A Mechanical Mounting System for Functional Near-Infrared Spectroscopy Brain Imaging Studies

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ABSTRACT

In this work a mechanical optode mounting system for functional brain imaging with light is presented. The particular application here is a non-invasive optical brain computer interface (BCI) working in the near-infrared range. A BCI is a device that allows a user to interact with their environment through thought processes alone. Their most common use is as a communication aid for the severely disabled. We have recently pioneered the use of optical techniques for such BCI systems rather than the usual electrical modality [1]. Our optical BCI detects characteristic changes in the cerebral haemodynamic responses that occur during motor imagery tasks. On detection of features of the optical response, resulting from localised haemodynamic changes, the BCI translates such responses and provides visual feedback to the user. While signal processing has a large part to play in terms of optimising performance we have found that it is the mechanical mounting of the optical sources and detectors (optodes) that has the greatest bearing on the performance of the system and indeed presents many interesting and novel challenges with regard to sensor placement, depth of penetration, signal intensity, artifact reduction and robustness of measurement. Here a solution is presented that accommodates the range of experimental parameters required for the application as well as meeting many of the challenges outlined above. This is the first time that a concerted study on optode mounting systems for optical BCIs has been attempted and it is hoped this paper may stimulate further research in this area.

Keywords: optical brain imaging, near-infrared spectroscopy, optodes, mechanical mounting systems, non-invasive physiological measurement

1. INTRODUCTION

NIRS is a relatively new field that has grown rapidly since its discovery in 1977 [2]. The fundamental components of any NIR system are the light source and detector. Driving electronics, amplification and data acquisition methods complete the system, as shown in figure 1. All of these components are carefully chosen according to the demands of the relevant application. NIR measurements are implemented in one of three ways - continuous wave, time-resolved or frequency-domain techniques. Figure 1 shows a continuous wave NIR system where the light source is modulated at low (kHz range) frequencies. Regardless of the approach taken careful design must be applied to the mechanics of coupling light from the optical sources and detectors (optodes) to and from the subject's head. Although this may seem a minor issue it has a huge bearing on the signal quality and must be considered as part of the system design. In recent years considerable effort has been devoted to optimum optical/electrical component design in order to improve system accuracy and resolution. However, the fundamental method of connecting optodes to a subject's head is often trivialised even though this seems to have the greatest bearing on the performance of the system. Stable connection between the optodes and scalp is vital to ensure the pathlength of the photons does not change and also to prevent ambient light saturating the detector. Such effects create spurious motion artifacts affecting the validity of the detected NIR signals. A means of ensuring good optical contact between the optodes and the head has yet to be perfected and there is a lack of literature regarding the topic. The challenge is to ensure rigid optode positioning while still allowing for subject comfort. Solutions to date include modified cycle helmets, thermoplastic moulded to the contours of each subject's head, spring-loaded fibres attached to semi-rigid plastic forms and fibres embedded in rubber forms[3]. Rubber patches are often used to hold a pair of optodes, being kept in place using straps or bandages; while this is an adequate solution for single point measurements, it proves unsuitable for multiple point tomographic imaging.

