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REVIEW ARTICLE

Optical imaging for human brain mapping

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Abstract

Optical imaging modalities for human brain mapping are noninvasive neuroimaging techniques that utilize light, typically in the near-infrared (NIR) wavelengths, to visualize and measure brain physiology and activity. These modalities provide critical insights into cerebral physiology by capturing hemodynamic and metabolic changes. They provide benefits such as real-time monitoring, portability, safety (no ionizing radiation), and cost-effectiveness. This comprehensive review outlines the current status of optical brain mapping technologies, highlighting key methods such as functional NIR spectroscopy and diffuse optical tomography while describing their effectiveness capabilities. It also traces the field's historical development from the past 10 years to current high-density optical imaging systems. Future directions are discussed, including emerging innovations to improve spatial resolution, depth penetration, and integration with other modalities, which promise to expand the utility of optical neuroimaging. These optical imaging techniques have become indispensable tools for neuroscience research and clinical brain mapping, and continued advances offer promising prospects for enhancing our understanding of the human brain.

Keywords: *Optical imaging. Brain mapping. Functional near-infrared spectroscopy. Neuroimaging.*

Imagenología óptica para cartografiar el cerebro humano

Resumen

Las modalidades de imagen óptica para cartografiar el cerebro humano son técnicas de neuroimagen no invasivas que utilizan la luz, normalmente en las longitudes de onda del infrarrojo cercano, para visualizar y medir la fisiología de la actividad cerebral. Estas modalidades proporcionan información esencial sobre la fisiología cerebral al captar los cambios hemodinámicos y metabólicos. Ofrecen ventajas como la monitorización en tiempo real, la portabilidad, la seguridad (sin radiación ionizante) y la rentabilidad. Esta revisión esboza el estado actual de las tecnologías de cartografía cerebral óptica, destacando métodos clave como la espectroscopia funcional en el infrarrojo cercano y la tomografía óptica difusa, al tiempo que describe sus capacidades. También traza el desarrollo histórico del campo desde hace diez años hasta los actuales sistemas de imagen óptica de alta densidad. Se analizan las direcciones futuras, incluidas las innovaciones emergentes para mejorar la resolución espacial, la penetración en profundidad y la integración con otras modalidades, que prometen ampliar la utilidad de la neuroimagen óptica. Estas técnicas de imagen óptica se han convertido en herramientas indispensables para la investigación neurocientífica y el mapeo cerebral clínico, y los continuos avances ofrecen perspectivas prometedoras para mejorar nuestra comprensión del cerebro humano.

Palabras clave: *Imagen óptica. Mapeo cerebral. Espectroscopía funcional en el infrarrojo cercano. Neuroimagen.*

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Introduction

Optical imaging modalities have significantly advanced over the past decade, becoming valuable tools for non-invasive human brain mapping. Techniques such as functional near-infrared spectroscopy (fNIRS), diffuse optical tomography (DOT), diffuse correlation spectroscopy (DCS), hyperspectral imaging (HSI), and photoacoustic imaging (PAI) measure neural activity and hemodynamics through light-tissue interactions. These methods are portable, safe, and cost-effective compared to magnetic resonance imaging (MRI) or positron emission tomography (PET), allowing bedside or naturalistic use, especially suitable for infants or active subjects[1]. fNIRS and DOT use near-infrared (NIR) light (650-900 nm) to detect oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) changes linked to neural activation[1]. DCS estimates real-time cerebral blood flow (CBF) by analyzing fluctuations of coherent NIR light[2]. HSI differentiates cortical tissues based on spectral reflectance, aiding tumor identification and assessing tissue oxygenation[3,4]. PAI combines optical contrast with ultrasonic detection, achieving deeper tissue penetration and high-resolution imaging despite skull-induced acoustic challenges[5]. From 2015 to 2025, these modalities have increasingly contributed to cognitive neuroscience, neurodevelopmental studies, and clinical neurology. A representative schematic of the modalities covered in this work is depicted in figure 1A. This review summarizes recent advancements, methodological trends, limitations, and future directions in optical brain mapping, following Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) 2020 guidelines[6].

Methodology

Search strategy

We performed a systematic literature search to identify relevant studies from January 2015 up to March 1, 2025. The search encompassed multiple databases: PubMed/MEDLINE, Web of Science, Scopus, and IEEE Xplore, to capture both biomedical and engineering literature. We used Boolean search queries combining terms for optical imaging modalities and brain mapping. For example, the PubMed query is illustrated in figure 1B:

For reproducibility, the full Boolean search strings for each database are provided in table 1 of the Supplementary Material. We also hand-searched reference lists of relevant papers and prior reviews to ensure inclusion of any studies missed by the database search. All results were imported into a reference manager, and duplicates were removed[7]. This review was conducted following the PRISMA 2020 reporting guidelines[6], aiming for a transparent and reproducible selection process.

Prescreening and eligibility criteria

We included primary research articles meeting the following criteria: (1) published in English in peer-reviewed journals between 2015 and 2025; (2) involved *in vivo* human participants (either healthy individuals or patients) undergoing brain mapping with one or more of the optical modalities of interest (fNIRS, DOT, DCS, HSI, PAI); (3) reported functional brain data (e.g. neural activation, hemodynamic changes) or diagnostic imaging relevant to brain structure/function. We excluded animal studies, cadaver or phantom studies, technical papers without *in vivo* human data, editorials/commentaries, and conference abstracts.

The selection process proceeded in two stages. First, one reviewer screened titles and abstracts of all retrieved records for relevance to human optical brain imaging. Obviously, irrelevant records were excluded at this stage. Next, full-text of potentially eligible articles was obtained and assessed against the inclusion criteria. Studies that did not explicitly report results from human brains (e.g., purely simulation or algorithm development papers) were excluded. In total, the search identified n = 1,247 records after duplicate removal, of which n = 220 articles underwent full-text screening. Finally, n = 118 studies were deemed eligible and included in this review. A PRISMA 2020 flow diagram (Fig. 2) illustrates the study identification and selection process.

