Development of High-Resolution Imaging System for Blood Activity Monitoring

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Declaration

I certify that this research work titled "*Development of High-Resolution Imaging System for Blood Activity Monitoring"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

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Acknowledgements

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Abstract

fNIRS is a non-invasive, portable & easy to use brain imaging modality. It can estimate the hemodynamic response of the brain by measuring the absorption of IR light with respect to time. The standard channel separation between source & detector in fNIRS is 3cm but this distance has a disadvantage of higher channel noise. To resolve the issue, we have presented a new fNIRS design with small channel separation to minimize the channel noise. In this research, we have designed the fNIRS device using 2 sources & 14 detectors in a circular configuration. The detectors are placed in two circles each circle having 7 LEDs with a radius of 1.5cm & 2.25cm respectively. After the software design, we implemented it on a hardware & tested the device using occlusion. Once the device got tested through occlusion, we acquired the brain signals by placing it on the left frontal cortex. After placing the device on the frontal cortex, we reverse counted for 200sec with rest & count intervals. The whole experimental design is described in the sections below. We applied Modified Beer Lambert Law (MBLL) to deduce results. The results proved to be promising as the channel noise reduced & we got better signals. The results can be improved further by using the high-power IR LEDs having better penetrating ability.

Keywords: functional near-infrared spectroscopy (fNIRS); reverse counting; frontal cortex; modified beer lambert law.

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1 INTRODUCTION

Pakistan is a developing country with a GDP of 278Billion USD. As per 2018 Pakistan spends 3.2% of the GDP on providing basic health facilities to its population. Basic health care system in Pakistan is good as there are 5000 Basic health care centers in Pakistan & 600 rural health units working across the country.

The availability of advanced medical facilities is still a major concern in Pakistan as the populace growth rate of Pakistan is 2% every year. Advanced medical devices like MRI & CT scan etc. are scarce. According to the Journal of Pakistan Medical Association the availability of MRI scan is one per 7.77 million people. There were 22 MRI scanners in the entire Pakistan as of a study conducted in 2018, 7 of them are in Karachi & Baluchistan has no MRI scanner in the whole province. People must travel long for access to modern health resources.

If we look at the importance of MRI scanners, it really helps in the detection of tumors & cancer. Doctors can exactly point out the place of a tumor or cancer & they can even decide if a tumor is cancer or not. MRI contrast dye is the best way of identifying tumors in the brain & spinal cord. According to [10], 117,149 people died of cancer. So, we can imagine if there was enough availability of these MRI scanners in the country many lives could have been saved.

Magnetic Resonance Imaging (MRI) is an imaging technique in which magnetic waves and computer-generated radio waves are used to produce high quality images of the human body's organs and tissues. An MRI scanner is a long cylinder or tube that has a large & a very strong magnet. The patient lies on a table that slides into the tube, and the machine surrounds the patient with a powerful magnetic field. The machine uses a powerful magnetic force and radiofrequency waves to pick up signals from the nuclei of hydrogen atoms in your body. A computer converts these signals into a black and white picture.

An MRI device costs around $1Million. The cost of a single MRI scan in Pakistan ranges from 2500-25000. The accuracy of the scans depends upon many factors which includes the expertise of the operator & artifacts during scan. Artifacts are the ambiguities which appear during that scan & they can be either on the patient's end or at the end of the operator. These artifacts can result in the false detection of the tumor, cancer of any disease for which MRI was conducted.

If we talk about the artifacts that occur due the patients, then the two most common reasons are the anxiety and depression attacks that occur during the scan. Due to these attacks patients move & the scan either ends prematurely or the results are false. These artifacts occur due to

the claustrophobic environment inside the MRI tube & there is a lot of noise in the tube due the magnetic resonance. It has been reported that most of these attacks occur during the brain and spinal cord scan. For the past many years research has been conducted to resolve the issue of these patient related artifacts but there is no success.

So, if we look at the fact that 21% of the Pakistan's population lives below poverty level, the cost of the scan is already expensive then if any of these people undergoes an MRI scan, the scan turns out to be false due to the artifacts & the patient is treated based on the false scan then it can prove to be life threatening.

