Critical Care

RESEARCH Open Access

Neuromonitoring with near-infrared spectroscopy (NIRS) in aneurysmal subarachnoid hemorrhage: A systematic review and meta-analysis

Mohamed Reda Bensaidane[1,2,3,4,5], Alexis F. Turgeon[1,4,5], François Lauzier[1,2,4,5], Shane W. English[6,7], Guillaume Leblanc[1,4,5] and Charles L. Francoeur[1,2,4,5,8*]

Abstract

Purpose Near-infrared spectroscopy (NIRS) is a non-invasive, real-time and continuous cerebral oximetry monitoring with potential applications in the management of aneurysmal subarachnoid hemorrhage (aSAH) and in the detection of delayed cerebral ischemia (DCI). The aim of this study was to evaluate the association between NIRS and outcome in aSAH and its diagnostic accuracy for DCI.

Methods Systematic review and meta-analysis of studies involving adult aSAH patients monitored with NIRS during index hospitalization. Primary outcome was the functional outcome at 90 days or more. Secondary outcomes included any functional outcome, mortality and diagnostic accuracy for DCI. Random effects meta-analyses were performed, and for diagnostic accuracy, forest plots and random effects meta-analyses were used to determine pooled sensitivity, specificity, diagnostic odds ratios and to generate a receiver operating characteristic (ROC) curve.

Results Of the 28,296 citations identified, 35 satisfied inclusion criteria. Three studies (202 patients) were included for meta-analysis of the primary outcome. Cerebral desaturation events or loss of autoregulation as detected with NIRS were associated with higher risks of unfavourable outcome at 90 days (RR 4.29 95% CI [2.10;8.79]). Significant associations were also observed with mortality (RR 4.24, 95% CI [2.43;7.41]). Diagnostic accuracy analysis demonstrated moderate sensitivity (0.85), specificity (0.65), and diagnostic odds ratio (10.42), with a receiver operating characteristic (ROC) curve area of 0.68. The certainty of evidence was moderate for the association between NIRS and patient outcomes, and low for its diagnostic accuracy in detecting DCI.The overall quality of evidence was limited by small sample sizes, high heterogeneity in study methods and patient populations, and potential publication bias.

Conclusion Cerebral desaturation events and impaired autoregulation detected by NIRS are consistently associated with poor outcomes and mortality in aSAH. However, NIRS alone provides only moderate diagnostic accuracy for DCI, with a considerable risk of false positives. The evidence is weakened by methodological limitations, heterogeneous thresholds, and the absence of a universally accepted reference standard for DCI diagnosis. Importantly, no

*Correspondence:
Charles L. Francoeur
charles-langis.francoeur.med@ssss.gouv.qc.ca

Full list of author information is available at the end of the article

interventional data are available to demonstrate an effect on patient outcomes. While incorporation into multimodal neuromonitoring strategies appears promising, robust prospective trials are needed before NIRS can be reliably adopted in routine clinical practice.

Keywords Near-infrared spectroscopy, Aneurysmal subarachnoid hemorrhage, Delayed cerebral ischemia, Vasospasm, NIRS

Introduction

Aneurysmal subarachnoid hemorrhage (aSAH) is a devastating type of hemorrhagic stroke that can lead to mortality or significant morbidity. As it disproportionately affects younger populations, it represents one of the leading causes of life-years lost. Among its complications, delayed cerebral ischemia (DCI) emerges in modern clinical series as the primary factor driving long-term unfavourable outcomes [1], doubling the risk of morbidity [2]. Although clinical criteria for the diagnosis of DCI are established, their practical application is often challenging, particularly in patients lacking a reliable neurological examination—such as those with severe aSAH admitted to intensive care units (ICU) [3]. High-grade aSAH patients have an altered level of consciousness and at high risk of developing "asymptomatic" (or undiagnosed) DCI, which may be associated with worse clinical outcomes than symptomatic cases [4]. Timely diagnosis is therefore crucial to optimize DCI management and the need for evidence-based alternatives to clinical examination are needed.

Near-infrared spectroscopy (NIRS) has been advocated as a non-invasive, real-time and continuous cerebral oximetry monitoring with potential applications in the detection, diagnosis and management for DCI [5]. NIRS relies on the emission of near-infrared light (700–850 nm) and the measurement of its attenuation due to absorption and scattering in biological tissue. Absorption mainly reflects concentrations of oxyhemoglobin (HbO_2) and deoxyhemoglobin (HHb), while scattering exacerbated by factors such as brain edema represents the major source of signal distortion [6]. Commercial devices typically use continuous-wave spectroscopy with multiple detectors to improve spatial resolution and mitigate extracranial contamination, although this remains a significant limitation. Probes are usually positioned on the forehead, and the measurement primarily reflects a small venous-weighted compartment (~ 1.5 cm^3 of gray matter) within the anterior and middle cerebral artery territories. Reported baseline values vary across devices and are influenced by proprietary algorithms, rendering absolute comparisons between systems difficult [7–9], although normal values in healthy adults typically range between 60% and 75% [10]. Regional oxygen saturation (rSO_2) reflects the balance between cerebral oxygen delivery and consumption, largely determined by cerebral blood flow (CBF) and cerebral metabolic rate of oxygen ($CMRO_2$). Pathological declines may signal arterial hypotension, low cardiac output, systemic hypoxemia, hyperventilation, stroke, or DCI, while elevations may occur with hyperemia, hypoglycemia, deep sedation, or hypothermia [11–13]. Comparisons with other monitoring modalities, such as brain tissue oxygenation ($PbtO_2$) and jugular venous oxygen saturation ($SjvO_2$), have demonstrated good correlations in dynamic trends, supporting the physiological validity of NIRS [14–17]. Fluctuations in rSO_2 have also been linked to CBF, with changes paralleling those measured by xenon-enhanced CT, CT perfusion (CTP), or invasive thermodilution probes [18].