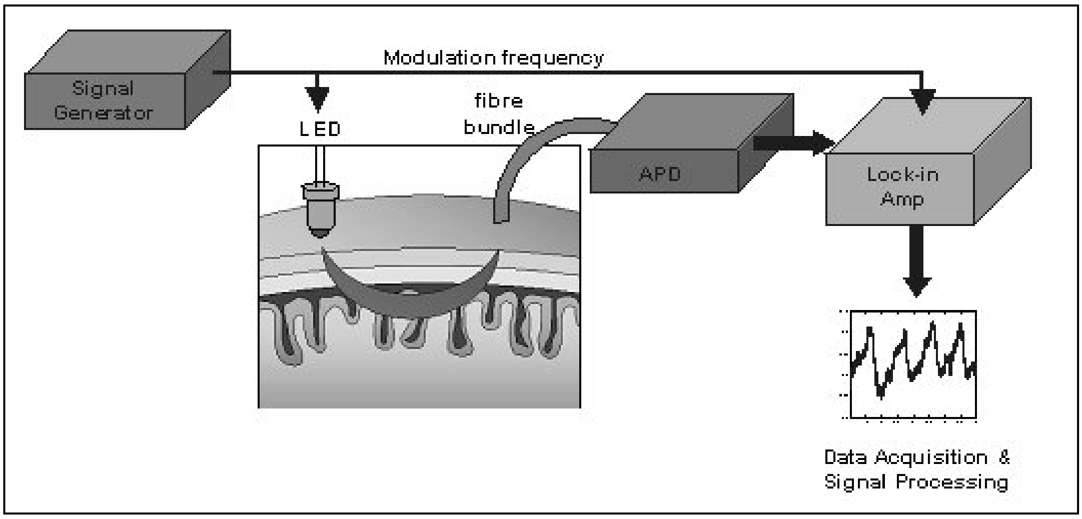


Figure 1: Components of a continuous wave NIR system

There are a number of factors to consider when designing the apparatus used to couple light to and from the head. Consideration must be given to the practical implementation and general safety precautions while at the same time trying to optimise the detected light signal and minimise noise effects. Some of the factors to be considered are outlined as follows:

i) **Secure support for optodes:** Sources and detectors can be placed directly in contact with the head if small and light enough e.g. LEDs and photodiodes, but is not always practical depending on their dimensions. Fibre optic probes are often used in biomedical optical imaging devices as they provide a flexible solution for interfacing between spectroscopic devices and the tissue to be examined [4]. They are useful in coupling laser diodes, avalanche photodiodes and photomultiplier tubes to the head. Fibre optic bundles can be quite heavy and need adequate support at the skin surface.

ii) **Hair:** The presence of hair is a key issue affecting the coupling of light to the head. Dark hair absorbs more NIR light than fair hair, however this does not exclude dark-haired subjects from NIR studies providing adequate care is taken during optode placement. While strands of hair affect the absorption of light, movement of hair may cause instability of the signal. In addition, hair follicles strongly absorb near-infrared wavelengths. Therefore in any NIR brain interrogation study carried out on a part of the head covered by hair, e.g. motor cortex, visual cortex, attention must be given to securing the hair in place to prevent its movement, and also ensuring that hair is pushed aside directly beneath the optode positions. Styling-gel and hair-pins are useful to fasten hair at this stage.

iii) **Optode positioning related to associated brain function:** The placement of the optodes is crucial, as the photon propagation path must traverse an area activated by the

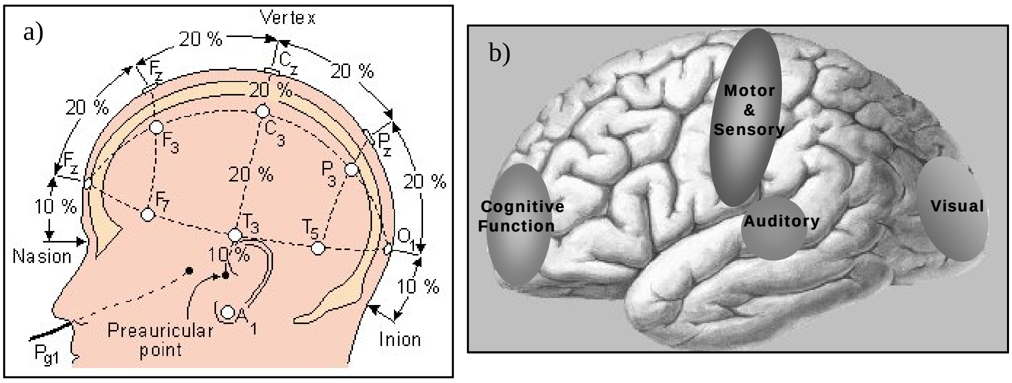


Figure 2 a)10-20 Electrode Placement System b) Cerebral cortex and associated functions experimental task. Movement of the optodes even a small distance from the region of interest can result in a huge reduction in the desired response. The conventional electrode 10-20 system is typically used as a basis for optode positioning in NIR brain functional investigation studies. The midpoint between source and detector is the point of maximum penetration depth; where photons reach the cortical grey matter, and the optodes should be positioned in a way that their midpoint lays at the required 10-20 electrode position e.g. C3 for hand movement.