This is the sole purpose of carrying out this research in which we are going to provide a solution for the correction of these anxiety and depression related artifacts. This can be done by identifying that part of the brain from where these attacks originate & then electrically stimulating that part. To address this problem, a technique called fNIRS can be really helpful. fNIRS is a brain imaging technique which produces up to 3 times more detailed brain images than MRI. Time domain & frequency domain fNIRS device is a highly expensive but Continuous wave fNIRS system is cost effective. The problem with CW-fNIRS device is that it does not cater for the artifacts which occur due to skin, bone & tissue.

So, in this research we will design & develop a CW-fNIRS device which will cater for the artifacts due to skin, bone & tissue during data collection.

1.1 Research Objectives

Artifacts which occur due to skin, bone & tissue have been catered in Time domain & frequency domain fNIRS system, but they are yet to be catered in CW-fNIRS system.

There will be two main objectives of this research:

- The design &development of the high-resolution CW-fNIRS machine.
- Integration of fNIRS with the software for blood activity monitoring.

1.2 Proposed Solution

The development of the fNIRS machine, is our proposed solution. Following is a summary of the solution:

- Hardware architecture design.
- Develop the hardware of the fNIRS machine
- We will use the developed hardware to cater the artifacts in fNIRS due to skin, bone & tissue.

Details of the research from literature review till results will be provided in the upcoming chapters.

2 Literature Review

Magnetic resonance imaging was first introduced in 1971. Since then, it has been widely used for the deep imaging of human body organs and tissues for examination. But since its launch, it has been noticed that patients go through the anxiety and depression attacks during the scan. Many studies and research have been conducted over the years to address the issue.

In 1993, a study was conducted to identify the cause of the anxiety during the scan. They gathered all the literature available on the MRI & the problems associated with it. They gathered all the published research from 1980-1993 & reviewed all of them. They concluded that these anxiety attacks occur in almost 4-30% patients during MRI scan &an examination of the patient prior to the scan will help in reducing the issue [1].

Claustrophobia is a major issue which effects the results of MRI scan as artifacts appear during the scan because of it. So, in 1998 a research was conducted in which the researchers examined 80 adults who were going through the MRI scan for the first time. They tried to find out the reason for the fear and anxiety during the scan. They developed a Claustrophobia Questionnaire and asked the patients to fill it. They concluded that 25% of the patients who went through the scan suffered anxiety and claustrophobia. They further concluded that this questionnaire could help the examiner to know beforehand if a patient will suffer anxiety attacks during the scan [2].

Artifacts in the results of MRI are a major concern. So, to minimize them researchers tried to pinpoint the moments at which the anxiety of the patients is at the highest level. The strategy they used was to continuously monitor the heart rate of the patients. They conclude that at the start of the scan the anxiety of the patients was highest. They further concluded that the patients who took anxiolytics before the scan were more anxious during the scan than those who did not take any anxiolytic [3].

MRI scanner is a tube-shaped structure hollow from inside & the diameter of the tube is generally not big. This is one of the reasons that anxiety and claustrophobia attacks occur to the patients who go through the scan. So, a study was conducted at Singapore General Hospital in which the researchers tried to figure out if MRI scanner which a larger bore can help in reducing the claustrophobia attacks. The results of the study suggested that the MRI environment is disturbing for the patients irrespective of the gender and age of the patient. They concluded that the MRI scanner with a bigger bore might reduce the anxiety during the scan [4].

No viable solution was presented till 2017 to cater the problem of artifacts during MRI scan. For this purpose, a research was conducted by RSNA (Radiological Society of North America) to address the problem of anxiety and depression during the MRI scan. The methods they used were the use of music during the scan & constantly communicating with the patient during the scan. Unfortunately, the methods they used did not work well as a solution to the existing problem [5].

