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Title: Improving fNIRS Signal from Long Hair Interference

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Abstract

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive neuroimaging technique that can potentially allow neural responses to be measured within ecologically valid environments. However, the hair often compromises this potential, especially in persons with thick or curly hair coupled with high melanin content, who tend to largely absorb the signal. Herein, we propose a new, non-invasive approach using a unique, biocompatible gel to remove hair interference for better contact between the optode and the scalp. A series of experiments showed that, compared with classical methodologies, gel application may improve SCI and reduce setup times. This may increase the signal-to-noise ratio without invasive preparations such as shaving. This further testifies to the approach's effectiveness, as it can cover most hair types and skin tones. It keeps the inclusiveness in neuroimaging research. This paper describes the development and testing of the gel application method and its effects on the quality of the fNIRS signal. A recommended approach for its application within diverse research and clinical settings is provided. The implications suggest that such non-invasive measures are valuable toward developing fNIRS technology that can be used without significant complications for accurate, reliable, and fair measurement of brain activity among different populations. This approach thus aligns very well with the ethical demand on neuroimaging research that it accounts for human diversity and, at the same time, looks forward to a future where it promotes the inclusion of neurodiverse individuals as much as possible without giving up its commitment to the unbiased pursuit of the understanding of the brain.

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Chapter 1. Introduction

Functional near-infrared spectroscopy (fNIRS) is a well-established non-invasive neuroimaging technology that measures hemodynamic responses related to brain function through modulations of near-infrared light. It finds applications in cognition, clinical diagnostics, and human-computer interaction.. However, long and/or thick hair interference during data collection poses a crucial obstacle to the efficacy of fNIRS measurements. In fNIRS, near-infrared light from sources passes through the hair, then through the scalp and brain tissue, until receivers detect it. Two general points complicate the process due to hair:

Access Quality to Scalp: This factor can lead to poor signal reception in fNIRS for individuals with curly and thick hair. The lack of proper physical contact between the emitters and detectors and the scalp's surface can limit signal quality attainment.

Signal Quality: Hair, especially dark hair, can attenuate the fNIRS signal despite possibly having unrestricted access to the scalp. Hair functions as a barrier, lowering the number of photons that can penetrate the scalp and reach the brain's surface, leading to incorrect estimates of absorption properties and errors in the recorded signal.

This interference is dependent on the concentration of melanin in hair and skin. Melanin, a powerful light-absorbing chromophore, can interfere with the absorption of near-infrared light. Increased light absorption due to increased pigmentation in dark skin and hair can lead to degradation of signal quality.[1][2]

The challenges we face for the inaccuracy of fNIRS measurements, specifically in individuals with skin pigmentation above level two on the Fitzpatrick scale, are even harder. That's because the precision of absolute hemoglobin estimates the impact of relative oxygenation changes, making the data collected relatively unreliable.[3]

To address these challenges, we propose methods to enhance signal registration in fNIRS measurements. We suggest simple maneuvers and actions that can enhance signal quality without changing the caps used for fNIRS or even invasive techniques like shaving the hair or braiding it. One methodology we explore is the Scalp Coupling Index. This index quantifies the importance of the photoplethysmographic heart waveform, mainly concerning the pulsatile blood volume at the scalp. It also helps identify poorly coupled optical channels, which can be excluded from further analysis at a threshold value of 0.8. [4]

We also look into analyzing physiological phenomena such as pulses and Mayer waves in fNIRS signals. It is a pulse-related component of fNIRS signals that oscillate around 1Hz and reflects cardiac output and blood volume changes per heartbeat. The concept of Mayer waves is that if they oscillate at about 0.1 Hz, they indicate a systemic arterial pressure change. [5]

This paper will provide more details on these methodologies and explore novel approaches to reduce hair interference in fNIRS measurements. The paper aims to advance fNIRS technology's accuracy and reliability, making it a versatile tool for studying brain activity in individuals with diverse hair types and skin colors.

Moreover, hair characteristic differences further increase the difficulty in getting proper fNIRS measurements, especially from subjects with skin pigmentation over level two on the Fitzpatrick scale. This type of data from such diverse groups is relatively unreliable since it may compromise the accuracy of absolute hemoglobin estimates and their impact on relative oxygenation changes. Variance in hair type, combined with different skin pigmentation levels, greatly influences the fidelity of the signal and makes it very hard to standardize measurements to accurately interpret the outcome of such tests.

We propose a multifaceted, innovative set of methodologies to meet these challenges for improving signal registration in fNIRS measurements. Non-invasive, pragmatic ways not to bother with adaptations to pre-established fNIRS caps or make use of invasive methods, such as hair shaving or braiding. One such approach is the Scalp Coupling Index (SCI), a newly introduced scalar value that quantifies the importance of the photoplethysmography heart waveform regarding the pulsatile blood volume at the scalp. This index contributes a lot when accessing optical channels that are poorly coupled; if they are below a value of 0.8, then these are the channels that should be discarded during analysis. Further, it includes work that explores the extraction and analysis of other physiological phenomena, such as pulses and Mayer waves, from the fNIRS signals. Pulses are oscillated at a frequency of about 1 Hz, one of the elements of the fNIRS signal, and they show reflexes in the cardiac output and blood volume changes following every heartbeat. Mayer waves oscillate at about 0.1 Hz and reflect the changes in the systemic arterial pressure. These variables helped improve the preciseness and repeatability of the fNIRS measurement. In particular, they contributed to the adverse conditions provoked by hair. [6]

This work is informed by experimental results and simulations, which show the capability of brush optodes to overcome poor optical contact due to hair interference. The optodes were designed as brushes and were attached to existing flat-faced fiber bundle optodes, which showed great promise in threading through the hair to increase optical contact with the scalp. In actuality, this improvement is more than just theoretical. Proof of this is in the nearly 100% study success rates, reduced setup times of measurement by a factor of three, and improvements in activation signal-to-noise ratio (SNR) up to a factor of ten. This further supported the obtained areas of activation (dAoA) with significant increases, identifying that, compared to fiber optics, brush optodes decrease the limitations introduced by the different types and densities of hair.