iv) **Interoptode distance:** The distance between source and detector must be large enough to achieve sufficient penetration depths but not so great that signal is attenuated profusely. A wider source-detector increases the photon path length and absorption, and therefore decreases the signal strength at the detector. Inter-optode distances of 2-7cm are typically used, based on experimental and theoretical studies[5, 6].

v) **Optode angle of incidence:** The angle at which the source and detector are arranged with respect to the head's surface is important so as to maximise the amount of light being coupled to and from the head. The relative effectiveness of light penetrating into the epidermis varies according to, approximately, the cosine of the angle of incidence, i.e. light incident on the skin at grazing angles is less likely to be transmitted through the epidermis [7]. Therefore to maximise light delivery the LED should have a narrow beam width and the beam should be positioned perpendicular to the scalp. The active area of the detector in contact with the head should also be perpendicular to the surface to maximise coupling efficiency. In the case of fibre bundles, prisms can be used to deflect the light at the end of the bundle by 90°. This allows fibres to run parallel to the head, taking the strain from the weight of fibre bundles, and can help to reduce motion artifacts.

vi) **Shielding light:** It is advisable to reduce the amount of ambient light in the room to ensure maximum detector efficiency. In addition to minimising the effects of stray light entering the head, it is essential to block light from passing directly from source to detector. If this does not have the effect of saturating the detector it affects the validity of any analysis that assumes that light has travelled in the classic banana-shaped path through the head. To avoid cross-talk the source and detector must be shielded from one another using a material that will absorb NIR light as shown in figure 3. Compressible black foam can be used, which also serves as a cushioning textile. Black PVC foam commonly used as a sealing strip and black polyurethane foam used for sound insulation are good solutions and can be easily integrated within the coupling mechanism. The foam should be tested for its efficiency in absorbing NIR light, as although an object appears black to the eye not all black dyes are fully absorbing in the NIR spectrum.

vii) **Safety and Comfort:** The subject's wellbeing and safety is central to the experimental procedure. The subject should be at ease throughout experimental procedures as stressful situations activate the autonomic nervous system which, among other physiological functions, affects cerebral blood flow [8]. Fastenings should not be too tight, and the head should be supported if the subject assumes a supine position. Optodes should make good contact with the skin, without applying undue pressure. For safety purposes the subject should be able to release themselves from the experimental apparatus easily and quickly should the need arise.