A research study was published in Egyptian Journal of Hospital Medicine in which the authors discussed the causes and effects of patient anxiety during MRI scan & also discussed the possible solutions for alleviating the problem. The results of the study suggested that sedation techniques, noise reduction during the scan & preparing the patients mentally before the scan can prove to be helpful in coping up with the problem of claustrophobia, anxiety, and depression during the MRI scan [6].

Dziuda, Ł., Zielinski, P., Baran, P. et al conducted research in which they monitored the relationship between anxiety declared patients & their respiratory rate. Total of forty-four participants were involved in the study. The mean respiratory rate for 2 minutes immediately after the beginning of the scan and 2 minutes after the end of the scan was monitored with optical fiber. The results of the study suggested that there was a decrease in the anxiety of the patients with decreased respiratory rate & no change was monitored in the anxiety level of the patients with stable respiratory rate [7].

The above-mentioned research suggests that anxiety during MRI is a commonly occurring issue. So, to address the issue a research study was conducted in which they used several methods like arranging pre-scan visits for patients, distribution of informative leaflets, music during the scan etc. but none of the procedures followed helped significantly. The results of the research suggested that the high level of anxiety is because patients fear what the scan will reveal [8].

MRI questionnaire had been used in the past to evaluate anxiety & depression attacks in patients during the scan. So, a questionnaire was prepared by the researchers in[9] to identify the patients with anxiety disorders during the scan. Participants of the research had scans for heart and spine. The results of the scan demonstrated that patients with heart MRI had more anxiety attacks than those of spine.

A new MRI device with smaller magnetic bore & 97% low acoustic noise was developed by the researchers. So, a research was conducted to evaluate that if low acoustic noise & smaller magnetic bore MRI devices can lower the claustrophobic reactions or not. Total 55734 participants were made part of the research. 44998 were scanned with the conventional MRI scanner & 12736 were scanned with the new MRI scanner. The results suggested that low noise can decrease the claustrophobia in patients by 3 factors if they are to be scanned with the newly developed MRI scanners [10].

Enders, J. *et al*. conducted a research to evaluate if open MRI scanning can reduce anxiety and claustrophobia attacks as compared to small bore MRI scans. 33 claustrophobia attacks were recorded in small bore scanner & 23 were recorded in open MRI scans. The results suggested that there was not a significant difference between the two & the development of more patient centered MRI scanners is needed [11].

Pre-mature termination of MRI is also a major issue which can produce false results & ultimately wrong examination of the patients. So, the researchers evaluated the MRI related

claustrophobia & premature termination of MRI scans due to claustrophobia. Total of 5798 MRI reports were examined. Out of all the reports 95 patients suffered claustrophobia & 59 were the premature termination of the scan. Most of these patients were women. The results suggested that premature termination of MRI is less affected by claustrophobia. The results further suggested that age, sex, and position during the scan impacts the pre termination of the scan [12].

Functional Near Infrared Spectroscopy is a highly effective & low-cost brain imaging technique. Using fNIRS, the researchers tried to find out that if fNIRS can detect the linear changes in response to cognitive load & functional connectivity when switching between resting state & task state. The results were deduced after performing an experiment on a group of sixteen adults. The results were very promising & suggested that fNIRS is highly responsive towards cognitive load and state. This means that fNIRS can prove to be highly effective in answering research questions related to neuroimaging. The results also concluded that fNIRS has an edge over fMRI & it is a better alternative of fMRI [13].

Using fNIRS, a research study was conducted in which the researchers tried to find out the cerebral hemodynamics in response to sensory, motor & cognitive tasks. They provided evidence from two different studies that fNIRS can be used to assess the (a) mental workload of operators performing standardized and complex cognitive tasks, (b) development of expertise during practice of complex cognitive and visuomotor tasks. This means that fNIRS is highly sensitive to hemodynamic changes in response to mental tasks & cognitive tasks [14].

Over the years brain imaging has come out to be a thing of interest. Many different techniques have been used. So, the authors compared two brain imaging techniques, fNIRS& fMRI in this study. The results concluded that fNIRS can be a highly effective alternative of fMRI for brain imaging. The results showed that fNIRS has a weak signal-to-noise ratio compared to fMRI. This suggests that fNIRS can be an appropriate replacement for fMRI in cognitive tasks and neuroimaging [15].