These methods, dependent on Monte Carlo simulations and analytic modeling of photon transport in the hair and scalp tissue, give a comprehensive way to minimize hair interference with fNIRS measurements. The ultimate goal of this work is to further advance fNIRS technology for more precision, reliability, and adaptability when applying this tool to the study of the brain activity of those with hair type and skin color effects. To improve these critical abilities, innovative approaches with the target of making fNIRS more applicable across different populations in neurological research and clinical diagnostics so that brain imaging may be both fair and accurate. [6]

Chapter 2. Literature Review

Functional Near-Infrared Spectroscopy (fNIRS) is a new wearable technology in which quantification of the cortical hemodynamics response of the brain is made through non-invasive, portable means by close sources of near-infrared light and detectors on the scalp. This new approach particularly measures variances in the concentration of two critical forms of hemoglobin, namely, oxyhemoglobin and deoxygenated hemoglobin (deoxy-Hb, sometimes abbreviated as HHb). The oxy-Hb carries the oxygen from the lungs to tissues in the brain, while deoxy-Hb arises after the transport of oxygen to the tissue, which acts as a marker for metabolic activity and, in turn, serves the brain-blood flow. Measuring deoxy-Hb with oxy-Hb is critically important because the equilibrium between these forms of hemoglobin presents essential information about tissue oxygen use and, therefore, its consequent vascular response to neural activity. Essentially, the fNIRS technology uses the differential absorption features of OxyHb and DeoxyHb to near-infrared light to quantify their concentrations. Such quantification would be important in understanding the brain's hemodynamic changes in response to the performance of specific cognitive tasks or stimuli, which, in turn, may allow for an estimate of the level of neuronal activity and the brain's health. [7]

fNIRS has many benefits that it shares in common with fMRI for research, such as portability, the lower cost of conducting a study, and allowing a more naturalistic study environment. This is primary because the fNIRS equipment is relatively smaller and does not subject the subject to staying within a contained, noisy space, which is an issue with fMRI machines. Furthermore, it has a far superior temporal resolution that enables researchers to capture the dynamics of changes in the hemodynamics of the brain more accurately and free from interference by loud operational noises. The signal processing in fNIRS is detailed with complex algorithms meant to correct artifacts of motion, surface superimposed layers like the scalp and skull, and physiological signals indirectly related to cerebral activity. These algorithms ensure that the data are clean and reliable because, without this reliability, there can be no meaning of accurate interpretation in any form. The Beer-Lambert law becomes instrumental in easily converting detected optical density changes by the fNIRS sensors to meaningful concentrations of oxy-Hb and deoxy-Hb. This is essential in converting the analyzed functional activity in the brain and understanding it concerning underlying physiological mechanisms. [8]

Since then, several major technological developments and the expansion of the fields of application have combined to change the history of functional Near-Infrared Spectroscopy (fNIRS) from a very important tool for non-invasive monitoring in human infants and adults of cortical activation in response to a variety of stimuli. The real initiation of evolution—when fNIRS was put in motion—was in 1992.

In this historic year, it was found that changes in oxygenation and hemodynamics allow probing the functional activation of the human cerebral cortex with the help of near-infrared spectroscopy. This discovery opened a new dimension to human functional brain mapping research, which developed into the development of fNIRS. This is fNIRS technology derived from principles similar to those applied in the research of near-infrared spectroscopy (NIRS) for the simultaneous measurement of variations in the optical properties of the human cortex at several measuring points. This technique visualizes these changes in the cortical regions as maps or images, which makes a thorough and clear understanding of the regions in the cortex that are processing the stimuli possible. This exceptional range of flexibility positioned fNIRS as a uniquely capable tool that outperformed all traditional methods in neuroimaging in some aspects, most importantly, in natural, non-invasive, safe monitoring.

This breakthrough set the stage for developing single-site to multi-site functional cortical measurements in fNIRS technology. Brain functional exploration using NIRS was, at first, a single-point measurement, which could only hint at the possibilities of an actual functional brain map. However, when the multichannel systems finally came, perhaps the greatest leap was in Japan, where the first 10-channel CW system was introduced by Hitachi in 1994. The development of functional near-infrared topography completely to map the cortex and move ahead of the brain activation patterns has only recently been possible with these systems. In addition, the integration of time- and frequency-resolved systems will add much capability to the fNIRS in the direction of optical tomography, allowing three-dimensional imaging and further discrimination against absorption and scattering in tissues, giving a much better insight into cerebral hemodynamics. The development time of wearables and wireless fNIRS systems has ultimately underscored the technology for real-world application and measurement, even during the subject's ongoing, non-experimental, ordinary daily activities.

The features of fNIRS technology qualify it to reach outside the laboratory for more dynamic and ecologically valid environments. The history of fNIRS research, as long as one has existed, has pushed towards better development of instruments and increased the breadth of application. From the first laboratory prototype to miniaturized, wearable, and wireless, sophisticated multichannel systems, the fNIRS has developed as an indispensable tool for studying brain activity across most conditions and in most populations. The history tracks the trajectory of innovation for the enhancement of human brain understanding, demonstrating how it mirrors the trajectory of this company and its technology in providing cutting-edge tools in support of neuroscience and clinical diagnostics. [9]

These supposed portability and cost-effectiveness features of fNIRS, over and against the highly expensive and heavy conventional neuroimaging techniques such as functional magnetic resonance imaging (fMRI), make it stand out. Allows one to investigate the hemodynamic changes measured within real-world settings because of the silent, non-invasive measurement of the fNIRS systems with high temporal resolution and the absence of constraining environmental requirements. An fNIRS would seem to be the perfect tool for use in neuroergonomic research: it can measure brain activity in settings that can be taken to real working or living conditions without large, non-portable equipment.

Therefore, fNIRS technology has applications in the aerospace industry, such as estimating the cognitive workload of air traffic controllers and pilots. Activation maps of the brain will be analyzed to help the researcher infer the mental demands imposed on subject individuals managing the workload of complex tasks in real or simulated flight conditions. All these insights contribute to developing training programs and technologies designed to enable heightened cognitive performance and improved situational awareness that will ultimately improve the safety and efficiency of operations. fNIRS has equally an exemplary application in health. For instance, it provides an understanding of the effect of cognitive aging on physical functions like gait. Thus, monitoring prefrontal cortex activity for an aging population while executing walking tasks under single- and dual-task conditions gives value to the neural correlates of locomotion in the context of dual-tasking.

This line of research bears implications for the risk profile of older people and intervention strategies oriented to preventing mobility impairments and falls. Despite its numerous benefits, fNIRS technology is not without its challenges. The other challenge that is still pending remains: how to ensure and achieve an ideal optical contact quality with the scalp, and even more so if the hair were to exist, which produces a great impact on the signal quality. All these are sources of variation in head shape, optical path lengths, and involuntary head movements, which make the search for repeatable, accurate measurements across different individuals exceedingly difficult.