Beyond oxygenation, NIRS-derived indices have been increasingly used to assess cerebrovascular reactivity. The tissue oxygenation index (TOx) and cerebral oxygenation index (COx) are calculated as a moving correlation coefficients between mean arterial pressure (MAP) (or cerebral perfusion pressure (CPP))and tissue oxygenation index (TOI), and between MAP (or CPP) and rSO_2, respectively [5, 19]. These indices mirror established cerebral autoregulation (CA) markers such as the pressure reactivity index (PRx) or transcranial Doppler derived Mx, providing non-invasive surrogates for dynamic autoregulatory capacity.

Current alternatives for detecting DCI in high-grade aSAH patients are mostly inadequate or unvalidated, highlighting a critical gap in both clinical practice and research. Transcranial Doppler (TCD) and continuous electroencephalography (cEEG) are both recommended by the American Heart Association (AHA) for monitoring patients with aneurysmal aSAH for the early detection of DCI [20]. Both modalities offer high sensitivity and are valuable for screening in patients who are comatose or unable to be reliably examined. TCD measures cerebral blood flow velocities and demonstrates excellent negative predictive value in the detection of DCI [21, 22]. However, it is prone to false positives, is operator-dependent, may be limited by poor acoustic windows, and primarily detects flow changes in large basal vessels, missing microvascular abnormalities that often underlies DCI [23]. cEEG can detect early signs of cortical ischemia through changes in frequency patterns [24]. It may be confounded by sedation or seizures and is resource-intensive, requiring expert interpretation. Furthermore, CTP provides direct assessment of regional cerebral perfusion and is valuable for early identification of patients at risk for DCI [25–27]. However, its accuracy may be

limited by artifacts or coexisting brain injuries, and there is a lack of standardized thresholds for DCI diagnosis [28]. Finally, $PbtO_2$ and cerebral microdialysis [29] provide continuous, real-time monitoring of regional brain oxygenation and metabolism, and have shown potential to identify patients at risk of DCI [30–32]. However, both are invasive, offer only focal information dependent on optimal probe placement, and their generalizability remains limited due to study design and selective patient populations [30, 33].

Although not part of routine standard care, the use of cerebral NIRS monitoring has expanded across some clinical settings. In adults, its use in intensive care remains largely limited to research contexts. By contrast, in perioperative cardiac surgery, cerebral NIRS monitoring has gained broad acceptance and is recommended by expert consensus statements, making it widely used across age groups [34]. For non-cardiac surgery, however, its adoption remains sporadic and not considered standard practice. Previous systematic reviews across neonatal, pediatric, and adult populations, including in very preterm infants, cardiopulmonary bypass, and general surgery, have found no conclusive benefit of cerebral NIRS monitoring. These results are mainly attributed to a paucity of high-quality, low-bias trials.

The present systematic review and meta-analysis had two primary aims. First, to examine the relationship between NIRS metrics and clinically relevant, patient-centered outcomes. Second, to assess the diagnostic performance of NIRS for the detection of DCI. The overarching goal to those objectives is to clarify NIRS potential clinical role as a bedside neuromonitoring tool in aSAH.

Methods

The research questions and study design were developed by a multidisciplinary team of intensivists, neurologists, health information specialists and epidemiologists. The study followed the recommendations of the Cochrane Handbook for Systematic Reviews and Meta-Analyses [35] and the Cochrane Methods for Screening and Diagnostic Tests [36]. Results are reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and the Preferred Reporting Items for a Systematic Review and Meta-analysis of Diagnostic Test Accuracy Studies (PRISMA-DTA) [37, 38]. The protocol was registered in PROSPERO (CRD42020077522) and was previously published [39].

Data source and search strategy

Data sources included MEDLINE, EMBASE, Web of Science, Google Scholar, OpenGrey, the Cochrane Central Register of Controlled Trials, and the Cochrane Database of Systematic Reviews, starting from their inception up to March 2024, as well as pertinent conference proceedings. The search strategy covered the themes of subarachnoid hemorrhage and cerebral oximetry. Medical Subject Headings (MeSH) terms were used to capture the principal elements of the research question, along with appropriate keywords. The applied MEDLINE search strategy (see appendix 1) was adapted for the other databases [39].

Eligibility criteria and study selection

We considered observational and interventional human studies, prospective or retrospective, randomized or not, conducted in adult (≥ 18 years old) patients hospitalised for aSAH. We included studies with mixed neurocritical care populations if aSAH patients made up at least 80% of the total. The studied intervention, NIRS monitoring, had to be evaluated during the hospitalisation, as a continuous or intermittent monitoring, regardless of the study objective (diagnostic, prognostic or management). No specific exposure or detection threshold were required, but we excluded purely exploratory studies without any definition of exposure. Studies limited to perioperative monitoring for aneurysm clipping or coiling procedures were excluded. We applied no language restriction.