In another research study the researchers reviewed 35 different fNIRS research articles. After carefully reviewing the articles, they came up with some recommendations for future fNIRS studies in the field of exercise cognition science. The reason why fNIRS is such an effective technique is that its non-invasive and provides a detailed view of the changes in oxygen concentration in the brain during different cognitive tasks. But there is no standardized method regarding application, data processing and data analysis of fNIRS. So, the authors provided with some recommendations for standardizing the procedure for fNIRS [16].

fNIRS is such an effective deep brain imaging technique that it can even help in identifying different emotions. So, the researchers worked on finding the hemodynamic changes in response to different positive emotions like laugh, serenity, gratitude etc. Some research had been done in the past on this using EEG and autonomic nervous system's measurement, but hemodynamic response is largely unknown. The researchers divided 10 positive emotions into 3 clusters & performed experiment by showing the subjects different video clips. While watching

the videos, hemodynamic responses of 13 participants were recorded using 24-channel fNIRS system. The average resulted accuracy of 3 clusters was 73.79 & the benefits of fNIRS was the cost effectiveness, robustness of results and portability. It was concluded at the end that these results can be improved using more finely grained system [17].

Autism is brain disorders which occurs in infants. So, a research study was published in International Journal of Psychophysiology in which the researchers investigated the functional brain adaptation in ASD using fNIRS. fNIRS offers several advantages over functional neuroimaging techniques including portability, low cost, and naturalistic environment setting. The results of the research showed a typical brain activation in some parts of the brain & also suggested that there is inefficient transfer of signals to some part of the brain in ASD. The overall research results suggested that fNIRS is a very promising tool for exploring neurodevelopment in ASD at an early age [18].

In the light of the above-mentioned, fNIRS can be extremely helpful in removing the artifacts in MRI but artifacts in fNIRS also occur due to skin, bone & tissue. If these artifacts can get removed fNIRS can be utilized efficiently. These artifacts are catered in time & frequency domain fNIRS system, but they are yet to be catered in continuous wave fNIRS. So, in this research we will design & develop a system to resolve the issue of these artifacts. In the coming chapters complete details of the proposed system will be provided.

3 Brain Imaging Techniques

Over the years many Brain Imaging Techniques have been used to make the diagnostics easier. The history of brain imaging goes back to 1924 when a German phyciatrist recorded EEG. Back then EEG was only able to detect the rise & fall of electrical signals in the brain as the brain cells communicated between each other.

3.1 Common Brain Imaging Techniques

Following are some of the commonly used brain imaging techniques these days:

- EEG
- PET
- CT Scan
- FMRI
- FNIRS

In this research, FNIRS is being used but I will briefly explain the other techniques as well for reference.

3.1.1 EEG

EEG stands for Electroencephalography. In this doctors measure the brain waves using electrodes which are placed on the patient's scalp & connected to the computer with wires. The electrodes detect brain activity, and a graph is made on the computer screen using the detected brain signals. EEG can detect issues like sleep, head injuries, epilepsy etc.

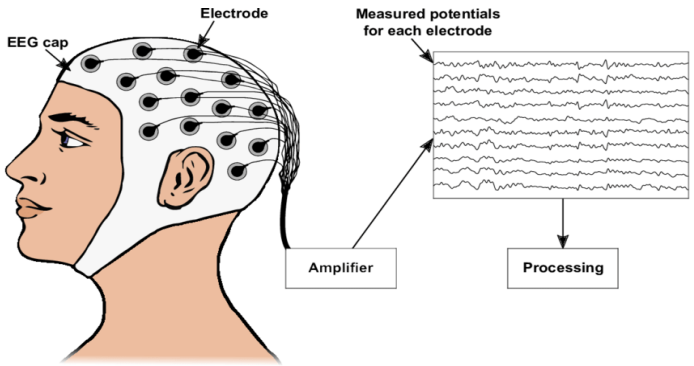

Figure 1: EEG Recording

3.1.2 PET

PET stands for Positron Emission Tomography. This technology uses radioactive tracer to detect the brain activity. Tracer attaches itself to the glucose in the bloodstream. As the brain uses glucose as the main fuel source so tracer gets attached to the areas for high glucose which enables the doctors to pinpoint the area where glucose is not moving correctly. It can be used to detect seizures, Alzheimer's etc.

