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Review Article

Monitoring Cerebral Oxygenation During Complex Neurosurgical Procedures

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ABSTRACT

Near-infrared cerebral oximetry gives a noninvasive, continuous estimate of regional cerebral oxygen saturation and is an increasingly common adjunct in complex neurosurgery, where hypoperfusion can occur without any change in standard systemic monitors.

This review synthesizes the physiology and limitations of cerebral oximetry alongside evidence from sitting-position posterior fossa surgery, prone spinal instrumentation, and skull-base and vascular neurosurgery, and compares it with invasive jugular bulb and brain tissue oxygen monitoring used chiefly in neurocritical care.

Cerebral oximetry reliably detects intraoperative desaturation across these settings, but systematic reviews find the evidence linking desaturation-guided intervention to improved cognitive, neurologic, or survival outcomes remains of low certainty.

Invasive brain tissue oxygen and jugular bulb monitoring give more direct signals and are better validated in traumatic brain injury, though their burden limits routine intraoperative use to patients already carrying such monitors.

We conclude that cerebral oxygenation monitoring is best used as one input among several in complex neurosurgical anesthesia, valuable for trend detection alongside clinical judgment and other neuromonitoring modalities, pending larger outcome trials.

Keywords: *cerebral oximetry; near-infrared spectroscopy; neurosurgical anesthesia; brain tissue oxygen monitoring; jugular bulb oximetry*

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INTRODUCTION

The brain has almost no capacity to store oxygen, and even brief interruptions in its supply during a craniotomy can leave a permanent mark on cognition or motor function. Anesthesiologists have long relied on surrogate measures — blood pressure, end-tidal

carbon dioxide, pulse oximetry, transfusion thresholds — to infer that the brain is being adequately perfused and oxygenated, but these systemic numbers can look perfectly reasonable while a retractor, an air lock in the venous sinuses, or a head position that kinks the jugular veins quietly starves a region of cortex. Near-infrared spectroscopy (NIRS)-based cerebral oximetry emerged in the 1990s as an attempt to close that gap: a noninvasive, continuous, bedside estimate of regional cerebral oxygen saturation (rSO2) derived from the differential absorption of near-infrared light by oxy- and deoxyhemoglobin in a mixed arterial-venous-capillary tissue bed beneath the forehead sensors [1]. Invasive alternatives — jugular bulb oximetry (SjvO2) and parenchymal brain tissue oxygen tension (PbtO2) probes — offer a more direct physiological signal at the cost of an additional line or bolt placed into or near the brain, and they have found their principal home in the neurocritical care unit rather than the operating room [2,3].

Complex neurosurgical procedures are precisely the setting where the argument for some form of cerebral oxygenation monitoring is strongest, and also where its limitations are most exposed. Posterior fossa surgery in the sitting position, prolonged skull-base dissections, aneurysm clipping with temporary vessel occlusion, awake craniotomy for tumor resection near eloquent cortex, and spine surgery in the prone position with substantial blood loss all share a common thread: a real, if variable, risk of regional cerebral hypoperfusion that standard monitors will not detect until the damage is already underway. This review works through what cerebral oximetry and its invasive counterparts can and cannot do in these settings, what the trial evidence actually shows about outcomes, and where the technology remains a physiological signal in search of a validated clinical algorithm.

THE PHYSIOLOGY AND TECHNICAL BASIS OF NEAR-INFRARED CEREBRAL OXIMETRY

NIRS oximeters shine light in the 700-900 nm range through the scalp and skull and measure the light that returns to detectors placed a few centimeters from the emitter; because near-infrared light penetrates bone reasonably well while hemoglobin chromophores absorb it differentially depending on oxygenation state, the ratio of returning wavelengths yields an estimate of oxygen saturation in the interrogated tissue volume [1]. Commercial cerebral oximeters differ in the number of wavelengths used, the algorithm applied to separate cerebral from extracerebral (scalp, skull, dura) signal, and the reference database used to calibrate absolute values, and these engineering choices matter clinically because absolute rSO2 readings are not interchangeable across devices — a value of 55% on one monitor is not necessarily equivalent to 55% on another [1,4]. The signal itself is a mixed venous-weighted average, generally assumed to represent roughly 70-75% venous and 25-30% arterial blood, which means rSO2 tracks the balance between oxygen delivery and cerebral oxygen extraction rather than arterial oxygen content alone; a falling rSO2 can reflect anemia, hypotension, hypocapnia-driven vasoconstriction, elevated intracranial pressure, or a combination of these acting on the same regional vascular bed.