Risk of bias assessment

A formal risk of bias assessment was performed on the included studies to gauge the reliability of their findings. Given that many studies evaluated imaging modalities against clinical or neuroimaging benchmarks (diagnostic-type studies) or reported observational results, we employed the quality assessment of diagnostic accuracy studies-2 (QUADAS-2) tool for quality assessment[8]. Each study was assessed in four domains: patient selection, index test, reference standard, and flow and timing. Signaling questions for each domain were answered based on information in the

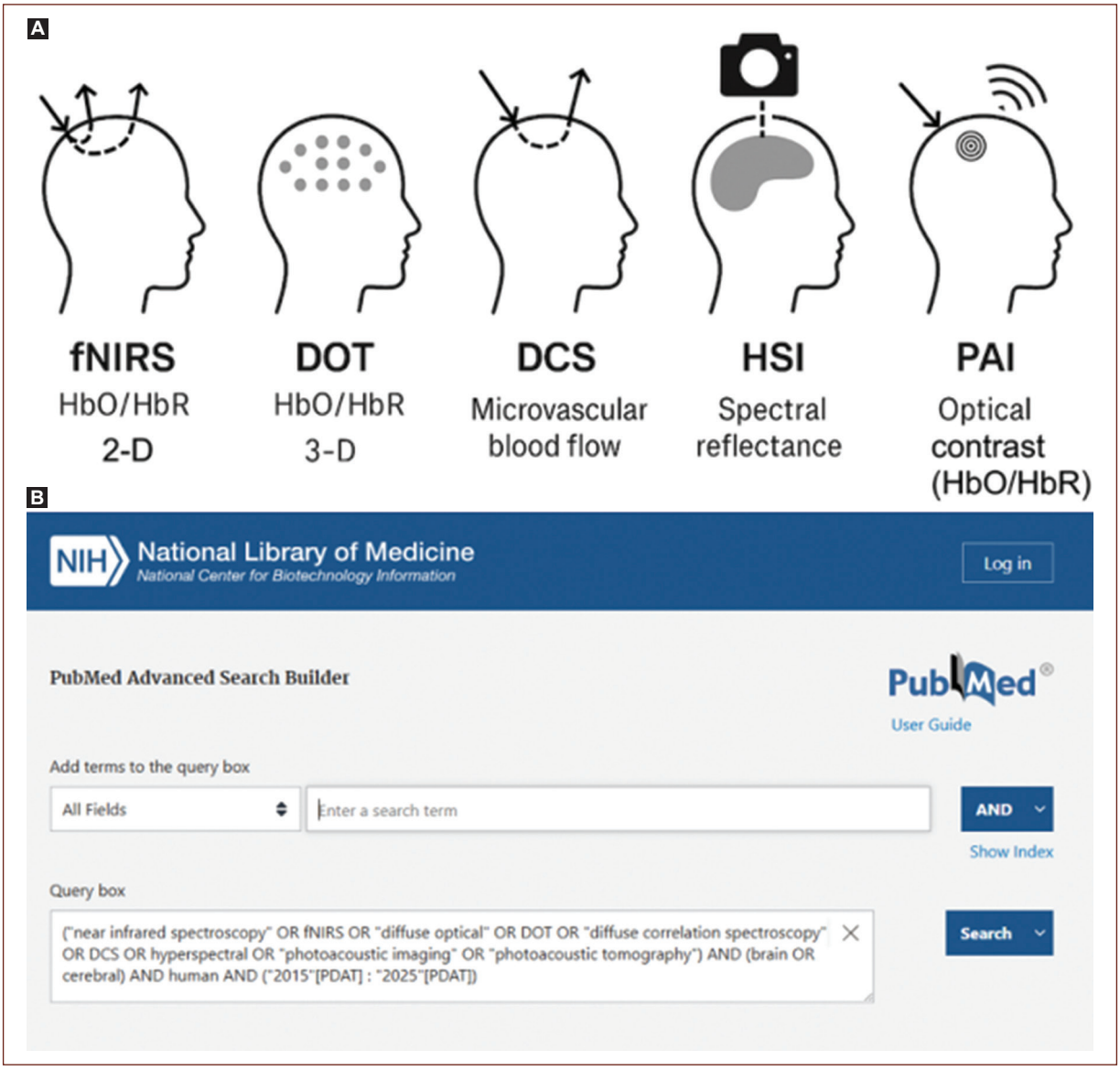

Figure 1. Overview of imaging techniques and literature search strategy. **A:** a representative schematic of the imaging modalities included in this review. **B:** example of a search query.

papers, and each domain was rated as "Low," "High," or "Unclear" risk of bias per guidelines[8]. A single reviewer (the first author) performed the risk of bias assessment for all studies. We acknowledge that having a single reviewer conduct the study screening and bias assessments is a methodological limitation; ideally, two or more independent reviewers would carry out these steps to strengthen rigor and reduce potential bias. Nevertheless, the reviewer adhered to the standardized QUADAS-2 protocol and consulted with co-authors regarding any uncertainties to mitigate subjectivity.

Results

A total of 118 studies met our inclusion criteria, encompassing applications of fNIRS, DOT, DCS, HSI, and PAI in human brain mapping from 2015 to 2025. We organized the findings by modality, highlighting key technical developments, typical applications, and overarching trends for each. These 118 primary studies form the basis of the results summarized by technique as shown in table 1.

Across optical brain-imaging methods, fNIRS and high-density DOT provide centimeter-deep cortical coverage with spatial resolutions of roughly 5-30 mm and

Table 1. Summary of 118 optical brain-imaging studies published 2015-2025, grouped by modality, typical human populations investigated, and representative key findings

Modality	Studies (n) 2015-2025	Typical human populations	Representative key findings
fNIRS	60	Healthy adults, infants, preschoolers, stroke, TBI, neuro-psychiatric cohorts	Portable systems enable naturalistic tasks, hyperscanning, and neuro-feedback; wearable caps combined with VR for social-development research
DOT	20	Adults, toddlers (1-7 year), epilepsy, peri-operative language mapping	High-density arrays provide fMRI-comparable cortical maps; feasible in awake children watching movies
DCS	15	Acute ischemic stroke, neuro-ICU, cardiac arrest survivors, healthy volunteers	Real-time bedside CBF monitoring; detects reperfusion after thrombolysis; reviews highlight no RCTs to date
HIS	13	Intra-operative brain-tumor patients (glioma, metastasis)	Spectral classifiers delineate tumor margins; first multi-site benchmark dataset released
PAI	10	Adults with hemicraniectomy, neonates (fontanelle), intra-operative vascular mapping	First transcranial functional PAI in a human; reviews outline roadmap and skull-mitigation strategies

fNIRS: functional near-infrared spectroscopy; DOT: diffuse optical tomography; DCS: diffuse correlation spectroscopy; HIS: hyperspectral imaging; PAI: photoacoustic imaging, CBF: cerebral blood flow, TBI: traumatic brain injury; ICU: intensive care unit; RCTs: randomized controlled trials.