Figure 2: PET Scan

3.1.3 CT Scan

Computerized Tomography scans use a series of X-rays & convert them into cross-sectional images of brain. They are combined to form a cross-sectional image of the brain or even 3D model of the brain. CT scan provides more details than a usual X-Ray. CT scan is useful in finding certain brain injuries, swelling or internal bleeding, tumors etc.

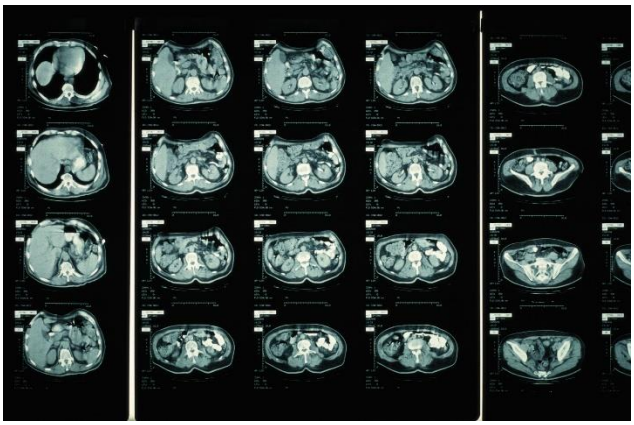

Figure 3: Sample CT Scan

3.1.4 FMRI

Functional Magnetic Resonance Imaging or FMRI uses magnetic field of the scanner which affects the nuclei of the hydrogen atoms so they can be measured & converted into image. It detects the changes in blood oxygen level in the brain. FMRI is used mostly for detecting abnormalities in brain, for creation of brain maps prior to surgery etc.

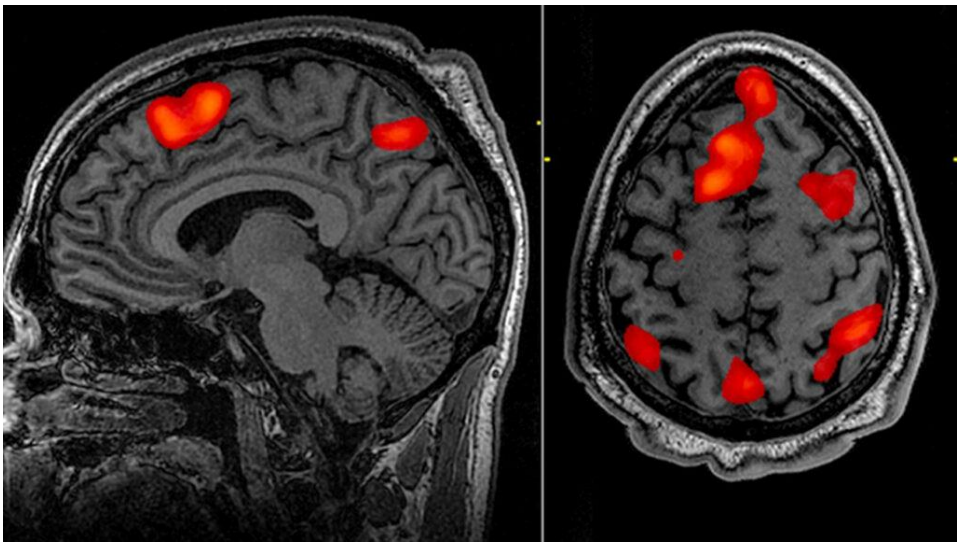

Figure 4: Sample FMRI

The research I am carrying out is based on fNIRS so I will be discussing that in detail in the upcoming section.

