A Case Study in fNIRS Data Extraction: Insights from OBELAB NIRSIT System Psychiatric Research Applications

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2025

Abstract

Functional near-infrared spectroscopy (fNIRS) is an emerging neuroimaging technology that is well known for its non-invasive, portable, and low-cost method of monitoring brain activity (Irani et al., 2007). When fNIRS technology was just beginning to show promise, neuropsychology, along with other behavioral science disciplines, were slow to embrace the new technology. However, over the past 10-15 years fNIRS systems have developed at a steady pace and wearable, wireless designs have made a variety of neural testing in real-world environments possible (Irani et al., 2007, Vidal-Rosas et al., 2023). Due to its uniquely compact and portable design, the device has been used to allow for more natural world movement of brain function in clinical and social environments. In this paper we will begin with an overview of the OBElab NIRSIT fNIRS design and its potential applications for the study of various psychiatric conditions. This paper presents a case-based analysis using the OBELAB NIRSIT device, which exemplifies current trends and challenges in fNIRS data extraction. While the focus is on NIRSIT, the methodological issues discussed apply broadly to the fNIRS field.

Introduction to fNIRS

Functional near-infrared spectroscopy (fNIRS) is an emerging neuroimaging technology known for its safety, non-invasiveness, low cost, and portability. The device adopts a similar mechanism as functional MRI (fMRI), using infrared light to map brain activation based on assessing changes in deoxygenated hemoglobin (HbR) and oxygenated hemoglobin (HbO) (Tran et al., 2023). Dense fiber based systems have generally restricted use of fNIRS technology to lab environments, however improvements in fNIRS wearability and weight have allowed design paradigms to study brain function in cognitive tasks that incorporate movement, exercise, and dynamic balance. Additionally, wearable fNIRS have been used to evaluate expertise of the feedback in laparoscopy procedures, cognitive deception, stress processing during sleep, and walking (Vidal-Rasas et al., 2023). In recent years, clinical trials with the fNIRS approach have garnered heightened interest as a potential adjunct in assisting diagnosis, predicting clinical outcomes, and evaluating treatment outcomes in psychiatry (Lai et al. 2018). Vidal-Rosas et al. define fNIRS as “methods that employ near infrared light to investigate brain function via measurements of changes in hemoglobin concentrations. While, the term fNIRS is traditionally used to describe methods that collect and examine optical data on a channel by channel basis, the term fNIRS has been increasingly used as a catch all for any approach that exploits diffuse transmission of near-infrared light to measure the human brain.”

Principles of fNIRS hemodynamics

The fNIRS relies on measuring the optical properties of hemodynamics in brain tissue by using light in the near-infrared range. Hemoglobin is a protein that forms an unstable and reversible bond to oxygen in red blood cells. These two states of oxygen are named according to their oxygen loaded state: 1.) The oxygen loaded form is bright red and is known as oxy-hemoglobin (HbO); 2.) The oxygen unloaded is purple/blue and known as deoxyhemoglobin or HbR for Hemoglobin Reduced (Lai et al.) The principle method for data extraction in fNIRS involves a mechanism known as neurovascular coupling, whereby activation of a brain region is reflected by an increase in HbO and a decrease in HbR levels. Neuronal activity is fueled by glucose metabolism and its oxygen consumption. So, where there is an increase in activity in a specific brain region, there will be an increase in HbO levels. Physiologically, this means that a reduction in local oxygen stimulates the brain to increase local arteriolar vasodilation, increasing local cerebral blood flow and volume. Vasodilation is a means to enhance blood flow to areas lacking oxygen or nutrients. Even though HbR will also increase due to oxygen consumption during brain activity, this would be compensated by an increase in blood supply, resulting in a net decrease in HbR levels (Lai et al. 2018, Irani et al., 2007).