Lastly, the motion artifact and the signal predominantly affect the superficial layers of the cortex, consisting of solely physiological noise, rather than the diversity in signals, which would be dealt with by the most sophisticated signal processing and analysis techniques to ensure data integrity. For this reason, research and development to improve fNIRS systems' temporal and spatial resolution are ongoing. Therefore, they focus more on detecting brain activity in detail; with the focus on the increase in data acquisition speed, through such measures, scientists and engineers enhance their technology in terms of better applicability and effectiveness. What an innovation it would be: wearable, wireless fNIRS sensors. This would mean a huge development, allowing researchers to move their studies from within normal laboratory settings. For the first time, it will make further insight into brain function in dynamic and ecologically valid environments possible.

Further development of the fNIRS technology, accompanied by hardware design and signal processing algorithms, would improve its possible application fields. From neuroergonomic assessment in high-stakes environments to monitoring neurological recovery and investigating the neural base for cognitive and motor functions in daily life, fNIRS is solidifying itself as a key tool in the neuroscience kit. Its further development has suggested potential not just for possible ways of improvement and deepening our understanding of the brain's activities in the most diverse context but also for its promotion as an innovative field that may change our work and learning or relationship with technology, and so forth. [10] [11]

The better spatial and temporal resolution of functional near-infrared spectroscopy (fNIRS) system performance is an important step in unraveling human brain complexities in the evolving landscape of neuroimaging. These advances provide the core for improving knowledge about neural dynamics; they push the boundaries of how we track, diagnose, and see treatment in neurological conditions. But in their relentless push for higher resolution and faster data acquisition, they inadvertently shine a spotlight on a systemic problem that bedevils much scientific research: the introduction of racial bias that, in turn, may magnify extant health disparities and skew the scientific knowledge base. This, in turn, represents one of the major technological and methodological weaknesses: issues with the quality of fNIRS signal capture, such as darker pigmented skins and thicker, denser hair types, that would be characteristics for many racial groups. The difference is that the physical fNIRS senses the changes in blood oxygenation by penetrating near-infrared light through the skin, scalp, skull, and cortex. However, this would make a difference in the concentration of melanin and the texture of the hair, which would, in turn, make a great difference in the penetration of the light and, hence, the quality of the procured data.

Such technical limitations bring out an urgency not only for reactivity within the field concerning health equity but also compromise the reliability and generalizability of research findings. As such, fNIRS will be included in the shift—theoretically and practically—to develop technologies and methodologies that are more inclusive of the full spectrum of human diversity. The design and process of implementing the studies with neuroimaging should be guided by theoretical frameworks emphasizing inclusivity and equity. This involves scrutiny of the level to which racial and phenotypic differences are considered critical, from the actual design of the fNIRS equipment to even the data analysis algorithms. If translated to the heart of neuroimaging research, it might reduce disparities with a risk of perpetuating or increasing racial inequality. The realization of an equitable paradigm in neuroimaging would be associated with developing interdisciplinary collaborations between neuroscientists, engineers, ethicists, and community representation.

These collaborations will secure the best minds and expertise in various areas to contribute to the innovation process, from technology development to the application of neuroimaging in clinical and research venues. In parallel, methodologies of community-engaged research that include diverse stakeholders of racial and ethnic backgrounds will have to be brought in from the onset of the research process to further ensure that fNIRS is indeed being developed and applied to meet the needs and concerns of all populations. In other words, efforts to improve the spatial and temporal resolution of the fNIRS systems need to go along with those of fNIRS—otherwise important for furthering neuroscience—since they place that imperative to ensure health equity. Comes the day when neuroimaging research envisions an accurate, just, and comprehensive understanding of brain function by taking all of the practical and theoretical commitment required for the development of this field. This obligation serves as one of scientific integrity and as one more step in building the foundation toward health disparities by allowing for a future that will increasingly accommodate all people in neuroscience research and healthcare. [12]

Chapter 3. Project Strategy

Initial Client Statement

In this area of the client's interest, in refining the capability of functional near-infrared spectroscopy (fNIRS), it shall try to focus on the minimization of interference challenges, more particularly those posed by hair in making optical contact with the scalp. The perfect approach should only improve the high accuracy of fNIRS measurements in all cases without adding to the cases in which hair would be problematic for signal acquisition. This avenue epitomizes a critical approach to overcoming one of the key barriers to improvement in neuroimaging, inspired by the kind of brush-like electrode structures that improve contact through penetration into hair (e.g., as seen in electroencephalography methodologies).

The major difference is that the standard fNIRS systems are designed in a manner that would be unfriendly to MRI, in one instance, because of hair interference. The standard fNIRS equipment is used in the biggest number of non-magnetic materials surroundings, which do not impose further limitations. However, it is an MRI-compatible fNIRS setup that can work within the magnetic environment of the MRI machine and make simultaneous fNIRS-MRI studies possible. Combining spatial resolution abilities analogous to MRI with the temporal insights given by fNIRS gives rich, multidimensional views of brain functional imaging. This, however, implies that there are difficulties due to signal interferences because of the special materials used by MRI-safe equipment. These materials are important to ensure safety within the MRI environment, although they may affect the efficiency of transmitting hair penetration for optimal optical contact in quality fNIRS measurements.

Hair interference issues will be much more challenging for MRI-compatible fNIRS systems, as MRI compatibility already limits the choice of material and design. It, therefore, means that innovative solutions should arise to maximize scalp contact and signal quality while at the same time assuring MRI safety conditions. Probable strategies would be in the design nature of the optodes, which are non-magnetic and hair-penetrating, such that these could efficiently part the hair and reach up to the scalp for minimum optical noise and gain the best accurate fNIRS data. The following pursuit of these innovative solutions to address a wider commitment toward advancing neuroimaging technologies in a manner that considers practical challenges on one side while broadening possibilities for multimodal brain research must follow. Such moves by the field bring it closer to the possibility of enabling the delivery of precise and trustworthy insights into brain function and disorders, borrowing approaches from across the neuroimaging disciplines and modifying them to meet the unique circumstances that define MRI-safe environments. Therefore, this work highlights the precision required in neuroimaging measurements and the continual urge to be inventive and flexible when developing neuroimaging technologies. [13]

Objectives & Constraints

The project's objectives have to be carefully designed, framed, and aimed at addressing the most critical challenge: developing optical contact with the scalp in the presence of hair—a major limiting factor in successful fNIRS measurements. It will, therefore, take the lead in tools or devices that will navigate hair expertly to secure perfect optical contact, hence reducing interference that usually interferes with data quality. A versatile system capable of feeling at home with the myriad head shapes encountered across individual cases would be a very ambitious engineering process. Assure, at the same time, that the technology is capable of finding much wider applications and can produce measurements of universal precision.