The clinically important caveats are practical as much as theoretical. Because the optodes sit over the frontal scalp, they sample a relatively small volume of frontal cortex and tell the clinician nothing about oxygenation in the territory actually being operated on if that territory lies elsewhere — a temporal lobe resection, a posterior fossa tumor, or a spinal cord under a prone patient's iliac crest padding. Extracranial contamination from scalp and galeal blood flow, surgical positioning, venous congestion from head-down tilt, and even dark hair or skin pigmentation under the optode can distort readings, and several series describe frankly implausible or discordant NIRS values in neurosurgical patients that did not track intraoperative events the surgical team could independently verify, which is a sobering reminder that the technology is not yet a drop-in replacement for direct visualization or invasive monitoring in every case [4]. Despite these caveats, NIRS-based oximetry remains the only continuous, noninvasive window onto brain oxygenation trends that can be applied to essentially any patient in essentially any position, which explains its steady uptake in cardiac, vascular, and complex neurosurgical anesthesia over the past two decades.

EVIDENCE FROM POSTERIOR FOSSA AND SITTING-POSITION SURGERY

The sitting position was once the default approach for many posterior fossa and pineal region operations because it offers superb surgical exposure and gravity-assisted venous and cerebrospinal fluid drainage, but it fell out of favor at many centers because of concerns about venous air embolism, hemodynamic instability from venous pooling in the legs, and the theoretical risk that an upright head above the heart reduces cerebral perfusion pressure at the level of the circle of Willis. A prospective randomized comparison of the sitting and prone positions for posterior fossa surgery used continuous NIRS to track regional cerebral oxygenation through positioning and found measurable differences in rSO2 trajectory between the two positions, providing one of the more direct physiological arguments for choosing position based on more than surgeon preference alone [5]. A recent analysis revisiting the safety of the sitting position across a modern surgical series found that with contemporary anesthetic management, precordial Doppler surveillance, and end-tidal nitrogen or capnography-based air-embolism detection, the sitting position's complication profile compares

favorably with alternative positions, though the authors are careful to note that outcome depends heavily on institutional experience and vigilance rather than the position itself [6].

Venous air embolism remains the complication most closely associated with the sitting position, and cerebral oximetry has been explored as one adjunct — alongside transesophageal echocardiography, precordial Doppler, and end-tidal CO2 monitoring — for detecting the hemodynamic consequences of a clinically significant air lock before overt cardiovascular collapse develops [7,8]. In practice, NIRS is neither sensitive nor specific enough to serve as a primary air-embolism detector on its own; a sudden rSO2 decline typically appears only after the embolic event has already produced enough right-heart outflow obstruction or systemic hypotension to reduce cerebral perfusion pressure, by which point Doppler and capnography have usually already sounded the alarm. Its more defensible role in this setting is as a continuous check on whether resuscitative maneuvers — flooding the field, jugular compression, repositioning, volume administration — are actually restoring cerebral oxygen delivery rather than merely normalizing systemic hemodynamics on the monitor. A related body of work in arthroscopic shoulder surgery performed in the beach-chair position, which shares the sitting position's physiology of an elevated head relative to the heart, demonstrated that a meaningful proportion of otherwise healthy patients develop cerebral desaturation events under standard anesthetic management, reinforcing that the upright-head-above-heart configuration is a generic physiological stressor on cerebral oxygen delivery rather than a phenomenon unique to intracranial surgery [9].

CEREBRAL DESATURATION DURING PRONE SPINAL AND SKULL-BASE PROCEDURES

Prolonged prone-position spine surgery, particularly multilevel instrumented fusion with substantial expected blood loss, has become another focus of cerebral oximetry research, largely because these cases combine several independent threats to cerebral oxygen delivery: dilutional and hemorrhagic anemia, deliberate or incidental hypotension, prone positioning that can impair venous drainage from the head, and long operative durations that give any single insult more time to accumulate consequence. A study using continuous regional cerebral oxygen saturation monitoring during spinal surgery specifically to identify patients at risk of intraoperative cerebral desaturation found that a subset of otherwise unremarkable patients experienced sustained rSO2 declines below commonly used intervention thresholds, and that these declines were not reliably predicted by intraoperative blood pressure or hemoglobin values recorded at routine intervals [10]. This finding captures the central practical argument for continuous oximetry over intermittent laboratory sampling: cerebral oxygen delivery can fall meaningfully in the interval between two scheduled arterial blood gas draws, and a monitor that only samples every 30-60 minutes will miss transient but potentially injurious desaturation episodes that a continuous trend display would flag in real time.