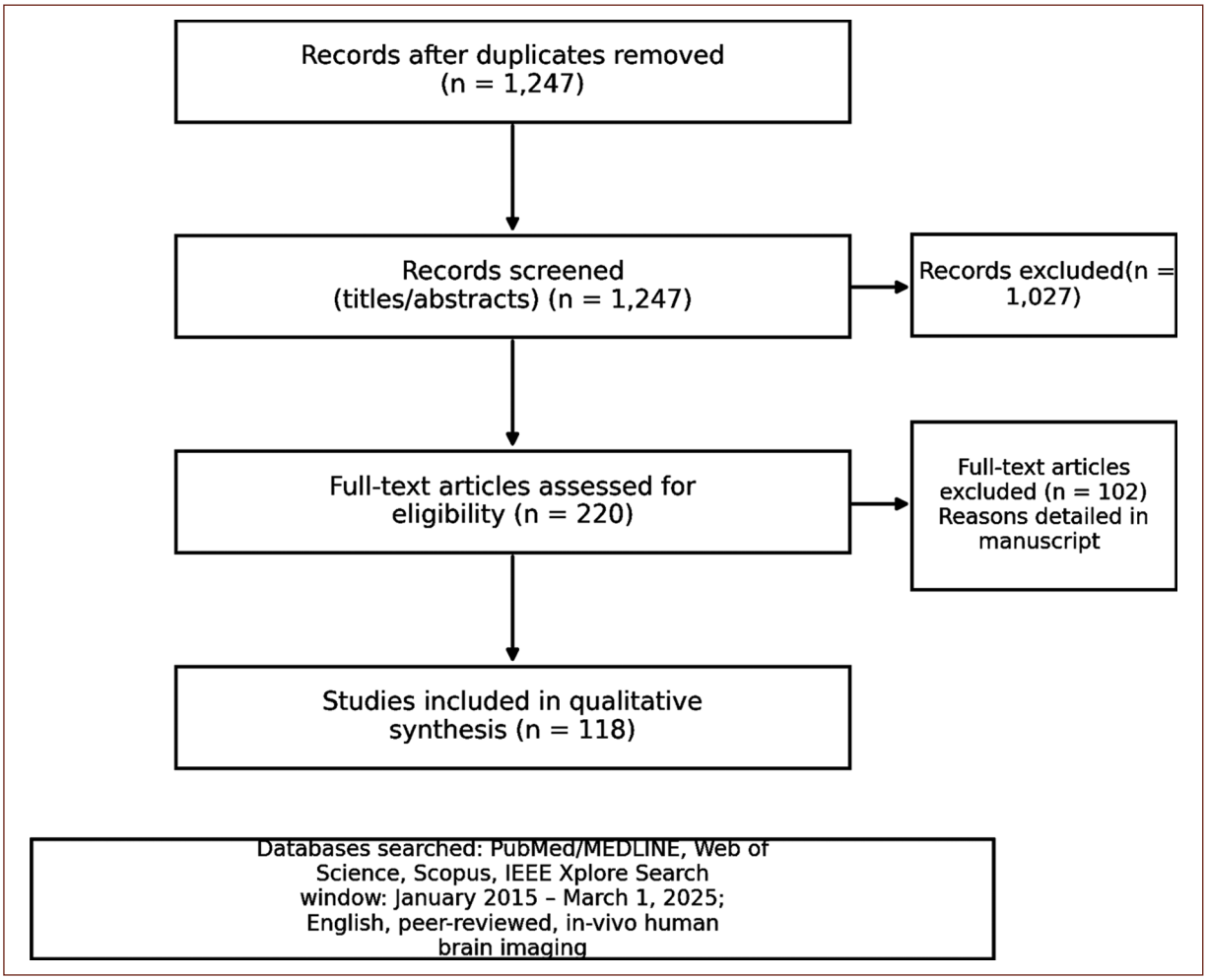

Figure 2. Preferred reporting items for systematic reviews and meta-analyses 2020 flow diagram for study selection.

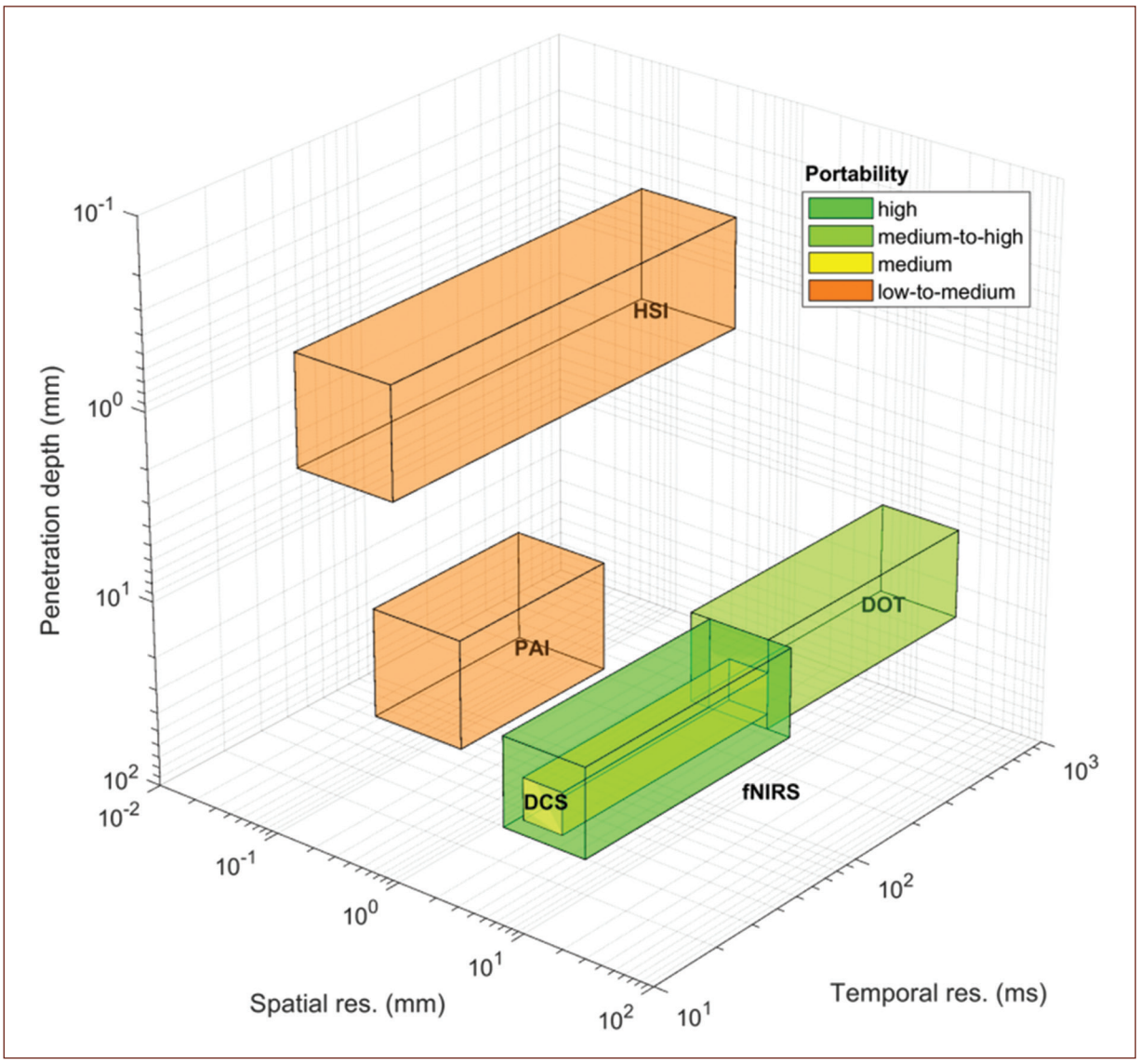

Figure 3. Comparison of the reviewed optical imaging modalities according to their temporal and spatial resolution, penetration depth, and portability.

the highest portability, while DCS offers similar depth but adds fast blood-flow metrics at moderate portability; HSI delivers sub-millimeter surface detail yet is limited to exposed cortex and remains less portable, and PAI uniquely penetrates up to several centimeters with sub-millimeter resolution but still faces skull-related constraints and lower portability. These results are summarized in figure 3.

fNIRS

fNIRS has become a widely used modality in human neuroscience over the past decade, reflecting its maturation into a robust functional imaging tool[1,9]. fNIRS uses sources and detectors placed on the scalp to measure changes in NIR light absorption associated with CBF and oxygenation changes in cortical regions[1]. From 2015 to 2025, there was an explosion of fNIRS research in diverse fields, including cognitive psychology, social neuroscience, developmental neuroscience, and clinical neurology[9-12]. This surge is evidenced by a large number of publications and review articles, which *"testifies to the maturity achieved by this non-invasive optical, vascular-based functional neuroimaging technique"*[1].