These objectives are dealt with through a set of limitations, or rather constraints, ranging from financial to pragmatic, in which there is a strong need to maintain balance for the 'Innovation-Feasibility' bar. Fiscal constraints will require a more pragmatic design emphasizing cost-effective solutions that do not compromise the requirements. The practical implementations of these innovations should be, in particular, portable, with a simple set of procedures, easily integrated, or be adapted into versatile experimental settings. Pragmatic considerations stress that these instruments should be effective and, at the same time, applicable in various research environments, with a tendency toward being user-friendly and versatile.

The ethical issues relating to the use of neuroimaging technologies, of course, increase the complexities. With the more sophisticated technologies we develop, we always need to be alert to potential advances in privacy and sensitive information, handling implications of our innovations and discoveries and ensuring that the associated ethical considerations are maintained at the highest standards. However, temporal feasibility and ease of use will emerge as the main guiding factors of this project. Much of the last preparation steps take an enormous amount of time, like hair braiding, which one can't abide by. Hence, our solutions must be designed with much consideration for being very time-efficient and drastically reducing setup time. This is critical, especially in dynamic research settings where time is always of the essence.

Equally important is that the technology is user-friendly and designed so that even basic training for research technicians or students suffices for effective procedures. In this streamlining of the operational protocol, we will attempt to democratize access to high-quality fNIRS measurements, thus enabling contributions in the field by a greater variety of researchers. This project is undertaken with an uncompromising commitment to clear visions that exceed the existing frontiers in neuroimaging, inclusivity, practicality, and ethical integrity. "It is with innovative engineering and careful consideration of the outlined constraints and objectives that we are poised to make huge strides in the utility and applicability of fNIRS technology to capture the subtleties of brain activity across the diverse tapestry of human anatomy."

Revised Client Statement

Considering the implications this project faced from the start, the statement has been revised. The incorporation of 3D modeling emerges as a pivotal implication, particularly in addressing the challenge of improving interference caused by hair during fNIRS measurements.

Project Approach

The project's approach is to provide a practical solution for mitigating interference caused by hair during fNIRS measurements without relying on 3D design; even though it was initially considered, the project has adapted to explore alternative avenues for resolving this issue effectively.

Chapter 4. Design Process

Needs Analysis

We can explore using different optode attachment materials or methods to incorporate a change to fNIRS signal quality. Specifically, testing the effectiveness of novel materials for improving optode-skin contact without causing discomfort or potential harm to the participant's hair and scalp. Some examples of materials to explore could be biocompatible hydrogels, which fulfill these criteria. Conductive fabrics could also be one material since they have adhesive properties and can offer improved contact while remaining comfortable for participants. Another material could be a skin-friendly adhesive, and we could develop one specifically for optode attachments that are easy to remove without hair damage. To test these methods, I would need a diverse group of participants with varying hair types, including those with long and thick hair and participants with different skin tones. I would need to compare the data collected with these methods with the method already used in the lab and be able to draw from it any changes that indicate the signal has been improved or if there are no changes at all. I would also need to collect participant feedback regarding their comfort, ease of attachment, and any adverse effects on hair or skin. Ultimately, the researchers ensured that the materials did not pose any safety risks or discomfort to the participants.

Important Industry Standards

a. The international standard specifies safety and essential performance requirements for fNIRS medical electrical equipment. All the aspects related to the electrical safety, electromagnetic compatibility, and performance of these devices [14]

b. The IEEE standard guides us in the calibration and use of near-infrared spectrophotometers to measure the concentration of chromophores in tissue.[15]

c. The International Society for Optics and Photonics provides various conferences, publications, and resources related to optics, photonics, and biomedical optics. [16]
d. The IEEE EMBS offers publications and standards related to biomedical engineering, including neuroimaging techniques like fNIRS. [17]
e. The ethical guidelines and the approvals from IRBs are crucial for conducting human research using fNIRS [18]

Conceptual Designs

In this design, within the conceptual design phase's ambit, the measurement improvement adopted by fNIRS is coupled with the development of a biocompatible hydrogel for fNIRS. Within this design, through the process of measurement enhancement adopted by fNIRS in the conceptual design phase, the coupling of the scalp to the development of a biocom In this regard, biocompatible hydrogels will be used to overcome the interfacing barriers characteristic of traditional interfaces. This initiative aims to bring drastic quality and comfort improvements for making fNIRS measurements, allowing for superior scalp-optode coupling simultaneously through integration with the Scalp Coupling Index to provide measurement quality feedback in real time.

Special optodes were envisaged to be interfaced with the scalp ingeniously through a layer of biocompatible hydrogel in the fNIRS cap. This layer has many roles: it is designed to improve optical contact, comfort the participants, and secure measurement integrity against potential slippage or misalignment of the optodes. A good example of a hydrogel is AquaGel, which has become one of the most widely distributed in the medical sphere due to its biocompatible, retaining, and user-friendly moisture properties in contact with the skin. [19]

The Hyaluronic Acid-Based Hydrogels show the capability of existing within the human body and portray characteristics of holding up a higher percentage of moisture. Their application in medical and cosmetic setups thus infers that the gels are biocompatible and can come into contact with even the most sensitive skins. While various hydrogels are in the market, a preference for a few that balance biocompatibility, effectiveness, and user-friendliness could be recommended for a purchase decision based on the feedback calling for exploration in focus. [20]

Other competitors include Polyvinyl Alcohol (PVA) Hydrogels, which are famous for their effectiveness in hydration. Carbopol Hydrogel is famous for its gelling and adhesive properties; it helps keep the sensor worn. Silicone hydrogels merge the new benefits of silicones with those of the hydrogels, specifically with the oxygen transmissibility properties crucial to skin health during long measurement sessions. [21]

Design elements in the helmet include hydrogel reservoirs within the fNIRS cap in the appropriate location for optode-skin contact points. The reservoirs are designed with a measured quantity of hydrogel to ensure the continuity of the whole scalp area in even contact with the material. At last, special attention will be given to the compatibility of the hydrogels with the fNIRS equipment. In this regard, one should always use NIRx systems to avoid compatibility issues. This evaluation will be necessary as it will help ensure that the instruments used for measuring and those used to conduct fNIRS are safe and durable. [22]