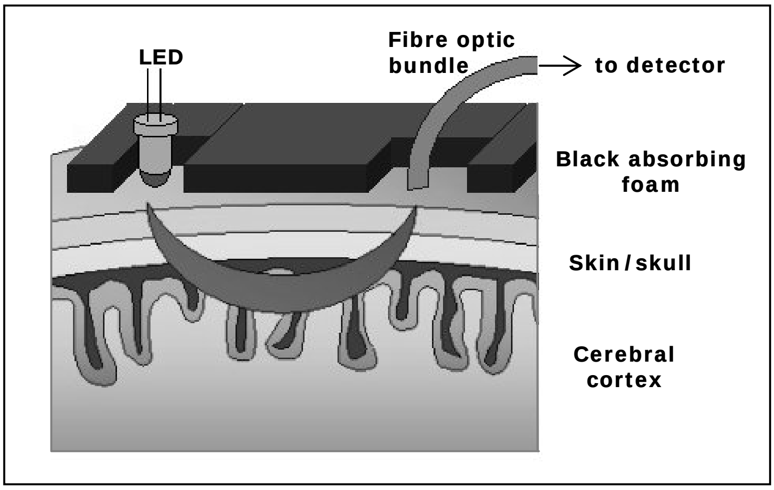


Figure 3 Use of black PVC foam to shield detector from stray light

METHODOLOGY

Traditionally BCIs have relied on Electroencephalography (EEG) signals recorded from the scalp to control external devices[9]. EEG electrodes are often integrated into caps that secure them tightly to the head, and this is quite effective as the electrodes themselves are light and are attached to thin wires. The vast majority of NIRS systems use fibre optics to deliver light to and from the head. Fibre optic cables are quite heavy and need to be anchored appropriately at the skin surface. Therefore the EEG cap does not suffice and a reliable means of coupling optodes to the head during optical imaging is needed. A mechanism providing adequate support for the weight of the fibre bundles and wires is needed. There are essentially two ways of dealing with this problem. Either a fixed structure to hold the optodes is employed whereby the subject's head must remain motionless within the structure, thus preventing the scalp pulling away from the optodes. This has the advantage of providing adequate support for the weight of the optode connections however locking the subject's head into a fixed position for any length of time is an uncomfortable solution. Alternatively, the optodes are securely fastened to the subject, and the subject is allowed limited motion. In this case the optodes and head move collectively and thus maintain optical contact. This method still requires a light rigid structure to support the weight of the optodes, the strain of which can cause optodes to pull away from the head. While this method more flexible for subject movement, ensuring stable optode connections to the head can require tight restrictive straps, which can cause discomfort for the subject.

The design of the mechanical mounting device evolved following various renditions of optode holding contraptions. At first, the use of a helmet was thought to be the most logical solution. However, the problem with helmets is that they do not conform to the shape of every subject's head. Ideally an optode mounting system that is adaptable for multiple users is required, or at least a few versions to suit similar sized heads. The main advantage of helmets is also ironically their disadvantage. While helmets, especially motorcycle helmets, block out light from the surroundings, they also impede the placement of optodes from a practical viewpoint, in terms of measuring positions for optode alignment and also shifting hair from beneath the optode position. Unless a large area is removed from the helmet over a section of the cortex to be examined there is little flexibility for optode positioning, and also accessibility to placement. A mechanism is needed whereby the optode position can first be identified, hair combed aside, and then the optodes placed carefully in their designated setting without displacing the hair significantly. Rubber patches holding individual or a pair of optodes can be positioned and subsequently held in place using straps or bandages. Mounting the optodes in this way was found to be more effective than rigid structures such as modified hats and helmets as the rubber patch makes it easier to comb hair out of the way of the optode. Embedded in the rubber patches were small brass tubes with a collar which provide mechanical support for the LED and fibre optic cable. The source and detector connect to the metal structures made to fit their dimensions. Two detector metal supports were embedded 3cm and 4 cm from the source support allowing an option for the interoptode distance. Separate rubber pads could be manufactured in order to have more manipulation of the interoptode distance. On the underside of the rubber patches, black foam was used to shield the source and detector. Velcro was embedded on the upper side of the rubber patches with which to attach headbands to hold the rubber patches and optodes in place.

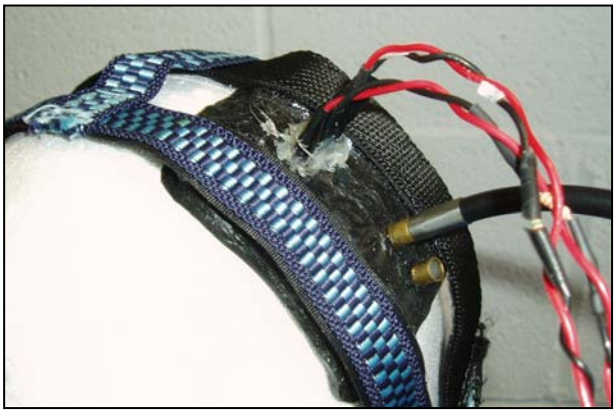


Figure 4 Rubber patch with embedded metal cylinders to support light sources and detector, Velcro straps hold the rubber patch in place