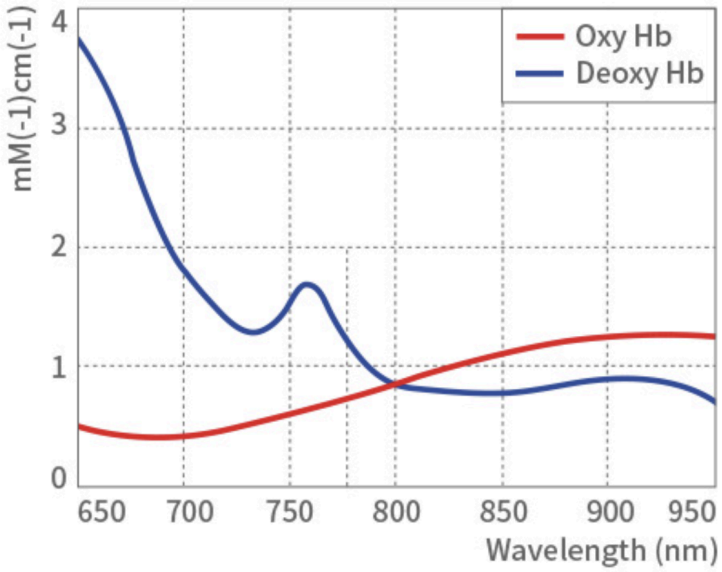

Figure 1. Diagram of HbO and HbR. HbO and HbR absorb light at wavelengths of 600-900, whereas light absorption by water and lipids in the brain is negligible. Therefore, fNIRS employs two wavelengths of 600-900 nm, which allow deeper penetration into brain tissue. (Obelab., 2025).

The fNIRS was developed based on preceding principles of near infrared light (NIR) spectroscopy. Human tissues are penetrable to near-infrared light of a wavelength in the 650-1000 nm range. The light can penetrate through the skin and bone with low absorption, but can reach hemoglobin in the capillaries with high absorption due to the chromophore properties of hemoglobin. HbO and HbR have specific chromophore properties in the visible and near-infrared light range at 750-850 nm. Therefore, the

difference in near-infrared absorption spectra in HbO and HbR allows the separation of the concentration of these two molecules, using the Modified Beer Lambert Law (MBLL) (Choi et al., 2016). This spectral band is referred to as the “optical window” for non-invasive assessment of brain activation because the chromophores HbO and HbR reflect distinct wavelengths in this range (qtd. in Irani et al., 2007). NIR light is emitted into the cerebral tissues using a Source-Detector channel paradigm. As photons are introduced at the scalp with the source (laser) diode, they are either absorbed, scattered, or reflected back from HbO and HbR as they pass through tissue. Scattered light is then detected by a detector probe, and the different light absorption rates of HbO and HbR within a brain region will be measured (Lai et al. 2018).

fNIRS Data extraction

In the emerging fNIRS field in the early 2000s, notable research efforts focused on expanding research instruments from single channel source detector paradigms to multichannel models. Later, in the late 2000s, research efforts switched to developing the analytical and statistical frameworks necessary for extracting robust information from these multichannel systems and addressing their limitations (i.e. motion artifacts, systemic interference) (Vidal-Rosas et al., 2023). These works introduced the need for even larger systems with extended field of views (FOVs) and superior spatial resolution.
In 2012, Choi et al. at the International Symposium on Circuits and Systems reported a new efficient method for the extraction of hemodynamic responses in fNIRS systems. The overall system size measured 200 x 200 x 80 mm^3, with a total weight of 450 g. Additionally, a compact integrated-circuit (IC) design allowed optical contacts to conform to the scalp, measuring directly from the forehead. The device was proposed to increase the spatial and temporal resolution without extensive hardware. The researchers attributed the performance improvement to high Signal-to-Noise-Ratio (SNR) receivers, a modulation scheme and Multi-Input-Multi-Output (MIMO) based data extraction algorithm (Choi et al., 2012). Overall, this technology formed the basis for the Obelab NIRSIT system, which provides prefrontal cortical sampling and is now commercially available (Zhao et al., 2017).

Signal to noise ratio receivers

Signal to noise ratio is generally defined as the dimensionless ratio of the signal power to the noise power contained in a recording (Johnson, 2006). Choi et al. explain, when a detector receives signals from multiple laser sources with varying path lengths simultaneously, the near-far problem occurs. The near-far problem, also known as the hearability problem, is the effect of a strong signal from a further distanced source due to adjacent channel interference. This problem can be overcome only if the dynamic range of the analog front-end is sufficiently enlarged so that even the minute signal has an adequate SNR for the extraction of hemodynamics (Choi et al., 2012).