Considering the diversity of hydrogel material used in practical design implementation, it must be remembered that the material chosen for a hydrogel should also be chosen for its ease of attachment and removal. This important practical consideration remains a prerequisite to maintaining participant comfort and measuring simplicity. Another critical design consideration is the encapsulation of the optodes within the protective housings integrated into the fNIRS cap. That is to say, the housings of the optodes are supposed to rigidly hold them in position without any movement in the hydrogel so that it will ensure that there is no mess in the application and, thus, improve the overall user experience for the operator and participant. [23]

The design proposed is to improve the measurement of fNIRS with the integration of Biocompatible Hydrogel and Scalp Coupling Index, which is conceptual in the futuristic approach of the idea for the image of neuroimaging. The current strategy offers quality and comfort improvement of the fNIRS caps used in measurements by carefully choosing biocompatible hydrogels and incorporating them inside the intelligently designed fNIRS cap, allowing for quality and comfort control in real-time. In so doing, outside of the realm of research, this approach further underwrites a commitment to participant comfort and measurement integrity that assures technology's applicability across wide demographics and diverse experimental conditions.

NirRex Medical Technologies Software and Hardware

The potential of Near-InNIRx systems from NIRS is unlimited and has never been actualized in neuroimaging for both the researcher and the clinician. In its core technology lies flexibility in designing a probe montage that will fit the wider range of research needs and experimental setup. Users can place the probes according to the 'standard' EEG layouts (for example, 10-20, 10-10, 10-5) or at any random position as per their requirement in the study. This flexibility extends to the measurement method, allowing the short- and fixed-distance approaches to be seamlessly integrated with other modalities, including EEG, tDCS, and fMRI. Thus, it is flexible in that the setup allows data collection from any part of the head, including the periphery, and thus may support detailed analysis of many brain regions of interest, such as the prefrontal cortex, primary motor cortex, and Broca's area.

NIRx's commitment to precision and easy operations is clear with the hardware and software solutions offered, which provide the correct spacing of the probes and guarantee perfect light penetration for quality signals. The system supports high-density measurements of up to 182 NIRS channels for prefrontal measurements from a "cloud" of 80 probes. Otherwise, more standard configurations are offered for motor measurements using a 16-source/16-detector layout. Each probe setup—whether it be topography or tomography—will be made with detail and optimized for the study's requirements to ensure that valid and reliable data collection is achieved. Furthermore, the caps from NIRx have a comfortable fit that ensures the subject feels comfortable yet remains still for good measurements.

The innovation extends even to the probes and caps: NIRx offers various optodes for comfortable and efficient measurements. Special probes are designed for long-term measurements of sensitive populations, such as infants and children; standard probes are also available for general purposes. The dual-tip optodes are an innovative design that is patent-pending and ensures both comfort and more sensitivity; through this, setup times are shortened. The low-profile NIRS optodes are designed to allow for comfy and stable measurements in case they are concurrently used with other neuroimaging modalities. In this way, NIRx will remain at the forefront of providing the best NIRS technology available to researchers and clinicians as they can best find the best tools for cutting-edge neuroscientific exploration.

Adding to the ingenious platform of NIRx Systems for neuroimaging, an impressive addition will be hydrogel applications integrated with the developed probes and caps within the realm of Near-Infrared Spectroscopy (NIRS) measurements. Then, there are opportunities for further optimization with NIRx uniquely designed probes, dual-tip optodes, and a specially designed cap to assure exact fitment and reliable data collection. Accordingly, if a certain hydrogel material is to be placed under the hair on the scalp, then these interfering effects that normally happen due to hair in the functional Near-Infrared Spectroscopy (fNIRS) signals shall be reduced with this solution. The hydrogel would serve as a medium that penetrates the near-infrared light by reducing scattering and absorption effects by the hair, making it easier to penetrate light towards the scalp and underlying brain tissue. This innovation may, in turn, ameliorate the quality of signals from all areas of the head, including those where hair is dense. This would widen the possibility for detailed analyses of critical brain areas without shaving or other preparations that participants, especially when working with highly sensitive populations like infants and children, may find problematic or cruel. This addition to hydrogel with NIRx's commitment to precision, ease of operation, and flexibility of probe placement could open up a new standard of non-invasive neuroimaging that enables measurement to be more accurate and time-efficient across a much wider gamut of research and clinical applications.

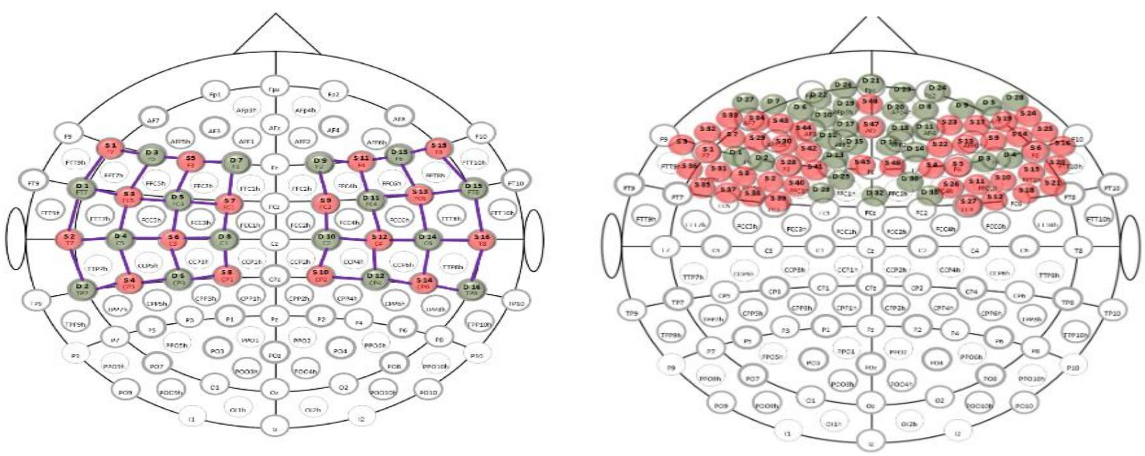

Figure 1 Multimodal integration with a fNIRS system. NIRS Caps and Probes.[24]

NirScout Acquisition Software

The NIRScout system embodies fNIRS technology with an unmatched lab-based flexibility and scalability solution for the neuroimaging research space. This is designed to give the highest flexibility to a very wide range of research applications and can be configured from an elementary four sources and eight detectors up to a sophisticated setup of 64 sources and 128 detectors. The NIRScout system differentiates itself in its versatility to deliver either the best-performing LEDs and lasers or the multi-wavelength laser sources, with a choice of value silicon photodiode (SiPD) or the best-in-class avalanche photodiode (APD) detectors. This makes the performance and pricing system flexible, based only on the specific needs and requirements the researcher sets. Moreover, the options have been broadened to include 8-mm short channels, MRI/TMS-compatible optodes, and integrations for EEG and VR.