3.1.5 fNIRS

fNIRS stands for Functional Near Infrared Spectroscopy. It is an optical brain imaging technique which uses near infrared spectroscopy for neuroimaging. It is a non-invasive technique for neuroimaging. In this technique brain activity is monitored or measured using near infrared to estimate cortical hemodynamic activity in response of neural activity.

The reason fNIRS has become so popular recently is that it is cost effective, portable, provides a naturalistic environment to carry out the experiment & the most important thing is that it is a non-invasive technology. We can perform fNIRS experiments from the scalp & we do not have to do it from inside of the scalp.

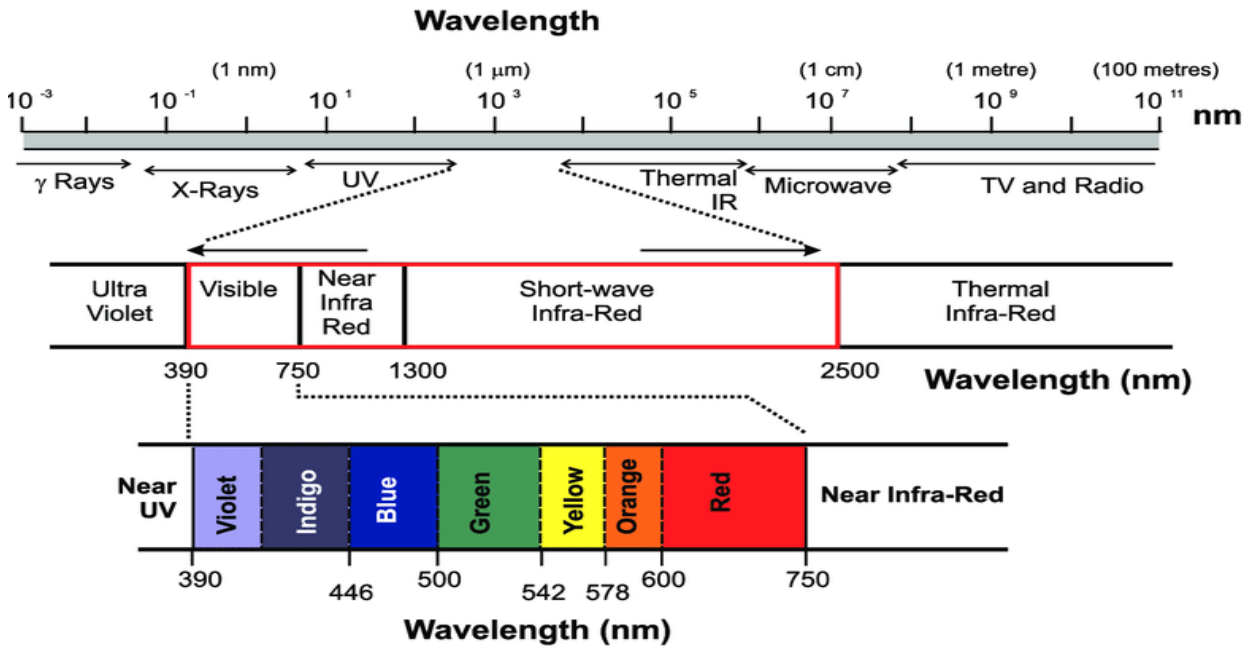

Figure 5: NIR Spectrum

Spectral interval of near infrared is 700-900nm. This spectral interval puts this technique to an advantage because skin, tissue and bone are transparent to this intensity of light, but hemoglobin is an absorbent on this intensity. So, in fNIRS we estimate the changes in the concentration of hemoglobin as the light moves through the head.