Light propagation

Choi et al. outline first a method for light propagation that improves quantification of chromophore concentration via the differential pathlength factor (DPF). The DPF accounts for increases in the photo pathlength caused by scattering and is a strong function of the penetrating medium. Light propagation is measured with two photodiodes as seen in Figure 1 (b). The instrument contains two tentative light paths towards two photodiodes. The path 1 and 2 model source and detector (SD) separations are spaced 2 cm and 4 cm, respectively. An incident light penetrates into surface tissue layers, skull, and cerebrospinal fluid (CSF) sequentially before reaching the cerebral cortex. The appropriate DPF are estimated by analyzing the light propagation under an infinite slab boundary. A conventional model calculates *DPFs* with a semi infinite boundary condition, which assumes the medium extends in all directions except one. However, Choi et al. estimated DPFs with differing boundary conditions according to light behavior in each model. For example, DPFs were estimated at 3.764 and 5.972 at a wavelength of 780 nm and 3.3 and 4.7 at a wavelength of 850 nm, respectively. DPF affects quantification of chromophore concentration (HbO and HbR) in fNIRS. Therefore, using the appropriate boundary model might yield more localized or region-specific estimations of DPF (Piao et al., 2015).

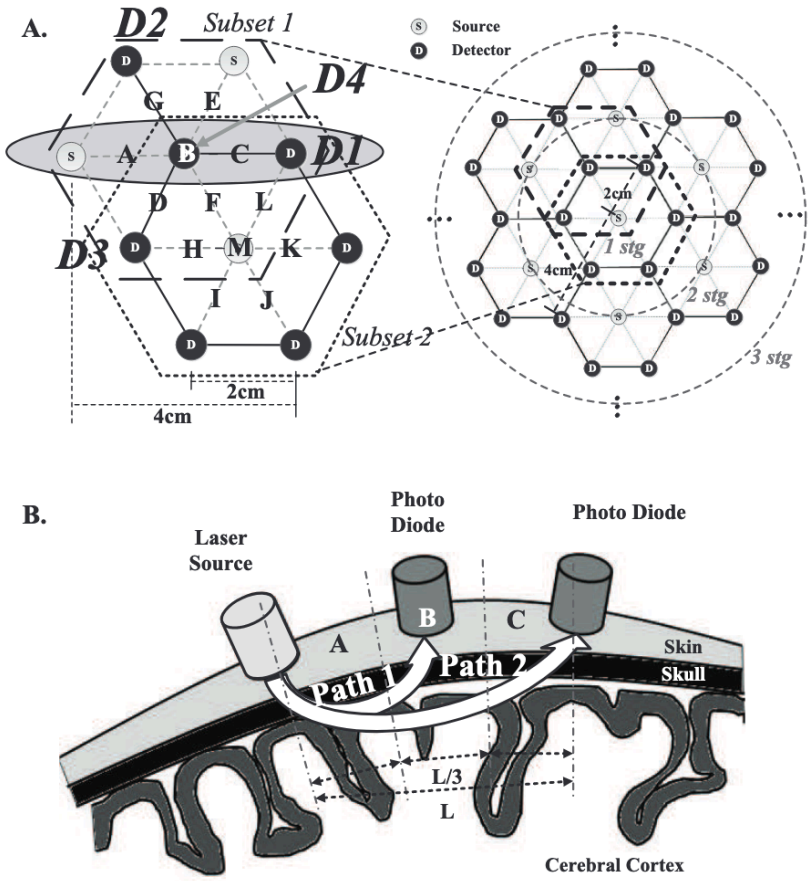

Figure 2. (a) Unit Hexagonal source and detector array. (b) Light propagation of the shaded region in Subset 1. (Choi et al., 2012).

Overall, the detected optical signals are converted to hemodynamic responses by using the Modified Beer Lambert Law (MBLL), where DPFs and absorption coefficients are obtained. The hexagonal source and detector array (SD array) scheme is directly attached to the front of the head without optical fibers and connected to internal detection circuitry.

Multi-input, multi-output (MIMO)

Many wireless communications channels consist of multiple signal paths from the transmitter to the receiver. The multiplicity of undefined lightwave paths leads to a phenomenon known as multipath fading (Costa et al., 2010). Multipath fading is when multiple paths are caused by the presence of objects in the physical environment that alter the path of the radiated energy. In fNIRS systems, brain activity and peripheral physiological changes may contribute to light absorption and may contribute to light absorption and influence data. For example, activity in the sympathetic and parasympathetic nervous system may lead to vasodilation or vasoconstriction in the skin (Lai et al., 2018). These objects are referred to as scatters. Multi-input, multi-output (MIMO) systems use the multipath diversity to their advantage. An MIMO system can translate increased spatial diversity into increased channel capacity. The proposed approach for NIRSIT incorporates a MIMO scheme to a hexagonal source and detector (SD) array structure which increases the spatial resolution without hardware excess.