Two reviewers (M.R.B. and C.F.) independently screened citations to assess eligibility for inclusion. Discordance was resolved by consensus and, when necessary, by consulting a third reviewer (S.W.E.).

Data extraction and outcome measures

The same reviewers independently extracted data from eligible studies using a standardized, pilot-tested, data extraction form developed using Research Electronic Data Capture (REDCap) [40], a web-based tool.

We extracted information on study characteristics (language of publication, country, study design, total number of patients, inclusion and exclusion criteria, blinding to NIRS, blinding to DCI and to functional evaluation), population characteristics (total number of aSAH patients, age, sex, clinical and radiological grading of SAH, location of aneurysm, number of patients with elevated intracranial pressure, and clinical setting), NIRS monitoring characteristics (type of cerebral oximetry monitor, rSO_2 values, location of sensors, duration of monitoring, other monitoring tools), NIRS results (any discriminative NIRS parameter and any reported association with outcome measures), and co-interventions. Clinical poor grade aSAH was defined as a World Federation of Neurosurgeons Scale (WFNS) grade of 4 or 5 or a Hunt and Hess scale (H&H) score of 4 or 5 at admission [41, 42]. Radiological high-grade was defined as a score of 3 or 4 on the Fisher Scale or the modified Fisher Scale [43, 44].

The primary outcome was the functional outcome at 90 days or more, measured by the modified Rankin Scale (mRS), the Glasgow Outcome Scale (GOS) or its

extended version (GOSe). Secondary outcomes included survival and functional outcomes at any time point. Data pertaining to diagnostic accuracy for DCI (DCI definition, reference standard, true and false positives, true and false negatives, reported sensitivity, specificity, positive predictive values [PPV] and negative predictive values [NPV], reported unadjusted and adjusted effect size) were also extracted. Authors were contacted when important information was missing.

Evidence appraisal

The risk of bias was assessed using the Newcastle-Ottawa Scale [45] for cohort or case–control studies, the Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) [46] for diagnostic studies and the Risk Of Bias in Non-randomized Studies of Interventions (ROBINS-I tool) [47] for non-randomized trials of interventions. Funnel plots were used to detect publication bias. Quality and certainty of evidence were assessed using the GRADE system [48].

Data synthesis and analysis

As described in the previously published protocol [39], studies were categorized and analyzed according to their primary objective: either evaluating the association with clinical outcomes or assessing the diagnostic accuracy for DCI. Studies addressing both objectives were included in both analyses. DCI definitions reported in each study were used. For clinical outcomes, random effects meta-analyses were performed, using the DerSimonian and Laird method. Heterogeneity was assessed using the I^2 statistic combined with the Q-test. All analyses were performed using R Statistical Software [49]. Primary outcome was converted into standardized dichotomous variables with a mRS of 0 to 3 and a GOS of 4 to 5 (or a GOSe 5 to 8) representing a favourable outcome. Planned subgroup analyses were performed based on the association of the exposure on outcomes, when two or more studies evaluated the same exposure, dividing exposure in low rSO2 values (Cerebral Desaturation Episodes – CDE) or impaired CA. For diagnostic accuracy, forest plots and random effects meta-analyses were performed using MetaDTA: Diagnostic Test Accuracy Meta-Analysis v2.1.5 [50], to determine pooled sensitivity, specificity, diagnostic odds ratios and to generate a receiver operating characteristic (ROC) curve.

In cases where multiple publications reported on the same or overlapping cohorts, we prioritized the report with the largest sample size and most complete outcome data, while excluding overlapping companions from quantitative synthesis to prevent duplication.

Results

Study characteristics

A total of 28,296 citations were identified. After duplicate removal, abstract screening and full-text review, 35 studies (n = 1466, 1415 hospitalized with aSAH) were considered eligible (Fig. 1). Three studies, involving 202 patients, were included in meta-analysis for the primary outcome [51–53] (Table 1). Eight studies (417 patients) were included in the meta-analysis of screening and diagnostic accuracy [51–59] (Table 2). No randomised controlled trials (RCT) were identified and no study reported on NIRS-based interventions.

Most patients were women (62%) with a mean age of 56 years old and when reported, poor grade aSAH represented 26% of the patient population. Most ruptured aneurysm (65%) were in the anterior circulation, and aneurysm exclusion approach was evenly distributed between clipping (52%) and coiling (48%). Seven studies evaluated the association between NIRS data and functional outcomes at any time point [51–54, 59–61], but data could be extracted and used for quantitative analysis in only five studies [51–54, 59], three of which evaluated outcomes at 90 days or more [51–53]. Mortality was reported in five studies [51, 52, 54, 59, 62]. Included studies used either the INVOS™ [30, 32] or the Fore-Sight™ [31]. Exposure was mostly based on CDE [51, 53, 54, 59], which was defined at variable rSO_2 thresholds (47% [51], 50% [53], 60% [54], 63% [59]). Two studies required a minimal exposure time of 30 min or more [53, 54]. Finally, one study used loss of CA, based on TOx values above 0.3, to define exposure [52]. Concerning NIRS screening and diagnostic accuracy, DCI was variously defined, and most studies relied on CDE (Table 2). Overall DCI prevalence was 31%.