One important trend has been the deployment of fNIRS in naturalistic and mobile settings. Whereas early fNIRS studies (pre-2015) often occurred in laboratory environments with participants seated still, newer studies have leveraged advances in portable and wireless fNIRS devices. By around 2018, truly wearable fNIRS systems enabled recording brain activity in freely moving subjects during realistic tasks[13,14]. For example, researchers have used fNIRS to monitor prefrontal cortex activity while people navigate real-world environments or engage in social interactions, which is infeasible with functional magnetic resonance imaging (fMRI). Pioneering studies even conducted hyperscanning (simultaneous fNIRS on multiple people) to study interactive brain dynamics (e.g., teacher-student or parent-child interactions). These developments were facilitated by compact wireless emitters/detectors and Bluetooth data transmission, as well as improved signal processing to filter out motion and ambient light artifacts. Today, fNIRS is utilized on healthy subjects moving freely in different naturalistic settings, an achievement anticipated to grow with further instrument development[1].

In parallel with mobility, the spatial coverage and density of fNIRS arrays have increased. Traditional fNIRS used sparse optode arrangements, yielding only rough topographical maps. Recent high-density configurations place many optodes in a grid, with overlapping measurements at multiple source-detector distances. This approach, often termed high-density DOT, when paired with image reconstruction, dramatically improves image quality over sparse fNIRS[15]. For instance, Tripathy et al. built a high-performance high-density DOT system with an array of sources and detectors specifically designed to be child-friendly[15]. They demonstrated that such high-density fNIRS can produce image quality benchmarked against fMRI – mapping functional responses in 1-7 year-old children watching movies, a scenario where fMRI is challenging due to motion and compliance issues[15]. The ability to obtain spatially detailed maps of cortical activation (e.g., distinguishing functional responses in Broca's area vs. adjacent cortex during speech stimuli) has garnered significant interest in both cognitive and clinical research[16]. Indeed, high-density fNIRS/DOT approaches have achieved enough spatial resolution to resolve localized activation comparable to fMRI findings, while retaining fNIRS's logistical advantages (silent, portable, tolerant to motion)[15,16].

Applications of fNIRS in healthy populations have expanded to a wide array of cognitive functions – from language processing and auditory perception to decision-making, attention, and motor control. In clinical populations, fNIRS has been explored for bedside functional monitoring and neurorehabilitation progress. For example, multiple studies used fNIRS to assess motor cortex activation in stroke patients during rehabilitation tasks, finding that fNIRS activation magnitudes correlate with motor recovery stages (references in included studies). fNIRS has also been applied to monitor frontal lobe activity in disorders of consciousness, to map language or memory function in epilepsy patients, and even to assist brain-computer interface (BCI) development for patients with paralysis[17]. The data suggest that fNIRS signals (changes in HbO and HbR concentrations) can serve as biomarkers for brain function in situations where MRI is impractical or unsafe (e.g., early after stroke, in the intensive care unit [ICU], or in patients with motor deficits[12,18,19]). Furthermore, interactive neuroscience paradigms have emerged, such as neurofeedback training using real-time fNIRS signals and studies of how physical exercise modulates cortical activation[1].

Despite these advances, limitations of fNIRS remain. The technique is fundamentally limited to sensing cortical surface activity (typically ≤ 1.5 cm deep) because NIR light is strongly attenuated in tissue[9-11,20-22]. Signals are also contaminated by superficial blood flow in the scalp/skull (systemic physiology, skin blood vessels), which can confound true cerebral signals. A pressing need for standardized protocols to remove or account for these extracranial signal components has been identified[1,22]. Short-separation detectors (to measure and subtract scalp-only signals) and improved algorithms (e.g., regression of global trends, machine learning classifiers) are being incorporated to address this. In addition, because many fNIRS setups are custom, results can vary across labs. Efforts like near-infrared spectroscopy (NIRS)-brain imaging data structure (BIDS) (a BIDS extension) have begun standardizing data formats to improve reproducibility[23,24]. Before fNIRS can become a clinical neurodiagnostic tool, consensus on systemic interference correction, probe placements, and quantification methods is needed[1,9]. Nonetheless, the trend over 2015-2025 shows fNIRS evolving from a niche laboratory technique to a mainstream neuroimaging modality with growing real-world and clinical applications, thanks to its non-invasiveness and flexibility.

DOT

DOT extends fNIRS using high-density source-detector arrays and image-reconstruction algorithms to generate 3D maps of cortical HbO and HbR. Between 2015 and 2025, it matured into a tool that can approach fMRI-level localization when optode spacing is ≤ 1 cm and measurements overlap densely, driving widespread adoption in cognitive and clinical research[15,25]. Continuous-wave (CW) DOT dominates because the hardware is inexpensive and portable; a 2024 systematic review tallied 83 CW -DOT human studies, underscoring rapid growth[16]. High-density systems have mapped language in toddlers, neonatal strokes, and peri-operative cortex, tasks previously impractical for sparse optics or fMRI[26].

Algorithmic advances, regularized inverse models, MRI-based head priors, and multi-wavelength fitting now resolve activity in individual gyri and yield quantitative hemoglobin changes; DOT activation patterns routinely overlap with fMRI benchmarks[25,27]. Pilot clinical work shows promise for stroke, epilepsy, and intraoperative mapping, where neuronavigation-guided DOT offers an optical analog to fMRI[16].

Challenges remain

Image quality depends on head-model assumptions, depth sensitivity is predominantly cortical, and high-density caps can be cumbersome. Standardized protocols and deeper-penetrating time-domain or frequency-domain systems are needed to improve quantification and broaden adoption[16,28]. Nevertheless, DOT as of 2025 remains primarily a research tool. No DOT system is yet widely approved for clinical use, and further validation in multicenter studies is needed to establish its accuracy and reliability compared to gold standards.

DCS

DCS probes CBF by tracking speckle-intensity fluctuations produced by moving red blood cells under coherent NIR illumination, yielding a continuous index of microvascular perfusion that complements fNIRS/DOT oxygenation data[2,29].

Bedside utility is illustrated by Delgado-Mederos et al., who combined DCS and NIRS in five acute-stroke patients and detected reperfusion within 2.5 h of thrombolysis, ahead of repeat imaging[30]. Subsequent clinical reports extend monitoring to hypothermic circulatory arrest, traumatic brain injury, and post-cardiac-arrest care, where continuous CBF trends inform management when ultrasound or MRI are impractical[31,32].