Extraction of hemodynamic response

Detecting point	In Fig. 1(A)	General Equation of # of Detecting Points (n=stage)
The center region of SD separated (2cm)	***A,E,F,H,I,J,K,L***	$6(3n^2-3n+1)$
The edges of UHS	***G,C,D***	$6n^2$
The center region of UHS	***M***	$3n^2-3n+1$
The vertex region of UHS	***B***	$6(n-1)^2$

Figure 3. Detection regions when the number of UHS stages is expanded to *n.* (Choi et al., 2012).

Figure 1(a) shows the hexagonal signal-detector (SD) array structure. In the diagram, subset2 is the basis of the structure and thus is referred to as the Unit Hexagonal Subset (UHS). The goal of the design is to detect the hemodynamics in entire internal points, vertices, and edges of the UHS. Subset1 is defined to show how the hemodynamics at the vertex (B) and the edges (C,D,G) can be extracted. The hemodynamics responses were estimated from 7 regions using 4 detectors and 3 sources. Detectors D1, D2, and D3 receive a signal for laser sources separated by both 2cm and 4 cm concurrently. The hemodynamic absorption coefficient measures how much light is absorbed per unit length (Jacques, 2013). The signals from the sources separated by 4cm can be separated and extracted via demodulations and variations in optical power density. Optical power density measures the amount of optical power delivered per unit area (Welch & van Gemert, 2011). The detector D4 can directly detect the hemodynamic responses in regions A, F, and E and laser sources separated by 2cm. Overall, in the UHS, the hemodynamics in 6 regions can be detected directly and the center region M can be interpolated.

Figure 3 categorizes and counts the number of detection regions when the number of UHS stages is expanded to *n* (Choi et al, 2012).

Diffuse Optical Tomography (DOT)

NIRSIT is also unique in being the first commercial fNIRS system to implement real-time diffuse optical tomography (DOT) to match fMRI resolution (OBELAB, 2025). Vidal-Rosas et al. define DOT as "the use of fNIRS measurements to create 3D images of optical tissue." Hoshi et al. explain that DOT recovers 3-D distributions of the optical properties derived from multiple boundary measurements. DOT enables a quantitative determination of regional cerebral hemoglobin without signal contamination arising from extracerebral tissue. DOT algorithms consist of two parts: 1.) a forward model to calculate light propagation and 2.) the consequential emissions at the boundary of the tissue. This is typically based on the diffusion equation (DE) or the Radiative transfer equation (RTE). In 2019, Choi et al. demonstrated in their preliminary findings the hemodynamics during isometric thigh muscle contraction validated their proposed NIRS system as a tool for measuring muscle oxygen saturation via tomography-based visualization (Choi et al., 2019). This technology is also the basis for mapping oxygen mediated brain activation onto the prefrontal cortex in the NIRSIT device shown in figure 5.

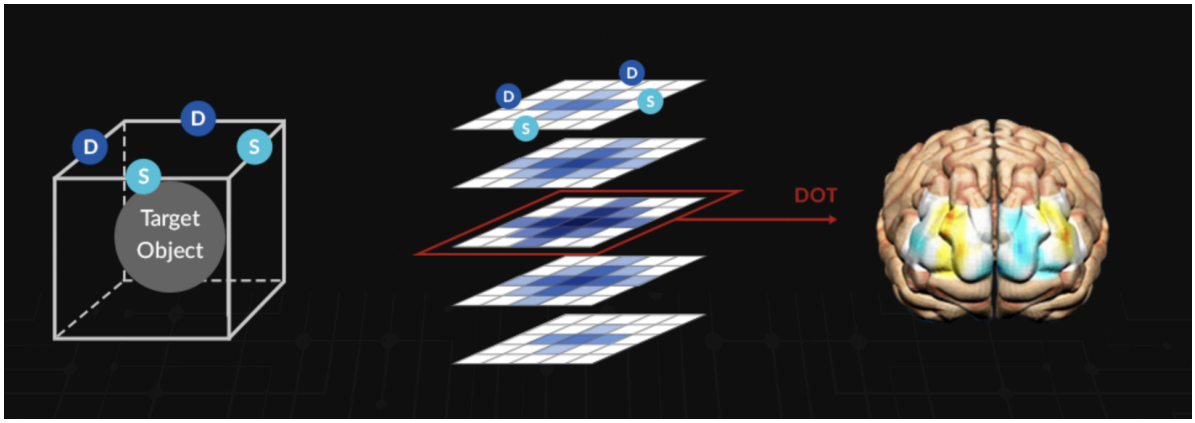

Figure 4. DOT analysis in NIRSIT. DOT analysis is typically done on the deepest tissue layer to avoid surface contamination and to investigate spatial information of the deeper tissue layers. (Obelab., 2025).