Association with clinical outcomes

CDE or loss of CA as detected with NIRS was associated with higher risks of unfavourable outcome at 90 days (RR 4.29 95% CI [2.10;8.79]) (Fig. 2). A similar association was observed for risks of unfavourable outcome at any time point (RR 4.18 95% CI [2.45;7.13]) (Fig. 3). Subgroup analysis based on various exposure definitions (rSO2 vs. TOx) yielded similar results. Amongst the five studies reporting mortality (n = 113) [51, 52, 54, 59, 62], exposure to CDE or loss of CA was also associated with higher risks (RR 4.24 95% CI [2.43;7.41]) (Fig. 4).

Screening and diagnostic accuracy

Pooled sensitivity was 0.85 (95% CI 0.56; 0.96) and pooled specificity 0.65 (95% CI 0.57; 0.72) (Fig. 5), with a diagnostic odds ratio (DOR) of 10.42 (95% CI 2.35; 46.25). This represents a PPV of 52% and NPV of 91%, for a diagnostic accuracy of 71%. A ROC curve was plotted with an AUC of 0.68 (95% CI 0.59; 0.77) (Fig. 6).

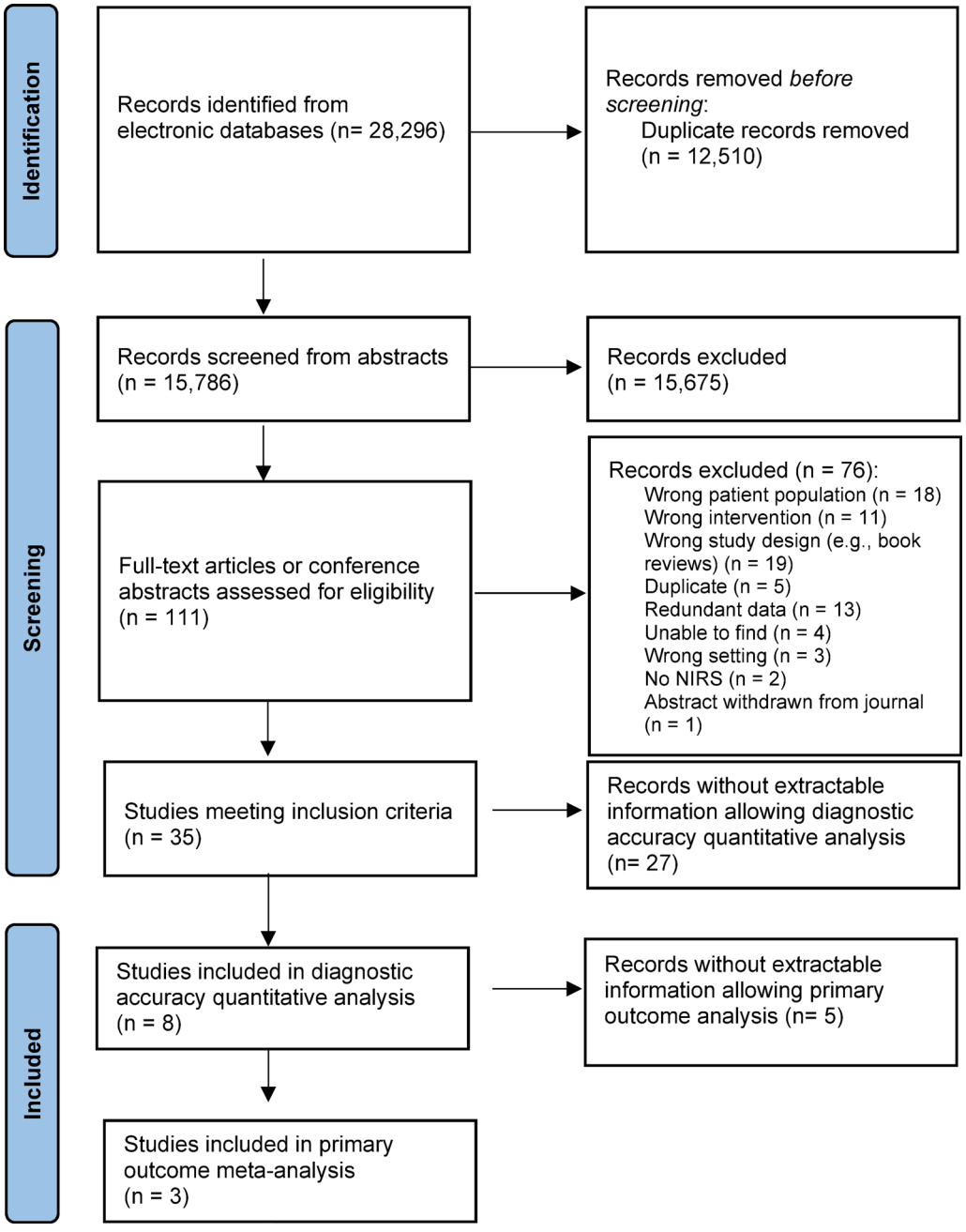

Fig. 1 Preferred reporting items for systematic reviews and meta-analysis flow diagram

Risk of bias assessment and quality of evidence

A detailed methodological quality assessment of the included studies is presented in Appendix 3. Regarding the primary outcome, the main studies were of fair quality. Sensitivity analyses using fixed-effect models yielded results similar to those obtained with random-effects models (Supplementary Material – Figs. 7, 8 and 9). The low number of studies included for the primary outcome precluded meaningful interpretation of funnel plots to assess potential publication bias.