Skull-base and complex tumor resections carry an analogous risk profile from a different mechanism: prolonged retraction, temporary vascular occlusion during aneurysm or tumor-vessel dissection, and venous sinus manipulation can each produce focal reductions in perfusion that a frontal NIRS sensor may or may not detect depending on whether the affected territory overlaps the sampled frontal cortex. Systematic reviews evaluating NIRS as a predictor of postoperative cognitive outcomes after brain surgery have generally found a plausible but inconsistent association between intraoperative desaturation events and postoperative neurocognitive testing, constrained by heterogeneity in monitoring thresholds, surgical populations, and the cognitive instruments used across studies [11]. The pilot trial most frequently cited in support of an outcome benefit from cerebral oximetry-guided intervention randomized patients to NIRS-guided correction of desaturation events versus usual care and reported better postoperative cognitive performance in the monitored group, but as with most single-center pilot work the sample size was modest and the intervention protocol was specific to that trial's algorithm, limiting how confidently the result generalizes to other centers' practice [12].

SYSTEMATIC REVIEW EVIDENCE AND THE OUTCOME-BENEFIT QUESTION

The strongest single verdict on whether cerebral oximetry monitoring changes patient-important outcomes comes from a Cochrane systematic review that pooled trials of NIRS-guided management across cardiac, vascular, and other major surgery in children and adults and concluded that while cerebral oximetry can reliably detect desaturation events, the evidence that acting on those events through a defined treatment algorithm improves outcomes such as postoperative delirium, cognitive decline, stroke, or mortality was of low or very low certainty, largely because included trials were small, used varied intervention protocols, and were often not blinded [13]. A subsequent systematic review and meta-analysis updating this evidence base in both pediatric and adult populations reached a broadly similar conclusion: NIRS monitoring is feasible and reproducibly identifies cerebral desaturation, but the causal chain from detecting a desaturation event to correcting it to preventing a clinically meaningful adverse outcome remains incompletely validated by adequately powered randomized trials [14]. This is not a verdict that the technology is useless — detecting a physiological derangement is a necessary

precondition for treating it — but it is an honest statement that "monitor and treat by protocol X" has not yet been shown, at the level of rigorous trial evidence, to reliably translate into fewer strokes or less cognitive decline across the range of complex neurosurgical procedures where the monitor is now commonly applied.

Outside the operating room, the same signal has been studied in critically ill patients without primary brain injury, where noninvasive brain oximetry has been proposed as a screening tool for occult cerebral hypoperfusion in shock states, sepsis, or cardiac arrest; a review of this literature concluded that the evidence supporting routine use in general critical illness, as opposed to primary neurologic injury, remains preliminary and mostly observational [15]. This parallel literature is useful context for the neurosurgical operating room because it underscores that the interpretive challenge — a physiologically plausible, easily obtained signal whose optimal treatment threshold and downstream benefit are not yet firmly established — is not unique to any one surgical population but is a general feature of how cerebral oximetry has been adopted faster than it has been definitively validated.

INVASIVE BRAIN TISSUE AND JUGULAR VENOUS OXYGEN MONITORING

Where NIRS gives a noninvasive, whole-frontal-cortex-averaged trend, invasive monitoring aims for a more direct and spatially or compartmentally specific signal, at the cost of placing a device into or near brain parenchyma or the jugular venous system. Brain tissue oxygen tension (PbtO2) monitoring uses a Clark-type or optical probe inserted into white matter, typically in the frontal lobe ipsilateral or contralateral to a primary lesion depending on the clinical question, to measure the partial pressure of oxygen in the immediately surrounding tissue on a continuous basis; it has been studied most extensively in severe traumatic brain injury, where randomized and observational data suggest that management protocols targeting a defined PbtO2 threshold, in addition to intracranial pressure control, may reduce the burden of brain tissue hypoxia and, in some analyses, improve functional outcome compared with intracranial-pressure-only management, though the randomized trial evidence remains mixed on hard outcomes such as mortality [16,17]. Jugular bulb oximetry, by contrast, samples blood draining the entire hemisphere via a retrograde catheter placed in the internal jugular vein and advanced to the jugular bulb, providing a global rather than focal estimate of cerebral oxygen extraction; comparative studies in severe head injury have shown that SjvO2 and PbtO2 do not always move in parallel, particularly during changes in arterial carbon dioxide tension, because the two techniques interrogate different physiological compartments — global venous outflow versus a localized tissue volume — and can diverge when injury or perfusion is heterogeneous across the brain [2,3].