Technical advances from 2015 to 2025 focus on signal-to-noise, depth, and coverage. Multi-speckle detection and parallelized cameras reduce variance and expand the field-of-view[2]. Longer wavelengths (1064 nm) improve penetration, while time-gated and time-domain DCS isolate late-arriving photons for deeper cortical sensitivity[33]. Hybrid systems integrate DCS with NIRS to estimate cerebral metabolic rate of oxygen or with DOT to create emerging 3D flow tomograms[29].

Limitations persist

Probes must remain immobile; absolute calibration requires external standards; adult measurements are confined to superficial cortex; and spatial localization is coarse unless high-density grids or MRI co-registration are used[2,29]. Nonetheless, progressive hardware miniaturization, depth-discrimination schemes, and early commercial devices position DCS as a valuable, real-time perfusion monitor poised for wider neurocritical and functional applications[33].

HSI

HSI records a complete reflectance spectrum for every pixel, yielding rich optical fingerprints that differentiate brain tissues without dyes. A systematic survey of clinical literature tallied > 25 operative HSI systems and 45 human studies, confirming rapid growth in neurosurgical use (though typically sample sizes were small)[34,35]. The foremost application is intraoperative tumor delineation: the HELICoiD consortium built an open VNIR database of 36 cubes from 22 glioma patients (> 300,000 labelled spectra) and showed that spatial-spectral classifiers could highlight tumor margins with ~ 80% accuracy in real time, guiding resection decisions[3]. A subsequent multicenter benchmark enlarged the dataset to 61 images from 34 patients and reported a median macro-F1 of 70% for tumor detection, establishing a common reference for algorithm development[36].

HSI also exploits hemoglobin absorbance to map cortical oxygenation and vascular anatomy during aneurysm repair, bypass grafting, or decompressive craniectomy, offering wide-field perfusion assessment that complements point probes[35]. Early reports indicate that task-evoked spectral changes can localize functional cortex in awake craniotomy, suggesting a

contact-free adjunct to electrical stimulation. Hardware advances have catalyzed translation: snapshot cameras using birefringent spectral demultiplexers now capture ≥ 64 spectral bands in a single exposure, delivering video-rate cubes compatible with the pulsating brain[37]. Compact modules mount on operative microscopes or exoscopes, allowing surgeons to toggle between white-light and hyperspectral views without workflow disruption[35]. Concurrently, deep-learning pipelines fed by public datasets generate color-coded overlays of tumor probability directly in the eyepiece, standardizing spectral interpretation and accelerating decision-making[3,4,36].

Despite these advances, HSI remains confined to the exposed cortex: reflected photons interrogate only the first few millimeters, leaving subsurface tumor or hemorrhage invisible. Image quality can be degraded by surface blood, irrigation fluid, or variable illumination, necessitating stringent calibration and spectral normalization[35]. Most clinical reports are single-center case series with modest cohorts; robust multicenter trials are still scarce, although the Leon benchmark represents a critical step toward standardization and external validation[36]. Active research goals include depth-resolved extensions (e.g., endoscopic or hybrid HSI-fluorescence systems) and harmonized acquisition protocols.

In sum, 2015-2025 saw HSI progress from proof-of-concept to a nascent operating-room adjunct that can delineate tumors, assess perfusion, and potentially map function in real time. While feasibility has been demonstrated in operative settings, HSI remains an experimental adjunct; no HSI system is yet cleared for routine neurosurgical use. Further, inter-patient variability in spectra means algorithms need robust calibration and possibly large training datasets to be reliable. As of 2025, HSI shows great promise for intraoperative guidance, but it will require larger trials (and possibly regulatory approval) to establish clinical utility.

PAI

PAI combines optical contrast with ultrasound detection to achieve deeper imaging than purely optical methods. In transcranial applications, PAI has been investigated in specialized scenarios – notably in patients with skull openings (e.g., hemicraniectomy or fontanelle in neonates) where acoustic coupling is feasible. About 10 studies from 2015 to 2025 applied PAI or photoacoustic tomography (PAT) to human brain imaging. One milestone was the first report of transcranial functional PAT in an adult human, achieved using a patient with a large skull defect to bypass skull attenuation[38]. Other studies imaged neonatal brains through the fontanelle, visualizing blood oxygenation changes during interventions. PAI has also been explored intraoperatively for vessel mapping or cerebral perfusion monitoring by applying an ultrasound detector over exposed brain tissue.

Technical innovations for PAI include using 1064 nm lasers (which penetrate bone somewhat better) and full-ring ultrasound detector arrays to capture signals from multiple angles[5]. Multiwavelength PAI has been employed in preclinical models to differentiate HbO versus HbR signals, yielding functional maps of oxygenation in the brain[5]. The primary challenge for human PAI is the skull: the bone greatly attenuates and distorts acoustic signals. Strategies such as skull thinning, cooling, or acoustic coupling media have been proposed to mitigate this, but remain experimental. Current PAI setups are also relatively bulky and require careful alignment of lasers and ultrasound sensors, limiting clinical practicality.

To date, PAI in humans is limited to feasibility demonstrations, and its clinical readiness is the most nascent among the modalities discussed. No large-scale human PAI studies exist yet, and safety considerations (ensuring laser exposure is within ANSI limits for skin/eye safety) must be managed as higher energies are considered for deeper imaging. Still, PAI's unique ability to provide high-resolution optical contrast at depth (by listening for photo-induced ultrasound) makes it a compelling future modality if technical barriers can be overcome. Reviews in the field have outlined a roadmap and remaining challenges for translating PAI into clinical neuroimaging[39,40].

Risk of bias and study quality

The overall quality of evidence across the included optical brain imaging studies is moderate, as assessed by our QUADAS-2-based analysis. Most studies were early-phase explorations, often lacking control groups or reference standards, which introduces various biases. Common issues included non-random participant selection (e.g., enrolling only young healthy adults for feasibility, or selecting patients with favorable conditions such as thin skulls or superficial tumors), which may overestimate the success of the modality in the general population. Blinding was seldom reported; for instance, investigators conducting fNIRS or DOT data analysis often knew the task conditions, and surgeons knew the ground truth of tumor locations when

evaluating HSI or PAI results, potentially biasing outcome assessment. Supplementary figure S1 provides an overview of the risk-of-bias ratings (low, high, unclear) across all included studies.

In studies where a reference like fMRI was used, some did not clearly state if the fMRI analysis was blinded to the optical results, raising the possibility of confirmation bias. Several patient studies (especially in stroke or ICU monitoring with NIRS/DCS) had no independent gold standard for the measured outcome, meaning they inferred clinical relevance indirectly (e.g., assuming that increased flow per DCS is good because the patient improved clinically, but without imaging confirmation). Flow and timing biases were present in longitudinal studies that had dropouts or where the optical measurement and reference test were not perfectly aligned in time. For example, in stroke monitoring, optical data were continuous, but the "ground truth" (such as an MRI scan) might have been done hours later, during which the patient's condition could have changed.