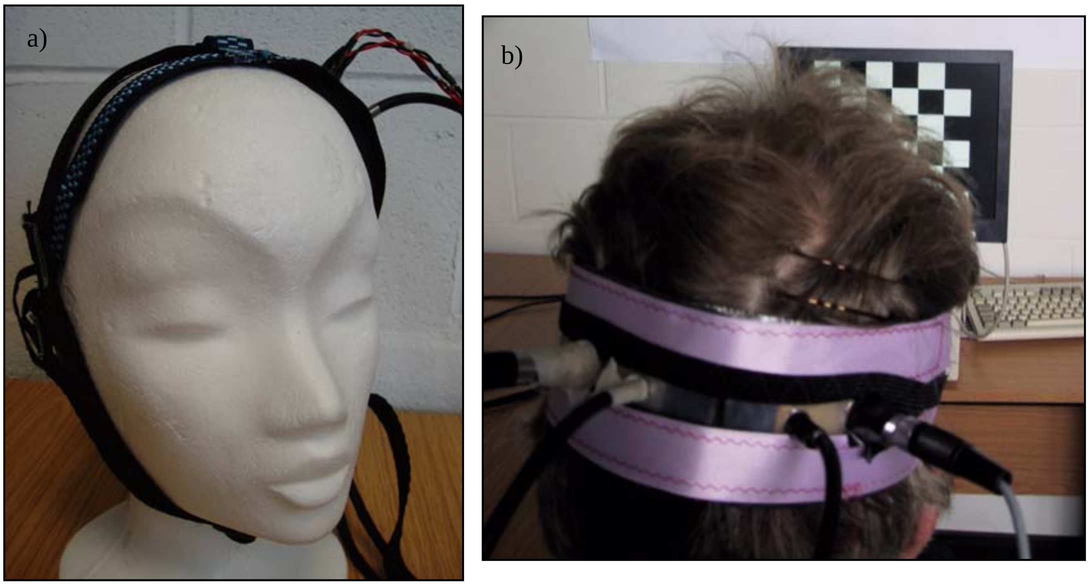


Figure 5 Strap configurations for a) sensory and motor function studies b) visual function studies

RESULTS

While the rubber patches attached by various strap configuration can yield satisfactory results, to improve the robustness of the signal, there was a need for a more stable structure to support the optical fibre bundles and LEDs while at the same time improving the subject's comfort level by taking away strain from tight restrictive straps. The concept of the mechanical mounting system allows the person to sit comfortably, then a supporting structure is positioned about the person to hold the optodes in place. The mechanical mounting system is connected to a seat with an adjustable back incline. The seat provides comfort and also the option of keeping the subject in a supine position during studies which can help reduce certain physiological noise effects such as the Mayer wave [10]. The original headrest of the seat was replaced by a mechanical framework to cradle the head and also to support and position the optodes as shown in figure 7. The position of the supporting structure can be altered by varying the height and also within the horizontal plane to allow for varying spinal curvations, i.e a subject's head sits more forward if there is a large curvature of their back. The framework allows optodes to be positioned over areas of the head that are generally of interest in functional brain imaging studies e.g. visual and motor association areas. The framework consists of semicircular rails onto which optode holders can be attached and removed. The optode holders can slide along these rails and be secured into a required position. One of the semicircular rails curves above the left and right sensorimotor cortices, which provides good optode placement for investigating motor imagery. This is of particular interest to our application as characterisation of the brain's response to motor imagery forms the basis of the optical BCI [1]. The mechanical framework allows for measurement above the left and right motor cortices and also the occipital cortices. For cognitive studies involving the frontal cortices there is a semicircular rail that passes across the forehead that can be attached to the framework. However this makes the entire structure quite restrictive and is not imperative for visual or motor studies. The optode holder is a cuboid structure with a cylindrical hollow (of 2cm diameter) to support an optical fibre bundle or LED arrangement. Three LEDs of different wavelength, to allow spectroscopic measurements to be performed, are encased in copper tubing that can be held within the optode holder. A cylinder, of the same diameter as the LED's encasement, holds the fibre optic bundle off-centre to allow greater adjustment of positon, as shown in figure 5. The conformity of the LED and optical fibre mounts means that the optode holders are standardised for both light sources and detectors. A cylinder is hollowed to accommodate the fibre bundle ferrule and a grub screw used to secure placement. The proximity of the light sources and detectors to the head's surface may be controlled by sliding the LEDs or fibre bundles, within their encasements, through the optode holder and fixing their position using a grub screw.