The certainty of evidence regarding the association with functional outcomes, both at 90 days and at any time point, is moderate (Supplementary Material – Appendix – Table 3). However, the quality of evidence concerning the association with mortality was low.

Most studies included in the diagnostic accuracy analysis exhibited a high risk of bias. A contour-enhanced funnel plot (Supplementary Material – Fig. 10) suggests missing studies on the right-hand side, where results would reflect lower diagnostic accuracy; thus, reporting bias cannot be excluded. The certainty of evidence for the

Table 1 Characteristics of studies included in primary outcome meta- analysis

Author	Year	No. of patients	Outcomes	NIRS variable	Quality Assessment (NOS)
Ekelund [51]	1998	14	90days GOS	rSO2 < 50%	Poor
Silverman [52]	2019	28	90 days mRS	TOx > 0.3	Fair
Yousef [53]	2014	139	90 days mRS	CDE: rSO2 < 50% for 30 min	Fair

CDE: cerebral desaturation episode; GOS: Glasgow Outcome Scale; mRS: modified Rankin Scale; NIRS: near-infrared spectroscopy; rSO_2 : regional cerebral oxygen saturation; TOx: tissue oxygenation index

reported sensitivity and specificity is low (Supplementary Material – Appendix – Table 4) [48].

Discussion

In this systematic review and meta-analysis, CDE and impaired CA detected by NIRS are associated with worse neurological outcomes and increased mortality. Statistical heterogeneity is low, results are consistent across studies, and the effect size is significant with an acceptable degree of precision. Quality of evidence varies from moderate to low.

Quantitative analysis of diagnostic accuracy demonstrated a moderate to good capacity of NIRS to detect DCI, albeit with a substantial risk of false positives. Reported sensitivities and specificities varied considerably across studies, and the overall discriminative performance of NIRS in distinguishing patients with and without DCI was only moderate. Although a greater number of studies were included in this analysis, their overall methodological quality was lower.

Table 2 Characteristics of studies included in screening and diagnostic accuracy for DCI

Author	No. of patients	DCI definition	DCI incidence (%)	No. poor grade clinical & radiological	NIRS device	NIRS variable
Burzynska (2020) [54]	38	Consensus[1]	34	16 (42%) 30 (79%)	Foresight	CDE: rS02 < 60% for 30 min
Constantoyannis (2007) [55]	75	Neurologic deterioration	20	0 N/A	INVOS	rSO2 < 52%
Kerr (1999) [56][2]	12	Xe-CT	42	N/A N/A	Unknown	rSO2 < 50%
Park (2020) [57][3]	52	Consensus AND vasospasm	35	23 (44%) 25 (48%)	INVOS	rSO2 decrease >12.7%
Yousef (2014) [53]	163	Consensus AND confirmatory imaging	58	38 (27%) 129 (93%)	INVOS	CDE: rSO2 < 50% for 30 min
Van der Harst (2023) [59]	41	Consensus	29	7 (17%) 15 (36%)	INVOS	rSO2 < 63%
Ekelund (1998) [51]	14	Undefined	7	4 (28%) 9 (64%)	INVOS	rSO2 < 50%
Silverman (2019) [52]	31	Consensus	19	N/A[3] N/A[4]	Foresight	TOx >0.3

DCI: delayed cerebral ischemia; NIRS: near-infrared spectroscopy; rSO2: regional cerebral oxygenation; TOx: tissue oxygenation index; Xe-CT: xenon-enhanced computed tomography

[1]Consensus definition of DCI established in 2010 by a multidisciplinary expert panel [3]

[2]Conference abstract

[3]A subsequent paper by Park et al. [58] reported an overlapping cohort; 23 of the 24 patients had already been included in the 2020 publication. To avoid duplication, the 2021 study was not pooled

Fig. 2 Forest plots describing the risk of unfavourable functional outcome at 90 days or more for patients exposed to CDE or loss of autoregulation detected with NIRS vs. non exposed patients

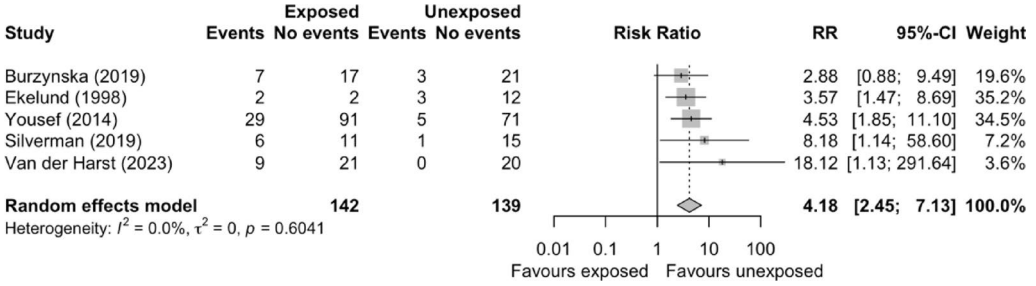

Fig. 3 Forest plots describing the risk of unfavourable functional outcome for patients exposed to CDE or loss of autoregulation detected with NIRS vs. non exposed patients