Another notable aspect is that many studies were small (median sample size 15 in our included set). This raises concerns about statistical power and selective reporting. Positive findings (e.g., successful mapping of a function or detection of a pathology) are likely over-represented in published studies, while negative or inconclusive studies may be underreported – a form of publication bias. This review cannot fully account for that, but it should be considered when interpreting the generally positive tone of results reported for each modality.

Encouragingly, some studies did incorporate measures to reduce bias: for instance, a few DOT versus fMRI comparison studies had independent analysts process each modality's data[15,25]; some HSI tumor studies used a third-party algorithm to classify spectra without knowing histology results[4,36], and then compared objectively. However, these were exceptions. The risk-of-bias assessment suggests that while the field demonstrates clear feasibility of each technology, the level of evidence is still preliminary, often in the form of case series or unblinded comparisons. There were no randomized controlled trials[16] and only a handful of multicenter studies[2,3,39]. Therefore, any quantitative performance metrics (tumor detection accuracy, stroke monitoring sensitivity, etc.,) should be considered provisional.

In summary, across modalities, there is a need for future studies with more rigorous designs: larger sample sizes, appropriate control conditions or reference standards, blinding of outcome assessments, and, if possible, multicenter collaboration to improve generalizability. The literature provides a strong proof-of-concept foundation, but the actual clinical utility and comparative performance of these optical techniques will require the next level of evidence.

Discussion and future directions

Over the last decade, optical imaging methods for human brain mapping have progressed from niche experimental techniques toward more mainstream neuroimaging and clinical research tools. Functional NIRS and DOT have seen the most widespread use, moving into real-world applications and complex populations (like infants and those who cannot undergo fMRI) while improving image quality. These modalities have clearly demonstrated feasibility for human brain mapping in research and even some translational clinical studies; however, they remain primarily research tools at present and have not yet achieved routine clinical adoption. DCS has added the capability to measure CBF, addressing a gap left by hemodynamics-only tools and opening new avenues in bedside monitoring. At the same time, DCS is still in an exploratory phase and requires further validation before it can be considered for standard clinical use. HSI and PAI, though still largely experimental in human brain applications, have demonstrated promising potential to provide rich spectral and high-resolution insights, respectively, although these results are still preliminary, especially in surgical or acute settings. At present, both HSI and PAI remain at a proof-of-concept stage in humans and are far from any routine clinical use.

The collective evidence from 2015 to 2025 indicates that these modalities can successfully detect functional activation and pathological changes in the human brain, but each comes with limitations that temper its current utility. Spatial resolution and depth remain key challenges: even with high-density DOT, optical methods cannot yet match MRI's sub-millimeter resolution or whole-brain coverage. Most fNIRS/DOT measurements are confined to cortical convexities, and deep structures (basal ganglia, hippocampus) remain noninvasively out of reach. PAI promises depth, but the skull's acoustic impedance is a formidable barrier. Efforts like using 1064 nm light and full-ring detectors[5] are partially mitigating this, and further innovations (e.g., skull cooling or coupling media to improve ultrasound transmission) are being considered. In parallel, the temporal resolution of optical techniques is high for

detecting hemodynamic oscillations (on the order of milliseconds for DCS speckle or instrument sampling, though physiological signals are slower). Still, they measure slower signals than neural electrophysiology. Integration with electroencephalography (EEG) or magnetoencephalography could provide a more complete picture of brain activity, combining fast neural and slower hemodynamic information.

A critical issue across modalities is signal quantification and specificity. fNIRS and DOT signals can be contaminated by scalp blood flow; standardizing short-separation regression and other preprocessing is a priority before clinical adoption[1,9]. DOT reconstructions need to become more quantitatively accurate (current images often require assuming bulk optical properties and use relative changes). DCS provides an index of flow, but calibrating it to absolute CBF is an area of ongoing research - one future direction is combining time-domain diffuse optics with DCS to independently measure optical path lengths and make DCS quantitative in absolute terms. For HSI, isolating the effect of one variable (say oxygenation) from others (such as blood volume or light scattering changes) is complex; advanced spectral unmixing algorithms and perhaps complementary measurements (like simultaneous NIRS for deeper layers) might help. PAI's specificity could be enhanced by multispectral PAT, taking images at multiple wavelengths to differentiate HbO versus HbR, lipid, and other tissue constituents. Indeed, multi-wavelength PAI has been used in preclinical studies to produce functional oxygenation maps of the brain and could be translated to humans to provide both structure and oxygenation in one modality[41].

From a technology standpoint, the next decade will likely see further miniaturization and integration. For fNIRS, one exciting avenue is the development of fully wearable, cap-based systems using flexible electronics and high-density grids that can record from most of the cortical surface. Some prototypes involve dozens of LED sources and silicon photodiode detectors embedded in a soft cap, powered by a battery pack or even operating wirelessly. These could turn fNIRS into a "wear it and forget it" technology for continuous brain monitoring in daily life or rehabilitation training. Similarly, integrating fNIRS and DCS in one device (as some research teams have done) provides a more complete hemodynamic picture (both oxygenation and flow). A logical next step would be commercial development of hybrid NIRS-DCS monitors for neonatal ICU or stroke units, which could noninvasively track cerebral oxygen delivery and utilization. The combination of flow and oxygenation can yield indices of metabolic rate (via Fick's principle), giving a window into brain metabolism at the bedside – a long-sought goal in neurocritical care.

Multimodal integration is another promising direction. We already see fNIRS being combined with fMRI (for cross-validation and to leverage fMRI's deep reach), with EEG (to support BCI designs where fNIRS provides complementary information to EEG signals), and even with transcranial electrical or magnetic stimulation (to measure brain hemodynamic response to neuromodulation). For example, concurrent EEG-fNIRS is used to study neurovascular coupling in epilepsy or to improve the accuracy of BCIs using two modalities. As we advance, one could envision trimodal systems (EEG + fNIRS + DCS) to monitor neural, hemodynamic, and perfusion changes simultaneously – this could be powerful in scenarios such as brain-computer interfaces for locked-in patients, where EEG might reveal intent and NIRS/DCS ensure adequate cerebral perfusion or track mental workload.

On the analytical front, the growing datasets from optical neuroimaging call for sophisticated analysis methods. Machine learning and deep learning approaches have started appearing for DOT image reconstruction and HSI spectral classification. For instance, deep neural networks can learn from examples of optical measurements paired with known brain activity (from fMRI or simulations) to directly reconstruct brain activation patterns, potentially outperforming traditional analytical models[42]. In HSI, deep learning is already used to improve the accuracy of tumor detection in the spectral images[43]. One challenge that ML can help with is denoising and artifact removal – for example, using convolutional neural networks to filter motion artifacts from fNIRS time series, or to correct for skull-induced distortions in photoacoustic data by learning the distortion patterns[5,42]. Caution is needed to ensure these models generalize and do not introduce bias, but early results are promising.