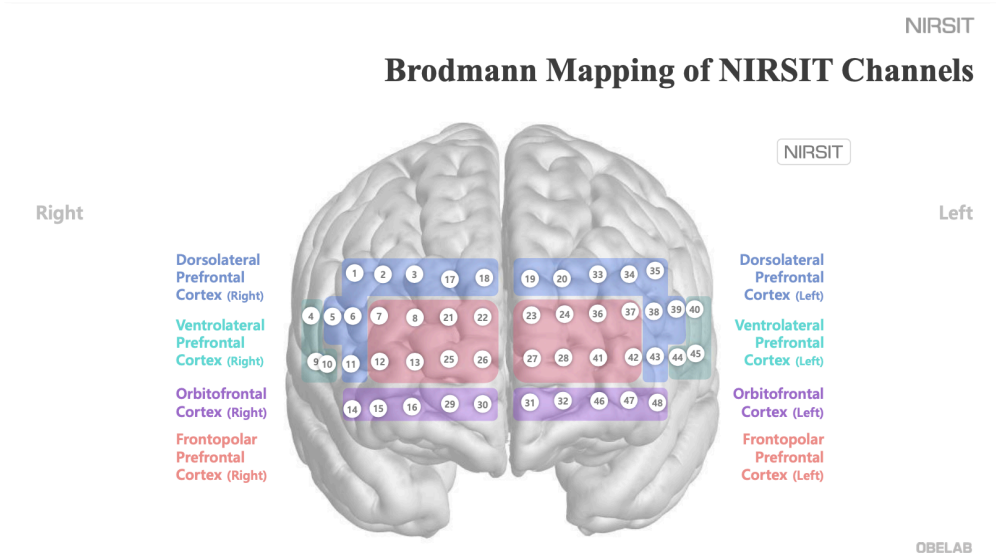

Figure 5. Brodmann Mapping of NIRSIT Channels. Developments in mapping and anatomical information have also improved with the development of the Obelab NIRSIT device. NIRSIT uses 22 lasers and 32 detectors and estimates their coordinates onto a map of the Brodmann areas of the brain. In total 48 channels are configured and measure information on the Dorsolateral Prefrontal Cortex, Ventrolateral Prefrontal Cortex, Orbitofrontal Cortex, Orbitofrontal Cortex, and Frontopolar Prefrontal Cortex of the brain. (Kim, TH., et al, 2022).

Figure of Merit

Choi et al. reported that the NIRSIT data extraction method improves figure of merit (FOM) by 72% as compared to conventional methods. To compare, a conventional detector model has 100 SD elements while the hexagonal structure has 133 SD elements. Additionally, intrinsic regions count increases from 180 points to 409 points in NIRSIT. The metric of spatial resolution increases from 1.8 to 3.1. Finally, the proposed structure operates continuously in a time domain. As a result, the researchers indicate that their method increases spatial resolution in the NIRS without sacrificing the temporal resolution (Choi et al., 2012).

Figure 6. Tran et al. measure hemodynamics with a portable fNIRS device in Vietnam. (Tran et al., 2023).

Applications in Research

Increasingly, fNIRS has been implemented in clinical research as a potential adjunct for assisting diagnosis, predicting clinical outcomes, and evaluating treatment outcomes in psychiatry. While fMRI is still considered standard for neuroanatomical imaging, fNIRS has the advantage of portability as compared to the still imaging required for fMRI. As such, it has the potential to expand clinical research paradigms to include more ecologically beneficial investigations in brain function in clinical and social environments. Lai et al. noted that studies indicated that when fNIRS and fMRI were used concurrently to measure activity during cognitive tasks, fMRI Blood Oxygenation Level Dependent (BOLD) signal records were highly correlated (r = 0.77-0.94) in the same neuroanatomical regions (Lai et al., 2018). Additionally, the light used in fNIRS does not interfere with other tools such as fMRI, PET, and EEG. Thus, multimodal measurements can be performed on study participants as a means to dually examine data.