Friendly, modular: at the heart of NIRScout design lies an easy, upgradable system that, at the same time, also facilitates the quick expansion of coverage whenever changing research requirements dictate such action. This allows, in principle, simultaneous topographic and tomographic measurements, giving the researcher freedom to place probes anywhere on the cortex and completely describe the system's properties. Besides, the NIRScout system is hyperscanning-enabled. It provides a possibility for synchronous signal acquisition from different subjects. This is made possible by its customizable illumination pattern, which features rates that allow for increased sampling and reduced crosstalk, increasing the quality of data one receives. The system supports up to 255 triggers input and output, highlighting its readiness for complex experimental designs.

Technical specifications of the NIRScout system underscore its high-performance capabilities. It will feature a high level of data quality for a dynamic range of 90 dBopt, with a sampling rate at 100Hz and detector sensitivities up to the low value of < 1 pW for SiPD and 0.5 pW for APD. NIRScaps are made for all demographic subjects—even infants and kids—and are equipped with special probes and headgear. The system continues to be designed with a very high user-centricity of NIRx. The system also hosts many other modalities, such as EEG, fMRI, and eye-tracking. It is the best choice for any researcher in need of an all-in-one package for neuroimaging. This is besides the fact that the NIRScout System is easy to set up and maximum efficient, supported by the best expert scientific consultants, and it is the driving system leading to high-impact research with the most extensive track record of publications. We propose to use the system the same way but with hydrogel application in the hair.

Alternative Designs

The work titled "Comparing fNIRS signal qualities between approaches with and without short channels," published in PLOS ONE, reveals important findings about optimal ways in which fNIRS (functional near-infrared spectroscopy) technology for neuroimaging should optimally be worked on, especially in its practical setup to overcome hair problems. The challenge, however, is that fNIRS signals are exposed to systemic responses in extracerebral tissue, with hair even obscuring the target neuronal activity signals. These researchers, therefore, propose a novel way to improve the quality of the signals in two distinct ways: first, by using short channels sensitive only to the extracerebral tissue responses that reduce systemic noise from deeper cerebral signals measuring neuronal activity.

The current study suggests it could be an improved method for managing systemic noise, including the interference caused by hair, using GLM-PCA. By shortening the channels that capture the responses from extracerebral tissue, this study applied GLM-PCA to regular fNIRS channels for the subtraction of these responses and showed an improvement in signal quality. This method shows improved performance in enhancing the quality of the fNIRS signal, reducing systemic noise, including hair interference, compared to traditional practices when short channels are not possible.

This underlines the salient point: the usefulness of the short channel fNIRS configurations lies in their flexibility and potential in neuroimaging research. This will further provide flexibility for the probe in such a way that the probe could accommodate short and regular channels so that a researcher has an easy adaptation of his probe montage according to the specifications of his study, either designed for the possibility to target specific brain areas or multi-distance to be integrated into other brain imaging techniques with fNIRS. For further fNIRS development, this is important and makes fNIRS a flexible tool in the hands of one who uses it within clinical practice and research, providing better precision and reliability concerning information on cerebral hemodynamics.

This study, therefore, yields a highly important result: there is an urgent need to address hair interference in fNIRS measurements, and it gives an effective solution for its mitigation through short channels combined with GLM-PCA methodology. Such a methodological approach will allow improved quality of the fNIRS signals and the possibilities of the tool in neuroscience, permitting more precise and expanded studies on brain activity.

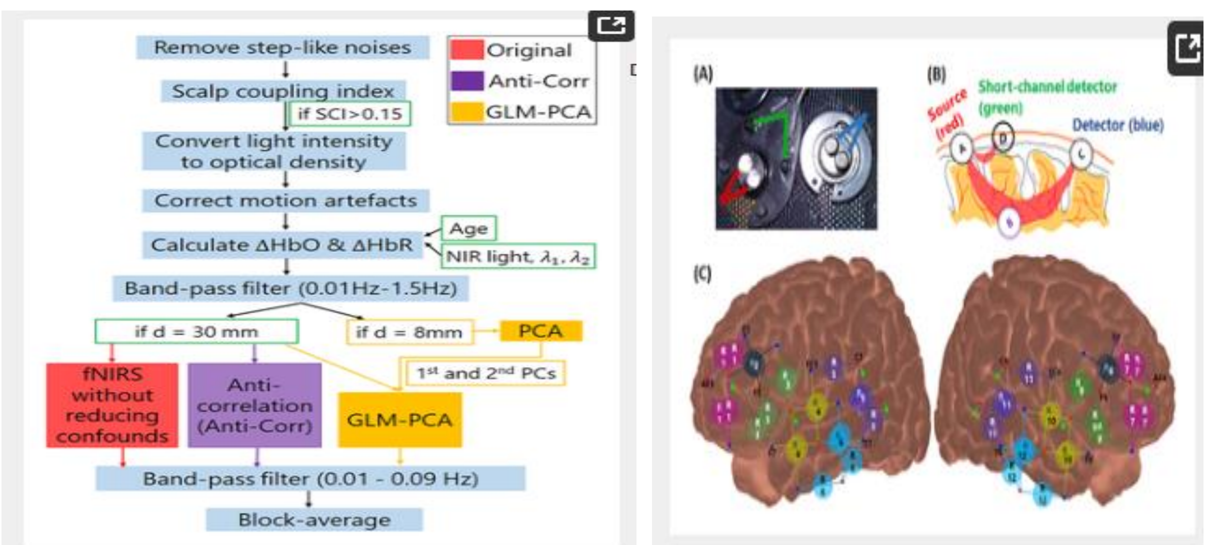

Figure 2 Comparing fNIRS signal qualities between approaches with and without short channels. [25]

Chapter 5. Final Design Verification

Procedure for Applying fNIRS Cap with Biocompatible Hydrogel

Pre-Procedure Preparation

Preparation of materials: All the necessary materials need to be set ready before the arrival of the participants. These should include the fNIRS cap, NIRScout acquisition software, the optodes of the NIRx system, and biocompatible hydrogel (e.g., AquaGel or Hyaluronic Acid-based Hydrogel). Also, clean the skin with wipes or materials that are ready for skin preparation.