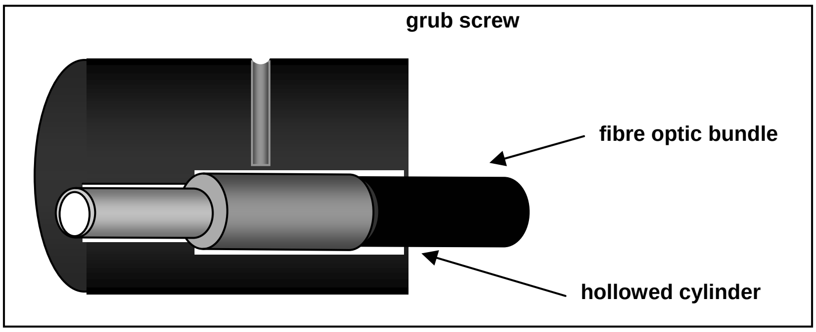


Figure 5 Fibre optic bundle attachment

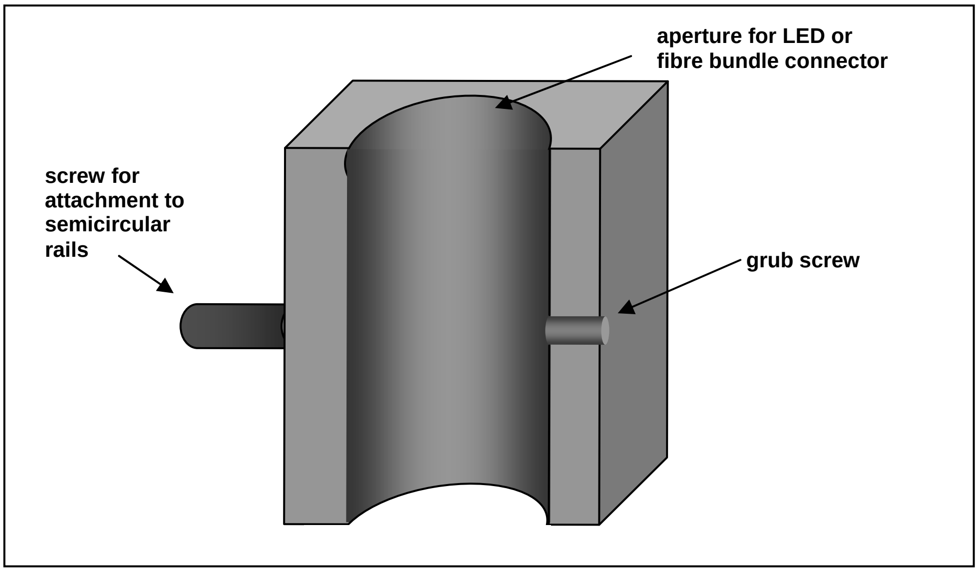
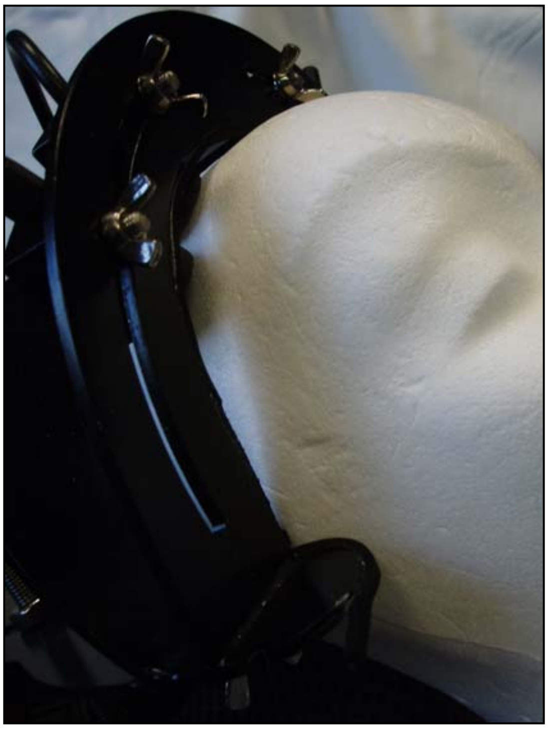
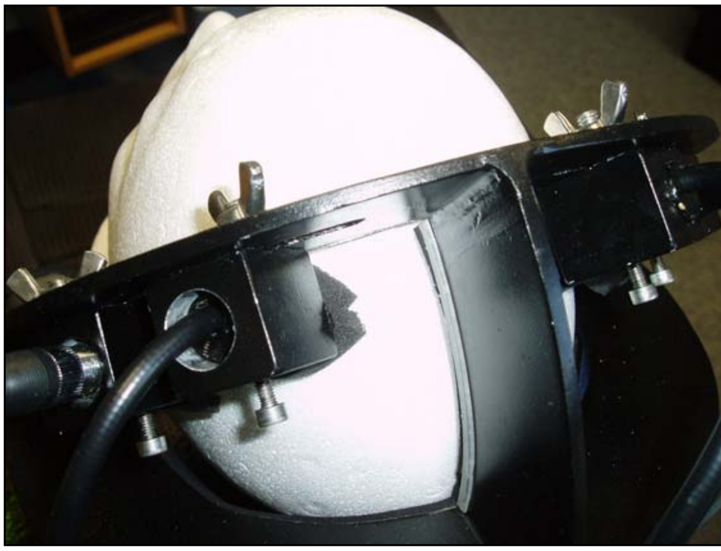