Currently, there is no standardized and widely accepted signal processing method for fNIRS as compared to fMRI or EEG. However, Yücel et al. in 2021, published very detailed recommendations that included a checklist on how to report fNIRS studies (qtd. in Albrecht et al, 2025). Non-standard signal processing can create situations where using data analysis tools provided by commercial companies create false positives or false negatives in the results for novice users (Pfeifer et al., 2018). In the case of NIRSIT, users are provided with an analysis tool manual that pairs the data from the device with a Matlab processing program. Users can create a time series graph, enter neural marking signatures, and calculate

connectivity. These methods provide useful statistical insight into the collected data from NIRSIT, however it would be difficult to compare to studies that vary in their fNIRS data analysis techniques.

Study Paradigms

The potential of fNIRS as a tool in determining neuronal markers is still fairly new and thus the majority of investigations require confirmation for validity. To make this process as concurrent to previous neuroimaging methods as possible, in 2017, Lai et al. outlined three parameters that researchers should consider when designing a study with fNIRS. According to Lai et al. researchers should consider: 1.) whether the spatial resolution of fNIRS is adequate to answer their question of interest; 2.) whether their design accounts for weaker signal-to-noise ratio, especially in brain regions more distal from the scalp; 3.) that the fNIRS-Hb signal mainly reflects the hemodynamic changes in the grey material. Additionally, fNIRS possesses several advantages to other neuroimaging tools. Because fNIRS is not sensitive to movement, it can be used in trials with fidgety patients, young children, and participants performing either sitting or movement based tasks. This opens up potential for studies in sports science, meditation, movement based tasks, and addiction studies due to connections in dopamine and movement.

Clinical Psychiatry

Lai et al. further outlined key principles in applying fNIRS for psychiatric conditions. Generally, they note, there are two types of design paradigms: 1.) block design and 2.) event related (or trial based) design. Block design examines the pattern of brain activation across conditions, such as an alternating pattern of one or more blocks during the resting condition and the task condition. Conditions can be set as a time source, (pre-task, during-task, and after-task period). Alternatively, event related design analyzes brain activity triggered by events that occur in a random order. Thus, event related measures transient changes in brain activity during short and discrete intervals of time (Lai et al., 2017).

NIRSIT has been used in various trial designs to correlate neuroanatomical structures to psychiatric conditions due to its high temporal resolution. Though limited to the prefrontal cortex, studies on Attention deficit hyperactivity disorder (ADHD), Bipolar disorder (BD), Major Depressive Disorder (MDD) also known as unipolar disorder (UP), and Schizoaffective disorders have been assessed with NIRSIT fNIRS technology to name a few. Low-cost and portability make this a landmark achievement for improving accessibility in neuroanatomical psychiatric diagnosis. In 2016, Tran et al. found distinct levels of activation in the left orbitofrontal cortex and left dorsolateral prefrontal cortex during the verbal fluency test (VFT) (Tran et al., 2016). In 2023, Yang et al., effectively discriminated children with ADHD from healthy controls with regularized linear discriminant analysis using only fNIRS (Yang et al. 2023). Additionally, in 2023, Kim et al. achieved a generalized classification accuracy of 70.3% in suicide high risk adolescents with MDD using fNIRS and iterative search-based feature selections. This finding implied that fNIRS channels could potentially be used as neurological biomarkers for distinguishing SHR adolescents from suicide low-risk (SLR) adolescents (Kim et al., 2023). In 2019, Baik et al. found that

prefrontal asymmetry during VFT was significant and positively correlated with suicide ideation in patients with MDD. In particular, greater changes in left oxy-HbO levels were associated with greater suicide ideations. These findings indicate that fNIRS assessed prefrontal asymmetry could serve as a potential biomarker for MDD and suicidal risk patients with MDD (Baik et al., 2019). In 2023, Tran et al. differentiated people with schizophrenia from healthy controls with a 72% correct classification rate. Their findings indicated that people with schizophrenia show deactivation in the frontal lobe during cognitive tests such as the Stroop Color-Word Test and VFT (Tran et al., 2023).