Preparation of Participants: Brief the participant on the procedure, explaining that he or she will use biocompatible hydrogel for comfort and signal enhancement. Get informed consent if not gotten.

Hydrogel Application and Cap Placement

Cleaning the scalp: Clean the areas over the scalp with optodes to be placed using non-alcoholic wipes for surface cleaning from natural oils and debris. Dry the skin.

Hydrate hydrogel: Open the hydrogel package and hydrate small amounts for each site of the optode. If applying through a syringe or applicator, get that ready for application of suitable quantities.

Application of the hydrogel to the scalp: A small and well-measured amount of hydrogel was applied, without overflowing the area, through circular motion, to each of the predetermined spots on the scalp where optodes are to be placed for the particular experimental condition. Spread a thin layer over the area where the hydrogel will be applied without overflowing the area with gentle and circular motion.

Placement of the cap: The cap of the fNIRS is placed ever so gently over the participant's head that the hydrogel-treated regions line up with the optodes in the cap. The cap should be gently applied, securing it over the scalp so that the optodes make good contact with the hydrogel-covered scalp.

Securing the cap: Secure the cap over the head using the straps supplied with it or its fastening. It should fit snugly but comfortably, as the person will record measurements that pertain to time.

Data Acquisition and Quality Assessment

Signal quality control: After the cap has been positioned over the head of the subject, a first control of the quality of the signal must be carried out. This consists of verifying the value of the SCI (Scalp Coupling Index) and monitoring, therefore, in real-time, the quality of the optode-scalp contact. Coupled back gently to the scalp is necessary if the signal quality recorded in the first check is coupled. For some sites on the scalp where additional hydrogel might be necessary, very little hydrogel may be used. An SCI signal quality check can be repeated until satisfying results are obtained.

Finishing setup: After assessing optimal signal quality, the experimental protocol may proceed. Advise the participant that at any time, he or she has the right to signal discomfort, which may require cap adjustment or hydrogel reapplied.

Post-Procedure care cap removal and cleaning: As soon as the cleaning stage is reached, carefully remove the fNIRS cap, taking much care in cleaning the head through any necessary gentleness for the elimination of any hydrogel that may have been left on the scalp by the participant. Help if necessary.

Equipment maintenance: Clean and sanitize the fNIRS cap and optodes by the manufacturer's instructions so that the cap is ready for use.

Data storage and analysis: Ensure the securely stored data is ready for subsequent analysis of the collected data. It's done through NIRScout software using other analysis tools when deemed necessary for interpreting results.