The field is poised for larger validation studies in terms of clinical translation and trials. For fNIRS/DOT, that might mean multi-site trials to test fNIRS as a tool for presurgical mapping of the language cortex (comparing it to the gold standard of direct cortical stimulation or fMRI). For DCS, a logical trial would be to validate DCS against established CBF measures such as PET or MRI-ASL (MRI-arterial spin labelling) in patients with cerebrovascular disease, to see how well DCS can track perfusion changes. If successful, DCS

could become an accepted monitor for conditions such as carotid stenosis or head-of-bed positioning effects in the ICU. HSI will likely see further clinical studies in neurosurgery: perhaps a Phase II trial of HSI-guided tumor resection, measuring if surgeons achieve more complete resection or better outcomes with HSI assistance (compared to standard white-light or 5-ALA (5-aminolevulinic acid) fluorescence guidance). PAI might initially find a niche in specific procedures – for example, monitoring cortical perfusion during cardiac surgery or neuroendovascular procedures, where a PAI probe could be placed on the head to watch for ischemia in real-time (something currently not done, but technically feasible with a craniotomy or thin bone window).

Regulatory and practical considerations will also shape future directions. Several fNIRS devices have already been approved for clinical use (e.g., for neonatal cerebral oximetry or functional brain imaging), but DOT systems and DCS are mostly confined to research. To translate, devices must be user-friendly and have cleared safety profiles. PAI systems will have to ensure laser exposure stays within ANSI (American National Standards Institute) limits for skin and eye safety; as energies increase for deeper imaging, ensuring no damage (especially to the eye from scattered light) is paramount. HSI devices should deal with issues such as sterilization (since they may be used in sterile fields) and real-time performance.

Finally, standardization and data sharing will significantly benefit the field. The past decade taught us that different groups sometimes reported divergent results for similar applications, likely due to differences in hardware or analytical choices. Initiatives such as open-source platforms for fNIRS (e.g. HOMER[44], AtlasViewer[45]) and shared datasets (like the DOI for the brain tumor HSI dataset[4]) should be expanded. A community consensus on reporting and comparing optical imaging findings (akin to the reporting standards in fMRI or EEG research) would help pool data and conduct meta-analyses. Applying the PRISMA framework in this review highlighted the need for more systematic reporting in optical neuroimaging studies themselves, such as more precise descriptions of participant selection and blinding.

Despite our focus on technological advances, it is important to acknowledge the limitations of our own review methodology. In particular, the study screening and quality appraisal for this review were conducted by a single reviewer. While this ensured consistency in applying inclusion criteria and bias assessments, it may also introduce subjective bias. Ideally, future systematic reviews in this area will involve multiple independent reviewers at each stage to enhance the reliability and reproducibility of the conclusions.

Conclusion

Optical imaging techniques have emerged as powerful tools for non-invasive human brain mapping, bridging gaps in traditional imaging modalities. Their versatility in clinical and naturalistic environments offers significant potential for advancing neuroscience and patient care. Future research should focus on standardization, quantification, multimodal integration, and rigorous validation through larger, multicenter studies. Enhancing depth penetration, spatial resolution, and real-time capability will further accelerate their translation from research to clinical applications, ultimately transforming how we understand and monitor the human brain.

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Conflicts of interest

The author declares that he/she has no conflicts of interest.

Ethical considerations

Protection of human subjects and animals. The authors declare that no experiments on humans or animals were performed for this research.

Confidentiality, informed consent, and ethical approval. This study does not involve personal patient data, medical records, or biological samples, and does not require ethical approval. SAGER guidelines do not apply.

Declaration on the use of artificial intelligence (AI). The authors declare that an artificial intelligence tool was used to support the preparation of the manuscript.

