specificity, TCD demonstrates high sensitivity, offering a promising approach to stroke prediction.

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