Figure 6 Optode holder for positioning light sources and detectors. It attaches to and slides along the supporting rails, securing optodes in place.



a)

b)



c)

Figure 7 (a,b,c) The mechanical structure replaces the seat head-rest, cradling and providing support to the head. Detector fibre and LED light sources are positioned over the left and right motor cortices.

DISCUSSION

Different research groups have developed distinct optodes for particular application and target populations. An interesting concept of using fibre hairbrushes, to overcome the problem of hair absorption has been presented [11]. Single fibres can be set in between hair strands. Holding them without bending or moving the "bristles". Other groups holding the fibres away from the scalp which reduces any risk of tissue damage due to excessive pressure, and also reduces motion artifacts as the light is covering a larger surface area. Thermoplastic can be moulded to a person's head, and allows for precise repositioning in subsequent studies, however wearing it for a long time is uncomfortable. Taking a cast solely of a region of interest can be used to overcome this drawback [12]. NIR imaging is a relatively novel approach presenting new hardware configurations that need some innovative designs to make it a truly accessible technology that can be easily implemented.

While there is a need to enhance optode coupling mechanisms, there is also a need for a standardised placement scheme, in order to be able to reproduce measurements from the same subjects and also to ensure consistency between studies. A well defined method of performing physical measurements needs to be defined. This is especially important in the absense of fMRI information, where anatomical and functional details are available. Electroencephalography has a standardised electrode placement system described by the 10-20 system[13]. Optical measurements are typically taken based on the EEG 10-20 system, which brings about a need for an optical equivalent of this. A possibility is to describe the optode positions using a type of polar coordinate system in terms of the 10-20 positions, where the optode distance and angle with respect to an EEG 10-20 position is defined e.g. for a source(S1) and detector(D1) placed 4cm apart, lying 2cm directly above and below C3 respectively by C3:2(π/2) and C3:2(3π/2), as shown in figure 8. This is important for concurrent measurements with other imaging technologies such as EEG and fMRI and an optode mounting system to accommodate such measurements needs to be considered jointly. Optical imaging is ideal for multi-modal imaging and BCI development as the optical signals do not interfere with electrical or magnetic fields. To use NIR with EEG the source and detector need to be positioned on either side of an EEG electrode. To use with fMRI the optode holders/mounting system must be made from plastic or other suitable non-metallic material, and the light transported to and from the subject via fibre optics.