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Supplementary data

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References

1. Quaresima V, Ferrari M. A mini-review on functional near-infrared spectroscopy (fNIRS): where do we stand, and where should we go? Photonics. 2019;6:87.
2. James E, Munro PR. Diffuse correlation spectroscopy: a review of recent advances in parallelisation and depth discrimination techniques. Sensors (Basel). 2023;23:9338.
3. Fabelo H, Ortega S, Ravi D, Kiran BR, Sosa C, Bulters D, et al. Spatio-spectral classification of hyperspectral images for brain cancer detection during surgical operations. PLoS One. 2018;13:e0193721.
4. Fabelo H, Ortega S, Szolna A, Bulters D, Piñeiro JF, Kabwama S, et al. *In-vivo* hyperspectral human brain image database for brain cancer detection. IEEE Access. 2019;7:39098-116.
5. Liang B, Wang S, Shen F, Liu QH, Gong Y, Yao J. Acoustic impact of the human skull on transcranial photoacoustic imaging. Biomed Opt Express. 2021;12:1512-28.
6. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71.
7. Corporation for Digital Scholarship. zotero/zotero. Zotero; 2025. Available from: https://github.com/zotero/zotero [Last accessed on 2025 Apr 28].
8. Whiting PF, Rutjes AW, Westwood ME, Mallett S, Deeks JJ, Reitsma JB, et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Ann Intern Med. 2011;155:529-36.
9. Ayaz H, Baker WB, Blaney G, Boas DA, Bortfeld H, Brady K, et al. Optical imaging and spectroscopy for the study of the human brain: status report. Neurophotonics. 2022;9:S24001.
10. Srinivasan S, Butters E, Collins-Jones L, Su L, O'Brien J, Bale G. Illuminating neurodegeneration: a future perspective on near-infrared spectroscopy in dementia research. Neurophotonics. 2023;10:023514.
11. Yeung MK. An optical window into brain function in children and adolescents: A systematic review of functional near-infrared spectroscopy studies. Neuroimage. 2021;227:117672.
12. Guevara E, Rivas-Ruvalcaba FJ, Kolosovas-Machuca ES, Ramírez-Elías M, Díaz de Leon Zapata R, Ramirez-GarciaLuna JL, et al. Parkinson's disease patients show delayed hemodynamic changes in primary motor cortex in fine motor tasks and decreased resting-state interhemispheric functional connectivity: a functional near-infrared spectroscopy study. Neurophotonics. 2024;11:025004.
13. Gaeta G, Gunasekara N, Pinti P, Levy A, Parkkinen E, Kontaris E, et al. Naturalistic approach to investigate the neural correlates of a laundry cycle with and without fragrance. Biomed Opt Express. 2024;15:5461-78.
14. von Lühmann A, Zheng Y, Ortega-Martinez A, Kiran S, Somers DC, Cronin-Golomb A, et al. Toward neuroscience of the everyday world (NEW) using functional near-infrared spectroscopy. Curr Opin Biomed Eng. 2021;18:100272.
15. Tripathy K, Fogarty M, Svoboda AM, Schroeder ML, Rafferty SM, Richter EJ, et al. Mapping brain function in adults and young children during naturalistic viewing with high-density diffuse optical tomography. Hum Brain Mapp. 2024;45:e26684.
16. Guan S, Li Y, Gao Y, Luo Y, Zhao H, Yang D, et al. Continuous wave-diffuse optical tomography (CW-DOT) in human brain mapping: a review. Sensors. 2025;25:2040.
17. Naseer N, Hong KS. fNIRS-based brain-computer interfaces: a review. Front Hum Neurosci. 2015;9:3.
18. Guevara E, Kolosovas-Machuca ES, Rodríguez-Leyva I. Exploring motor cortex functional connectivity in Parkinson's disease using fNIRS. Brain Organ Syst Neurosci J. 2024;2:23-30.
19. Guevara E, Solana-Lavalle G, Rosas-Romero R. Integrating fNIRS and machine learning: shedding light on Parkinson's disease detection. EXCLI J. 2024;23:763-71.
20. Almajidy RK, Mankodiya K, Abtahi M, Hofmann UG. A Newcomer's guide to functional near infrared spectroscopy experiments. IEEE Rev Biomed Eng. 2020;13:292-308.
21. Bonilauri A, Sangiuliano Intra F, Pugnetti L, Baselli G, Baglio F. A systematic review of cerebral functional near-infrared spectroscopy in chronic neurological diseases-actual applications and future perspectives. Diagnostics (Basel). 2020;10:581.
22. Yücel MA, Lühmann A, Scholkmann F, Gervain J, Dan I, Ayaz H, et al. Best practices for fNIRS publications. Neurophotonics. 2021;8:012101.
23. Poldrack RA, Markiewicz CJ, Appelhoff S, Ashar YK, Auer T, Baillet S, et al. The past, present, and future of the brain imaging data structure (BIDS). Imaging Neurosci (Camb). 2024;2:1-19.
24. Luke R, Oostenveld R, Cockx H, Niso G, Shader MJ, Orihuela-Espina F, et al. NIRS-BIDS: brain imaging data structure extended to near-infrared spectroscopy. Sci Data. 2025;12:159.
25. Markow ZE, Trobaugh JW, Richter EJ, Tripathy K, Rafferty SM, Svoboda AM, et al. Ultra high density imaging arrays in diffuse optical tomography for human brain mapping improve image quality and decoding performance. Sci Rep. 2025;15:3175.
26. McMorrow SR, Park SM, George TG, Sobolewski CM, Yang D, King KT, et al. Bedside neuroimaging using high-density diffuse optical tomography in a pediatric patient on extracorporeal support. Stroke. 2025;56:e3-5.
27. Hernandez-Martin E, Gonzalez-Mora JL. Diffuse optical tomography in the human brain: a briefly review from the neurophysiology to its applications. Brain Sci Adv. 2020;6:289-305.
28. Re R, Spinelli L, Martelli F, Di Sieno L, Bargigia I, Amendola C, et al. A review on time domain diffuse optics: principles and applications on human biological tissues. Riv Nuovo Cim. 2025;48:157-239.
29. Wang Q, Pan M, Kreiss L, Samaei S, Carp SA, Johansson JD, et al. A comprehensive overview of diffuse correlation spectroscopy: theoretical framework, recent advances in hardware, analysis, and applications. Neuroimage. 2024;298:120793.
30. Delgado-Mederos R, Gregori-Pla C, Zirak P, Blanco I, Dinia L, Marín R, et al. Transcranial diffuse optical assessment of the microvascular reperfusion after thrombolysis for acute ischemic stroke. Biomed Opt Express. 2018;9:1262-71.
31. Zavriyev AI, Kaya K, Farzam P, Farzam PY, Sunwoo J, Jassar AS, et al. The role of diffuse correlation spectroscopy and frequency-domain near-infrared spectroscopy in monitoring cerebral hemodynamics during hypothermic circulatory arrests. JTCVS Tech. 2021;7:161-77.
32. Poon CS, Langri DS, Rinehart B, Rambo TM, Miller AJ, Foreman B, et al. Enhanced cerebral blood flow sensitivity using time-gated diffuse correlation spectroscopy for monitoring of traumatic brain injury. In: Biophotonics Congress: Biomedical Optics 2022 (Translational, Microscopy, OCT, OTS, BRAIN) (2022), paper JM3A66. Optica Publishing Group; 2022. p. JM3A.66. Available from: https://opg.optica.org/abstract.cfm?uri=OTS-2022-JM3A.66 [Last accessed on 2025 May 05].
33. Mogharari N, Wojtkiewicz S, Borycki D, Liebert A, Kacprzak M. Time-domain diffuse correlation spectroscopy at large source detector separation for cerebral blood flow recovery. Biomed Opt Express. 2024;15:4330-44.
34. Anichini G, Leiloglou M, Hu Z, O'Neill K, Elson D. Hyperspectral and multispectral imaging in neurosurgery: a systematic literature review and meta-analysis. Eur J Surg Oncol. 2025;51:108293.
35. Kotwal A, Saragadam V, Bernstock JD, Sandoval A, Veeraraghavan A, Valdés PA. Hyperspectral imaging in neurosurgery: a review of systems, computational methods, and clinical applications. JBO. 2024;30:023512.
36. Leon R, Fabelo H, Ortega S, Cruz-Guerrero IA, Campos-Delgado DU, Szolna A, et al. Hyperspectral imaging benchmark based on machine learning for intraoperative brain tumour detection. NPJ Precis Oncol. 2023;7:119.
37. Marois M, Olson JD, Wirth DJ, Elliott JT, Fan X, Davis SC, et al. A birefringent spectral demultiplexer enables fast hyper-spectral imaging of protoporphyrin IX during neurosurgery. Commun Biol. 2023;6:341.
38. Zhang Y, Na S, Sastry K, Russin JJ, Hu P, Lin L, et al. Transcranial Photoacoustic Computed Tomography of Human Brain Function. arXiv; 2022. Available from: http://arxiv.org/abs/2206.00248 [Last accessed on 2025 May 05].
39. Liu X, Li H, Pang M, Liu J, Song X, He R, et al. Photoacoustic imaging in brain disorders: current progress and clinical applications. VIEW. 2024;5:20240023.
40. Choi S, Kim J, Jeon H, Kim C, Park EY. Advancements in photoacoustic detection techniques for biomedical imaging. NPJ Acoust. 2025;1:1-21.
41. Levin HS, Diaz-Arrastia RR. Diagnosis, prognosis, and clinical management of mild traumatic brain injury. Lancet Neurol. 2015;14:506-17.
42. Hsu KT, Guan S, Chitnis PV. Comparing deep learning frameworks for photoacoustic tomography image reconstruction. Photoacoustics. 2021;23:100271.
43. Puustinen S, Vrzáková H, Hyttinen J, Rauramaa T, Fält P, Hauta-Kasari M, et al. Hyperspectral imaging in brain tumor surgery-evidence of machine learning-based performance. World Neurosurg. 2023;175:e614-35.
44. Huppert TJ, Diamond SG, Franceschini MA, Boas DA. HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain. Appl Opt. 2009;48:D280-98.
45. Aasted CM, Yücel MA, Cooper RJ, Dubb J, Tsuzuki D, Becerra L, et al. Anatomical guidance for functional near-infrared spectroscopy: atlasviewer tutorial. Neurophoton. 2015;2:020801.