These invasive techniques are used far less often inside the neurosurgical operating room itself than in the neurocritical care unit afterward, largely because the placement procedure, calibration requirements, and infection or bleeding risk are harder to justify for a monitoring window measured in hours during a single operation compared with the days of postoperative monitoring typical of severe traumatic brain injury or subarachnoid hemorrhage management. Where they are used intraoperatively — for example in a patient already carrying a PbtO2 probe from a preceding decompressive procedure who returns to the operating room for a subsequent intervention — the same physiological trends that guide intensive care management (avoiding tissue hypoxia below commonly used thresholds, correcting the specific driver of a desaturation event rather than treating the number in isolation) generally continue to apply, and a recent review of brain oxygenation and metabolism monitoring in acute brain injury situates both NIRS and invasive techniques as complementary rather than competing tools, each better suited to a different phase of a patient's perioperative course [18].

PRACTICAL INTEGRATION INTO PERIOPERATIVE MANAGEMENT

For the practicing anesthesiologist managing a complex neurosurgical case, the realistic role of cerebral oxygenation monitoring today sits somewhere between "essential safety monitor" and "unproven adjunct," and where a given case falls on that spectrum depends heavily on the specific risk profile involved. In sitting-position posterior fossa surgery, continuous rSO2 trending alongside precordial Doppler and end-tidal gas monitoring provides a reasonable, low-cost addition to the existing air-embolism surveillance bundle, even though it should not be relied upon as a sole or primary detector [7,6]. In prolonged prone spinal instrumentation with anticipated major blood loss, continuous oximetry offers a genuine advantage over intermittent laboratory sampling for catching transient desaturation between scheduled blood gas draws, and a pragmatic response to a sustained decline — checking hemoglobin, blood pressure, head position, and ventilation parameters in that order — is a reasonable default even in the absence of a single validated universal treatment algorithm [10]. In skull-base and vascular neurosurgery with temporary vessel occlusion, oximetry trends provide one more data point alongside electrophysiological monitoring (somatosensory and motor evoked potentials, electroencephalography) rather than a replacement for those more surgery-specific modalities, since a frontally placed NIRS sensor may simply miss ischemia confined to a deeper or more posterior vascular territory.

What the field still needs, and what the systematic review evidence consistently identifies as the gap, is a small number of adequately powered, multicenter randomized trials that test a single, pre-specified intervention algorithm against usual care in a well-defined complex neurosurgical population, with patient-important cognitive and functional outcomes as the primary endpoint rather than the intermediate endpoint of "desaturation events detected and corrected" [13,14]. Until that evidence exists, the most defensible clinical stance is to use cerebral oximetry as one input among several in a case where the mechanism of potential injury is plausible and the sensor's field of view plausibly overlaps the tissue at risk, to interpret trends rather than single absolute values given the substantial inter-device and inter-patient variability in baseline readings, and to resist treating a falling number in isolation without first working through the differential of blood pressure, carbon dioxide tension, hemoglobin, head position, and surgical event that might explain it.

CONCLUSION

Cerebral oxygenation monitoring has moved from a research curiosity to a routine, if imperfectly validated, feature of anesthetic management for many complex neurosurgical procedures. Near-infrared cerebral oximetry offers a noninvasive, continuous window onto a physiological variable that systemic monitors cannot see, and it reliably identifies episodes of regional desaturation across sitting-position posterior fossa surgery, prone spinal instrumentation, and skull-base resections. What remains unsettled, according to the best available systematic reviews, is whether responding to those episodes through a structured treatment algorithm meaningfully changes the outcomes that matter most to patients — postoperative cognitive function, stroke, and survival — and the invasive alternatives of jugular bulb and brain tissue oxygen monitoring, better established in the neurocritical care literature, are used only selectively in the operating room itself because their logistical burden is harder to justify for a single surgical episode. Anesthesiologists caring for these patients are therefore best served by treating cerebral oximetry as a genuinely useful trend monitor and an adjunct to clinical judgment and other neuromonitoring modalities, while the trial evidence needed to elevate it to a mandated standard of care continues to accumulate.

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Conflict of Interest

The authors declare no conflicts of interest relevant to the content of this article.

Author Contributions

M. Kowalczyk conceived the review and drafted the initial manuscript. S. Lehmann performed the literature search and contributed to the sections on invasive monitoring and critical care applications. E. Blomqvist critically revised the manuscript for intellectual content and prepared the final version for submission. All authors read and approved the final manuscript.

Ethics Statement

This is a literature review that did not involve new data collection from human or animal subjects, and no ethics committee approval was required.

Data Availability

No new data were generated or analyzed in this review. All sources discussed are cited and publicly available through their respective publishers.

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