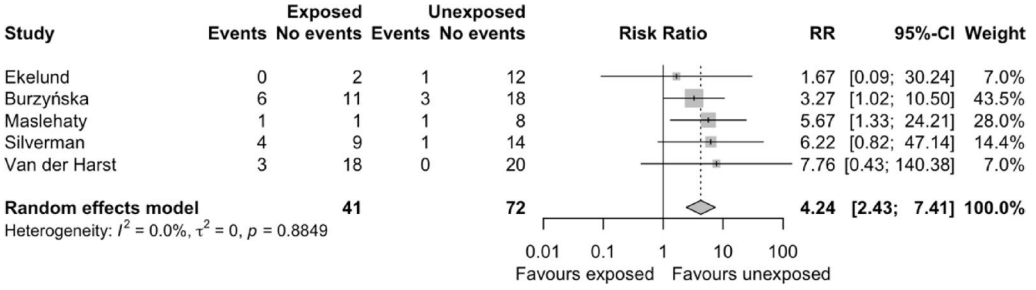

Fig. 4 Forest plots describing the risk of mortality for patients exposed to CDE or loss of autoregulation detected with NIRS vs. non exposed patients

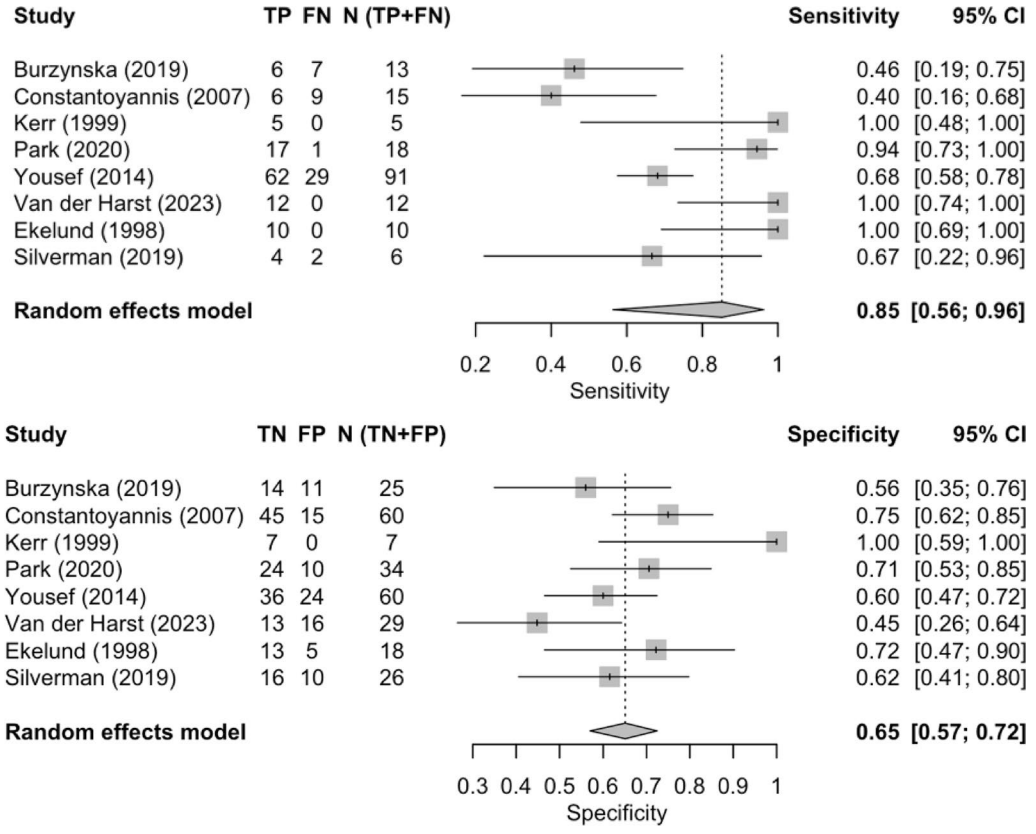

Fig. 5 Forest plots describing the sensitivity and specificity of abnormal NIRS parameters (CDE and TOx) to detect DCI