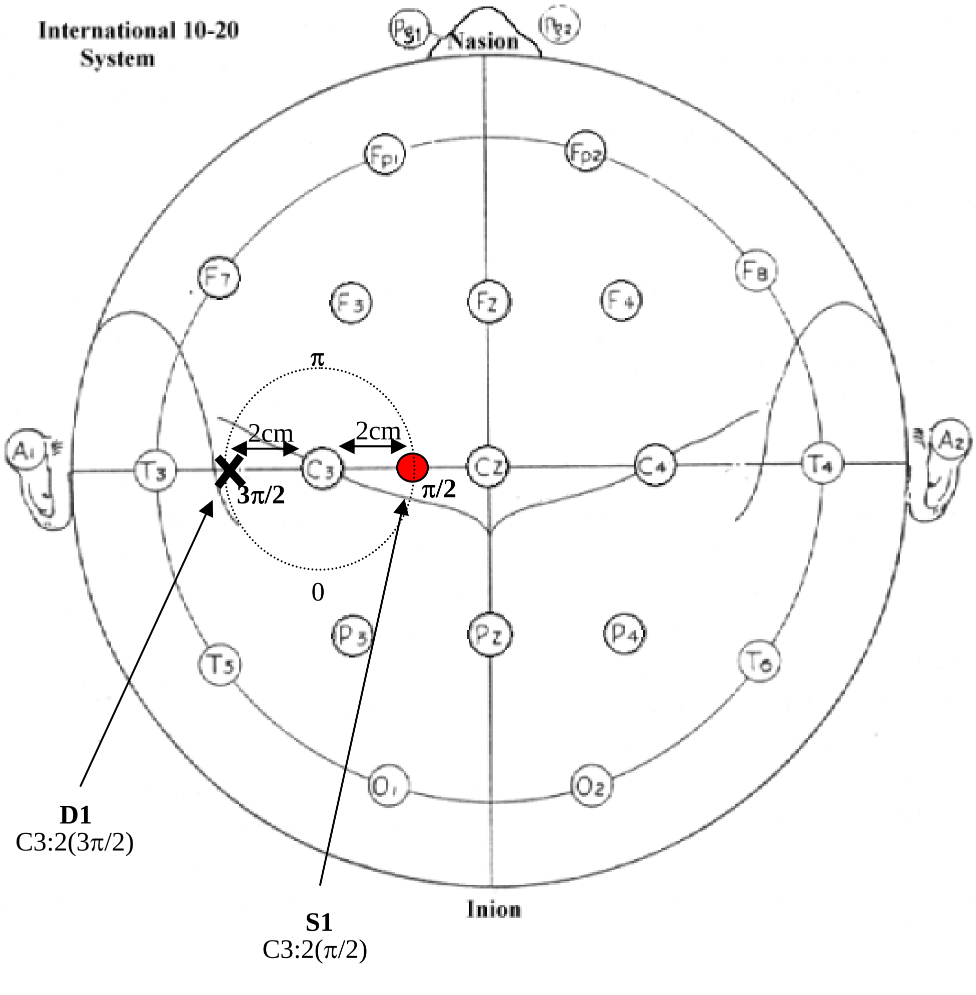


Figure 8 Proposed Optode Placement System

CONCLUSIONS

The placement of light sources and detectors to ensure good optical coupling has a critical bearing on the performance of near-infrared spectroscopic systems. The mechanical mounting system presented here allows secure placement of optodes during BCI experimental trials. The seat and cradling mechanism is ideal for subject comfort which is important is long experimental trials. Howewer using a fixed head mount is quite restrictive and does not allow for any movement. Strap configurations allow limited movement but can be uncomfortable. An intermediary approach is needed to give support to the optodes and secure placement, but also allow limited movement. As yet there is no solution to optode placement that rates well with all requirements. It is an issue that is often overlooked in reports of optical imaging but is a critical issue. Secure optode placement is needed to ensure signal integrity while accurate optode placement is needed in order to produce tomographic images of the brain.

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