Discussion

In the last decade, fNIRS technology has been heavily investigated as a neuroimaging tool resulting in a wide range of diversity of data extraction methods. Overall, the commercial fNIRS device, NIRSIT utilizes an efficient method of hemoglobin extraction methods, due to its inclusion of high SNR receivers, a MIMO modulation scheme, and DOT imaging technology. NIRSIT overcomes previous challenges documented in fNIRS literature including limited spatial resolution, high density fiber optodes, comparisons of fNIRS between subjects, and signal noise attenuation (Irani et al., 2007). There is potential for fNIRS in predicting clinical outcomes and evaluating treatment outcomes in social and interactive environments. Vidal-Rosas et al. note that they expect that the, “highly artificial simulations and constraints that are associated with fMRI measurements will be gradually complemented, or even replaced by the neuroimaging of natural world movement, cognition, and interactions that are possible with DOT and fNIRS technologies” (Vidal-Rosas et al., 2023). Improvements in wearability and weight have permitted dynamic functional neuroimaging to examine brain activity in paradigms that incorporate movement, exercise, and dynamic balance (Vidal-Rosas et al., 2023).

Clinical interviews and questionnaires may have difficulty differentiating psychiatric conditions because some conditions can present with overlapping behavioral symptoms. For example, BD and UD may both present with depressive symptoms. Neuroimaging and biomarkers may potentially provide information to enhance the accuracy between bipolar disorder as a low cost, noninvasive, and portable method. The clinical trials outlined in this paper suggest that Assessing hemodynamics during cognitive testing can serve as potential as an adjunct diagnostic tool for mood disorders in low resource environments. In 2023, Tran et al. even reported using fNIRS as cost-effective effective neuroimaging solution for developing countries (Tran et al., 2023). However, further research is needed to validate and determine the utility of the fNIRS device as an adjunct diagnostic tool for psychiatric disorders.

The penetration power of light is another limitation to fNIRS because it limits the depth of the brain region that can be reached. As a result, fNIRS may not be suitable for examining the activity of subcortical or deep brain regions. NIRSIT is limited in functionality only to the PFC regions, however this is a region that is critical to cognitive diagnoses. For example, Alzheimer’s disease (AD) involves deficits of deep brain structures, including the parahippocampal gyrus and hippocampus, which cannot be measured by a fNIRS device (Pfeifer et al., 2018). However, in 2021, Kim et al. investigated a new neuromarker called the “refined network” in the PFC that revealed pathological features of AD with a

95% classification accuracy. However, further investigation of statistical methods is needed in order to analyze the increasing highly multidimensional neural dynamics data collected through fNIRS technology. Statistical models and machine learning models have been widely researched because of their specialization in multivariate pattern analysis. In one study, researchers identified a possible biomarker of pain using feature selection through machine learning in fNIRS datasets (Kim et al., 2024).

Recently, Zhao et al. conducted a review on the progress toward a fiberless, whole-scalp DOT system. The researchers report that the development of a whole-scalp, high density, DOT system is a critical next step in the evolution in the field of DOT and fNIRS technology. They note that, while NIRSIT is impressive in its distinct approach using an compact integrated circuit, it is difficult to comment on the system's potential sampling density, its dynamic range, or its suitability for high density measurements and DOT. Additionally, while the system provides 42 channels that access PFC range, “Choi et al. have yet to address the challenges associated with expanding this technology to provide whole scalp sampling.” Ultimately, creating a whole-scalp fiberless, high density, DOT system would require designing a system that is high density, small and lightweight enough for wearability, conformity to the curved surface of the head, and subject safety (Zhao et al., 2018).

Conclusion

As the field of fNIRS is steadily advancing, Obelab’s NIRSIT is an example of how efficient data extraction techniques can have critical applications in the field of neuroscience and clinical psychology. Overall, incorporations of MIMO, DOT, and high SNR receivers prove to be an efficient means of data extraction for hemoglobin dynamics. Over the course of the NIRSIT’s development, release onto the market, and use in clinical and non-clinical trials, it has proved to have potential as a diagnostic and research device for psychiatry. However, this system is limited in its capacity and has been demonstrated only over the forehead for PFC investigations. While this system can provide high resolution imaging into PFC regions of the brain, Choi et al. have yet to publish insights for expanding this technology for whole scalp sampling, a crucial next step. However, this barrier is still overcome with statistical modeling and neuromarkers such as the refined network in AD. While further research is needed to understand the scope and validity of refined neural markers in other neural conditions, it brings potential into improving portable, accessible neuroimaging to communities where fMRI is not available.

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