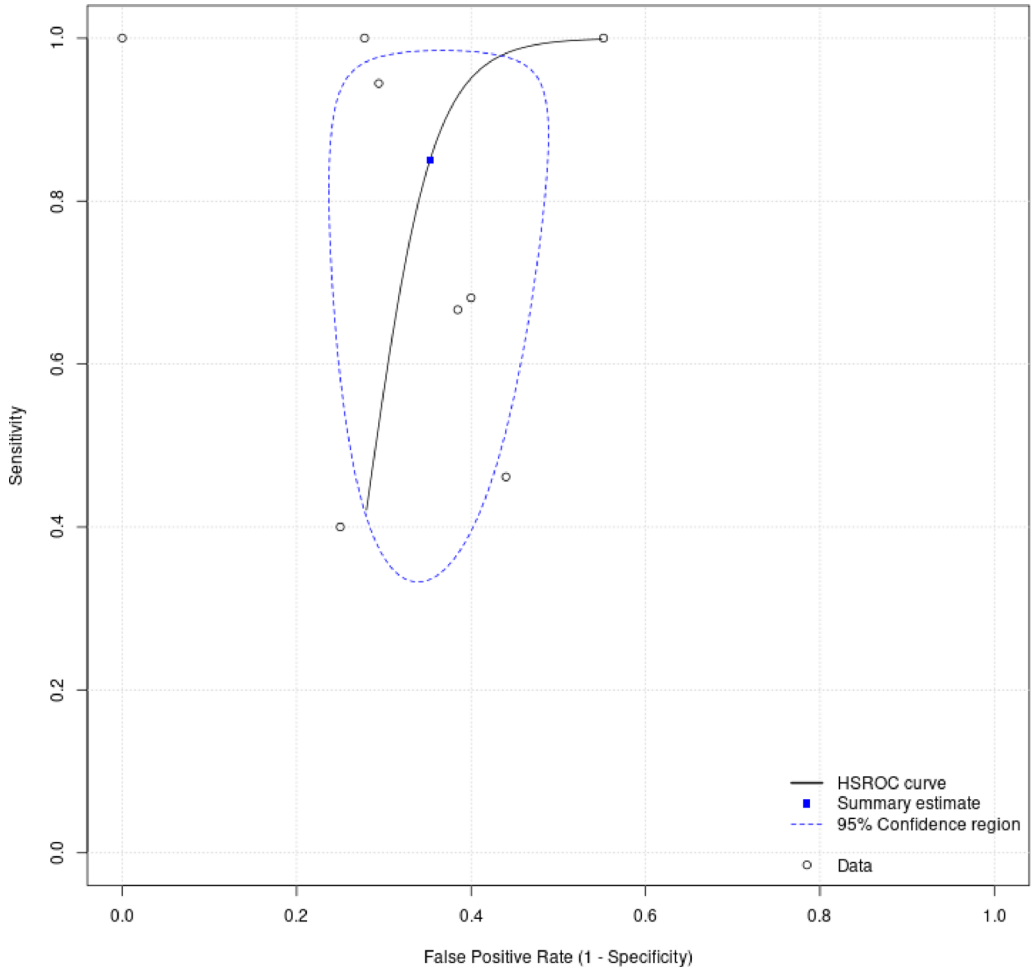

Fig. 6 Summary ROC curve of abnormal NIRS parameters (CDE and TOx) for DCI detection

Our study has several strengths. This systematic review and meta-analysis is the first to quantitatively synthesize the evidence on NIRS in aSAH. Conducted under a preregistered, published protocol and in accordance with contemporary guidelines, it combines rigorous methodology and broad inclusion criteria with a systematic evaluation of the available evidence. The inclusion of quantitative pooling provides more precise estimates of diagnostic accuracy. Beyond summarizing current evidence, the review also identifies critical gaps that should guide future research priorities.

Our study also presents several inherent limitations. Reports on the associations with clinical outcomes rely on observational, unblinded, uncontrolled, single-centered studies with some including less than 15 patients Only three studies reported on outcome at 90 days, and none at later time points, preventing any conclusion about long-term outcomes [63–65]. NIRS parameters used to define brain at risk of injury are quantitatively and conceptually very heterogeneous, preventing any attempt at establishing an intervention threshold or to give precedence to a parameter over another. No study reported on NIRS-based interventions, precluding any definitive conclusion on its role in clinical management.

Concerning the second objective, in the absence of high-quality diagnostic and technological evaluation study, we relied on the inclusion of numerous small studies with heterogeneous methodologies, objectives, and patient populations to appraise NIRS diagnostic capacities. Some decades-old conference abstracts without a follow-up paper were also included, limiting our ability to evaluate the quality of the evidence. The heterogeneous DCI definitions are particularly problematic. The current clinical consensus criteria remain a flawed gold standard, especially in intubated and sedated patients where evaluation is inherently limited [3, 29, 66]. There is imperfect inter-rater reliability in the clinical evaluation [67], and no adjudication process were described in any of the included studies. Furthermore, although vasospasm is a risk factor for developing DCI [22], its use as a surrogate endpoint, as done in some studies [57, 58], is inadequate given that vasospasm may represent an epiphenomenon

rather than a direct cause of ischemia [68–70]. These challenges reflect the broader limitations in our current pathophysiological understanding of DCI. Finally, evidence of funnel plot asymmetry raises concerns regarding potential publication bias, which may have influenced the completeness and balance of the available evidence. (Supplementary Material – Fig. 10).

Although 35 studies met the eligibility criteria, only a minority provided data that could be extracted for quantitative synthesis. It is plausible that high-grade aSAH patients might derive the greatest benefit from continuous bedside monitoring, early DCI detection, and targeted interventions. However, most included studies primarily enrolled low-grade patients, limiting the ability to draw meaningful conclusions for this higher-risk population. Risk of bias and quality assessments were conducted using various recommended tools; however, the lack of consistency among these tools limited our ability to objectively summarize the overall quality of the evidence. Additionally, despite multiple attempts, no supplementary data were obtained from the original study authors.

As noted, the current state of evidence surrounding the use of NIRS in aSAH is limited by several critical factors, despite its widespread availability for over two decades. Current findings do not support the use of NIRS as a standalone tool to detect DCI, due to a lack of sufficient diagnostic accuracy. In high-grade aSAH patients, the scarcity of available options might be put forward as an argument to promote NIRS integration with other diagnostic modalities to improve bedside management, within a multimodal neuromonitoring strategy. Multimodal neuromonitoring aims to combine the strengths of different technologies to offer a more comprehensive, physiologically grounded, and temporally continuous picture of cerebral function [32]. Each of these modalities provides unique, yet limited, insights into cerebral physiology [17, 20, 30, 71]. For example, combining impaired CA measured by TOXa (>0.1) with a TCD-derived index (SXa) within the first five days after ictus resulted in better diagnostic performance for DCI prediction than TOXa or SXa alone [72–74].

