Saturation Isn't Flow: Limitations of Cerebral Oxygenation Sensors for Perfusion Assessment and the Value of Noninvasive Regional Cerebral Blood-Flow Monitoring

Clinical cerebral near-infrared spectroscopy (NIRS) systems such as INVOS (Medtronic) and FORE-SIGHT (BD) are widely used as adjunct monitors of regional cerebral oxygen saturation (rSO_2). These trends are often utilized to infer cerebral perfusion status in intraoperative and critical-care settings. However, rSO_2 is a venous-weighted tissue hemoglobin metric that reflects the balance between cerebral oxygen delivery (blood flow × arterial oxygen content) and metabolic demand ($CMRO_2$), not blood flow itself; therefore, when autoregulation is intact and oxygen extraction fraction (OEF) rises to compensate, rSO_2 can remain relatively stable despite moderate reductions in cerebral blood flow. (1). This limits the timeliness and granularity of rSO_2 for perfusion assessment.

Controlled intraoperative models illustrate this buffering. Across two randomized trials of functional endoscopic sinus surgery using deliberate hypotension, mean arterial pressure was reduced by approximately 20 to 30 percent yet cerebral rSO_2 changed only minimally (about zero to five percent on average), and no patients met critical desaturation criteria. (2), (3) Taken together, these data show that rSO_2 can remain relatively unchanged when moderate perfusion declines are offset by cerebral autoregulation and increased oxygen extraction, which limits its utility as a real-time index of regional cerebral blood flow.

Clinical protocols reflect this physiology by using relatively large rSO_2 thresholds to trigger intervention, commonly a ≥20% decline from individual baseline and/or an absolute value below about 50–55%. (3) Additionally, head-to-head hypoxia studies also show device-dependent dynamics and differences in reaching common thresholds during identical physiologic challenges.(4) Cerebral NIRS also lacks tight cerebral specificity because a meaningful portion of the optical path traverses scalp and skull. Forehead cuff experiments that induce isolated scalp ischemia demonstrate substantial rSO_2 decreases on cerebral oximeters without intracranial change, confirming that extracranial tissues can materially contribute to the measured signal and confound interpretations.(5) Systematic reviews highlight this as well the variability across clinically available devices. (6)

A flow-based metric quantifies cerebral perfusion itself, not the downstream balance of delivery and extraction. OpenMotion uses speckle-contrast optical sensing (SCOS), a camera-based variant of diffuse correlation optics, to quantify microvascular blood-flow dynamics from speckle fluctuations produced by moving red blood cells. The system's pulsed near-infrared illumination and multi-camera detector array are integrated inside the wearable headset, improving signal-to-noise, reducing fiber-motion artifacts, and enabling beat-to-beat relative blood-flow waveforms. OpenMotion employs centimeter-scale source–detector separations (on the order of ~2.5–3.2 cm) to weight deeper cortical microvasculature and thereby increase cerebral specificity compared with surface-weighted techniques such as laser speckle contrast imaging or laser Doppler perfusion monitoring. Beat-to-beat temporal fidelity has been demonstrated with Openwater's wearable optical system. In a peer-reviewed validation, beat-to-beat optical relative blood-flow waveforms on the forehead correlated strongly with beat-to-beat transcranial

Doppler cerebral blood-flow velocity during breath-hold hypercapnia; the linear fit slope indicated close agreement, and waveform-based reactivity metrics were concordant with Doppler. (7)

In practical terms, clinically available NIRs devices are indicated as adjunct trend monitors of regional tissue oxygen saturation, not direct measures of cerebral blood flow. They are valuable for detecting large or sustained oxygenation changes, but they are severely limited in detecting rapid, real-time changes in cerebral blood flow or perfusion pressure; moreover, their oxygenation-based measurements are susceptible to contributions from extracranial/superficial tissues that may not reflect true cerebral physiology. A noninvasive flow metric that operates at the beat-to-beat time scale and samples deeper tissue volumes addresses these limitations by measuring a variable mechanistically tied to perfusion, as demonstrated by Openwater's OpenMotion system with beat-to-beat, cortical-weighted rBF waveforms validated against TCD.

References

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