Chapter 6. Final Design Validation

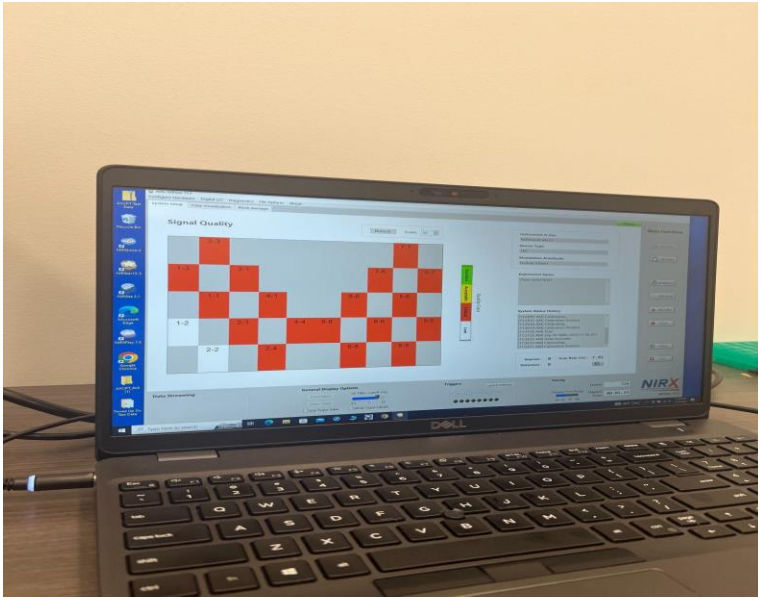

Figure 3. Signal without hair

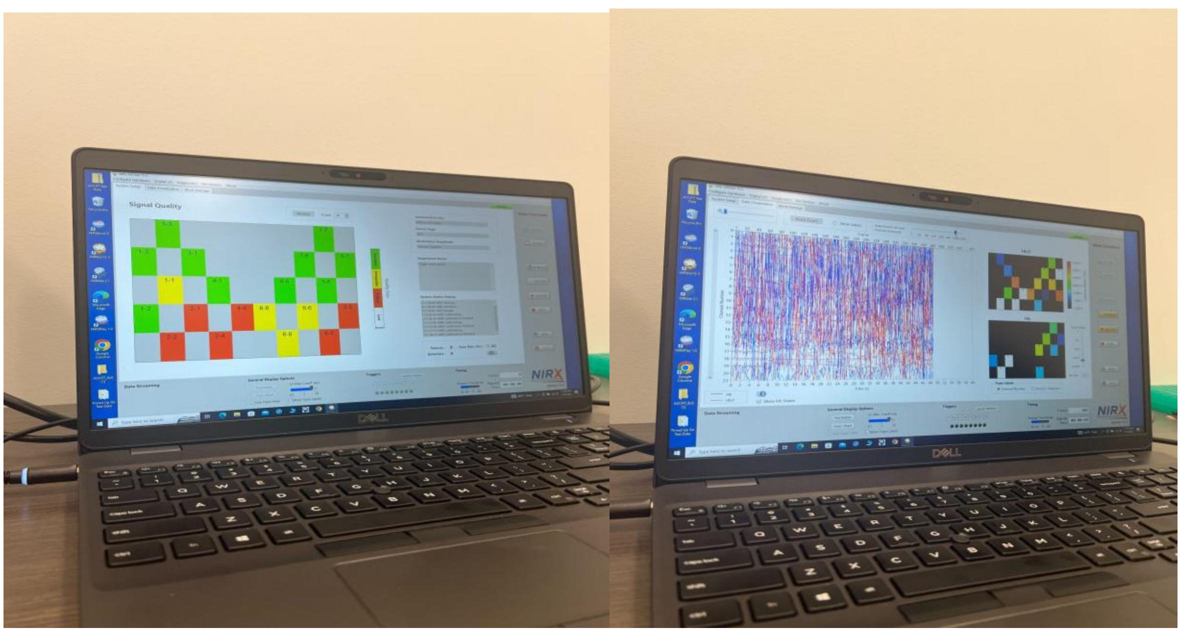

Figure 4. Signal with long, straight hair without hydrogel

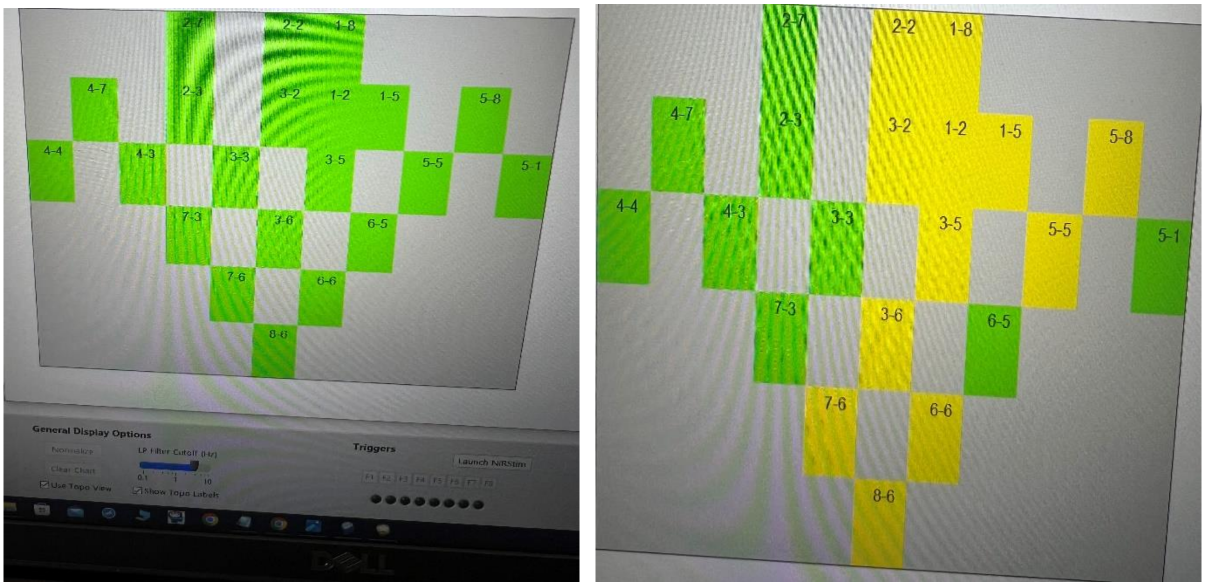

Figure 5. Signal with long straight hair with hydrogel

Chapter 7. Discussion

A special focus was on choosing an appropriate biocompatible hydrogel during the development of our functional Near-Infrared Spectroscopy (fNIRS) application, whereby the interfacing of the optodes with the scalp is improved. One of the significant aspects of the selection is ensuring integrity in measurement and comfort and avoiding reduced irritation, allergic reactions, or any other harmful side effects. From among the options: AquaGel, Hyaluronic acid-based hydrogels, Polyvinyl alcohol (PVA) hydrogels, Carbopol hydrogel, and Silicone hydrogels—it has been zeroed in that the best of the lot is Hyaluronic Acid-Based Hydrogels.

Hyaluronic acid is a natural compound in human skin, offering incomparable safety and efficiency. For this reason, it has found extensive applications in medical and cosmetic use, representing a very well-understood safety profile. Innate properties of the Hyaluronic Acid-Based Hydrogels show minimum chances of adverse skin reactions, hence being most suitable for sensitive skin. It should be admitted, in any case, that skin sensibility, probable allergic reactions, or some definite health conditions can determine separate individual reactions to hydrogels. While the Hyaluronic Acid-Based Hydrogels are included in our fNIRS applications for their biocompatible and optically supportive properties—surviving to minimal interferences in the optical path of the near-infrared light—it is recommended to proceed with skin patch tests before any wide use recommendation. This guards against meeting participant compatibility with different individuals in that diversity in skin types and the general safety of the participant are taken care of.

It is, therefore, interesting to note the favorable nature of a hydrogel for fNIRS applications, going beyond biocompatibility to optically friendly, useable, and amenable in an fNIRS setting. Therefore, it is a supporting criterion that Hyaluronic Acid-Based Hydrogels meet these by allowing the transmittance of near-infrared light without significant interference. Due consideration, of course, should still be given, and this should certainly not mean that due consideration is given to the wide variety of hydrogels available that can address individual participants' special requirements. In other words, the preference for Hyaluronic Acid-Based Hydrogels was high since they have excellent properties that match well with the application of fNIRS, but individual participant considerations could not be overruled. Human skin is so varied that some issues are bound to arise, so the testing process should be flexible. A few of the studies mentioned the availability of some alternative options to hydrogels, which ensure the safety and comfort of the participants in obtaining approval for its integrity and correctness in measuring fNIRS.

Chapter 8. Conclusions and Recommendations

The current study attempted to critically examine the effect of hair on the fNIRS signal quality and the effectiveness of the non-invasive gel method in reducing it. My study has proven that the application of special gel did increase the Scalp Coupling Index, portraying the better optical contact of the fNIRS optodes with the scalp. This technique was the key to a massive reduction in setup times and increases in signal-to-noise ratio, which is very relevant to subjects with variable hair and melanin. Most importantly, the gel method provides an alternative approach to ensure both inclusivity and maximal participant comfort in the face of often highly demanding contexts of neuroimaging research.

It would be helpful to standardize the gel application procedure to keep uniform results between these different populations in future applications. Adjusting for individual variations in hair texture and skin sensitivity in all subjects will make the protocol applicable to all individuals, so it was optimized. Further refinements in the gel's formulation can continue, improving gel transmittance and fNIRS system capability in detecting near-infrared light. Thus, the long-term effects of the gel should be investigated in further studies to avoid possible compromise of the integrity of fNIRS measurements or hazardous effects on the participants' heads. This will further the generalizability of the findings and will allow the neuroimaging methodology to be built upon with a more inclusive model.

Therefore, the results obtained in this research give rise to other additional ways that are not carried out invasively to optimize the quality of the fNIRS signal. Cross-fertilization of ideas in material science, dermatology, and engineering may help develop novel solutions to the recurring challenges of differences in hair and skin. Developing a predictive model with hair characteristics, gel properties, and signal metrics from fNIRS might just make way into the personalized approach for neuroimaging in multicultural settings. Ultimately, this work aims to make neuroimaging equitably available to accurately measure brain activity across all populations without bias or signal compromise.

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