Future research should prioritize confirming and refining the NIRS parameters most strongly associated with outcomes. This requires prospective enrollment, prespecified and clearly defined NIRS metrics, with blinded and long-term functional outcome assessment. Importantly, the studied parameters should not only enable intervention before DCI causes irreversible sequelae but should also serve as potential surrogates or therapeutic targets themselves. Such parameters could support, for example, the implementation of therapies to reverse CDEs or guide hemodynamic management based on CA. Once these actionable parameters are validated, randomized controlled trials of NIRS-guided interventions will represent the logical next step. In this context, the upcoming $NeurO_2$ study (NCT04935866), a multicenter cohort study, should provide some much needed insight as aSAH and TBI patients will be monitored with NIRS, in a blinded fashion, and will report long term functional outcomes [75]. An ongoing trial evaluating the impact of targeting a NIRS-directed optimal cerebral perfusion pressures (CPP) on GOS at 6 months in 150 aSAH patients might also provide additional information on the potential utility of NIRS in managing aSAH patients [76].

This systematic review and meta-analysis provides a comprehensive evaluation of the current evidence on the use of NIRS in aSAH. It underscores its potential as a neuromonitoring tool in patients but also highlights its current limitations. While NIRS parameters, such as CDE and TOx, were associated with neurologic functional outcomes and mortality, the diagnostic accuracy of NIRS for DCI remains moderate, with a significant risk of false positives and limited specificity. The lack of consensus on NIRS thresholds or targets for interventions, let alone on the choice of intervention itself, precludes any recommendations for clinical use.

Nevertheless, NIRS's unique advantages, such as non-invasiveness, real-time continuous monitoring, and its potential for integration with other modalities, support ongoing research efforts. Future studies hold promise for clarifying its impact on long-term, patient-centered outcomes. Until then, NIRS should be regarded as a complementary tool rather than a definitive solution for the management of aSAH.

Take-home message

Cerebral desaturation events and impaired cerebral autoregulation detected by NIRS are associated with worse neurological outcomes and increased mortality. Although the use of NIRS to identify DCI is limited by risks of false-positive results and moderate specificity, it remains a potentially valuable clinical adjunct in high-grade aSAH management, given the limited number of alternatives.

Tweet

The authors do not wish to be associated with social media platforms such as X.

Abbreviations

aSAH	Aneurysmal subarachnoid hemorrhage
AUC	Area under the curve
CDE	Cerebral desaturation episode
CI	Confidence interval
COx	rSO_2-derived cerebral autoregulation index
DCI	Delayed cerebral ischemia
DOR	Diagnostic odds ratio
GOS	Glasgow Outcome Scale

GOSe	Extended Glasgow Outcome Scale
HbO_2	Oxyhemoglobin
HHb	Deoxyhemoglobin
ICU	Intensive care unit
MAP	Mean arterial pressure
MeSH	Medical Subject Headings
mRS	Modified Rankin Scale
NIRS	Near-infrared spectroscopy
NPV	Negative predictive value
$PbtO_2$	Brain tissue oxygenation
PPV	Positive predictive value
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRISMA-DTA	Preferred Reporting Items for a Systematic Review and Meta-analysis of Diagnostic Test Accuracy Studies
QUADAS-2	Quality Assessment of Diagnostic Accuracy Studies-2
RCT	Randomized controlled trial
ROC	Receiver operating characteristic
RR	Risk ratio
rSO_2	Regional cerebral oxygen saturation
TOI	Tissue oxygenation index
TOx	TOI-derived cerebral autoregulation index
WFNS	World Federation of Neurosurgeons Scale

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13054-025-05701-3.

Supplementary Material 1

Acknowledgements
Non applicable.

Author contributions
MRB screened citations and articles, extracted data from the included studies, and drafted the manuscript. CF also screened citations and articles, performed data extraction, conducted statistical analyses, and wrote substantial portions of the manuscript. AFT provided significant input on the methodological and statistical aspects of the review and critically revised the manuscript. FL, SWE, and GL critically revised the manuscript.

Funding
The authors declare that no funding was received to support the preparation or submission of this manuscript.

Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval and consent to participate
No ethical approval was requested as no human or animal subjects were involved.

Consent for publication
Non applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Anesthesia, Service of Critical Care Medicine, CHU de Québec—Université Laval, Québec City, Québec, Canada
[2]Department of Medicine, Université Laval, Québec City, Québec, Canada
[3]Department of Neurosciences, Service of Neurology, CHU de Québec—Université Laval, Québec City, Québec, Canada
[4]Population Health and Optimal Health Practices Research Unit (Trauma—Emergency—Critical Care Medicine), CHU de Québec—Université Laval Research Centre, Université Laval, Québec City, Québec, Canada
[5]Division of Critical Care Medicine, Department of Anesthesiology and Critical Care Medicine, Université Laval, Québec City, Québec, Canada
[6]Acute Care Research, Ottawa Hospital Research Institute, Ottawa, ON, Canada
[7]Division of Critical Care, Department of Medicine, University of Ottawa, Ottawa, ON, Canada
[8]Population Health and Optimal Health Practices Research Unit (Trauma—Emergency—Critical Care Medicine),, CHU de Québec—Université Laval Research Centre, 1401 18e rue, Québec G1J 1Z4, Canada

Received: 3 July 2025 / Accepted: 1 October 2025
Published online: 14 November 2025

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