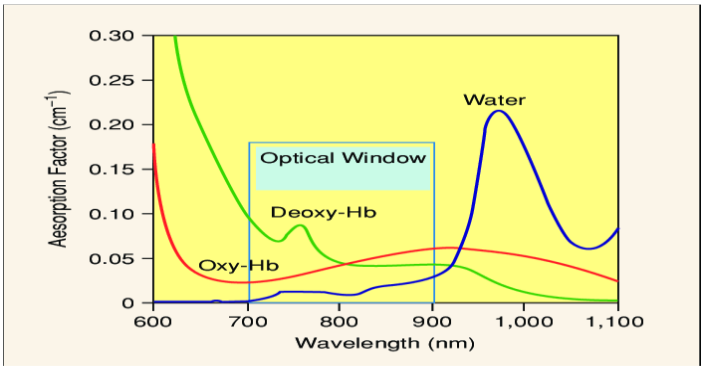

Figure 6: fNIRS Sample

There are six different ways in which the infrared interacts with the brain tissue. Those six ways are direct transmission, diffuse transmission, specular reflection, diffuse reflection, scattering & absorption.

Out of all the six, fNIRS focuses primarily on absorption. The absorption spectra of the oxygenated-hemoglobin & deoxygenated-hemoglobin is measured. At 810nm both oxy-hemoglobin & deoxy-hemoglobin have same absorption coefficients so one wavelength above

and one below is selected. MBLL (modified beer-lambert law) is used to calculate the relative changes in the concentration of hemoglobin.

3.2 Recording of Hemoglobin Concentrations

To record the relative changes in the concentrations of hemoglobin a source and emitter combination is used. Both source and emitter are Infrared LEDs. The distance between source and emitter is 3cm. fNIRS is most effective in detecting the changes in hemoglobin concentrations near scalp. When IR rays hit the scalp they scatter, so multiple detectors are placed round a source to catch the reflecting radiations.

Modified Beer Lambert Law is used to calculate the changes in the concentrations of hemoglobin based on the data recorded from the combination of source and detector placed near scalp.

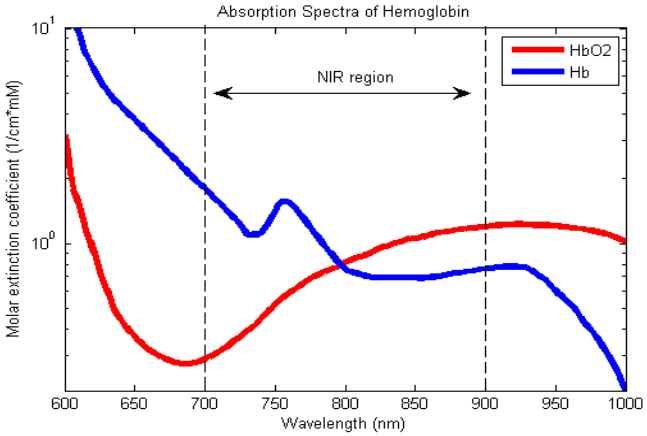

Figure 7: HbO & HbR Recording

3.3 fNIRS Techniques

Currently 3 different fNIRS techniques are being used:

- Continuous Wave
- Frequency Domain
- Time Domain

In this research we are using Continuous Wave fNIRS system.

3.3.1 Continuous Wave fNIRS

Continuous wave fNIRS system is the simplest & cheapest system available. It is cost effective & most widely used worldwide. It has more channels & ensure high temporal resolution. It does not distinguish between scattering and absorption changes; it does not measure absolute absorption values that is why it is not sensitive to changes in HbO concentration.

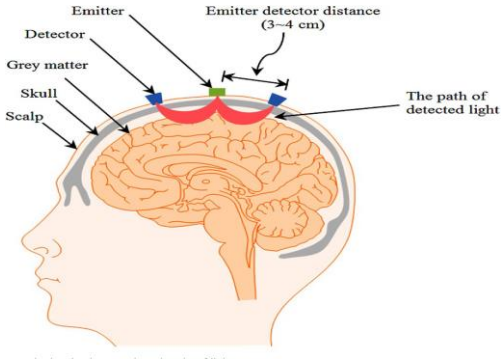

Figure 8: fNIRS Recording

Continuous wave fNIRS uses a light source with constant amplitude and frequency. CW fNIRS does not provide any information about photon path length & to measure the relative changes in HbO concentration using MBLL we need to know photon path length. So, changes in HbO concentration are relative to an unknown path length.

Following is the Modified Beer Lambert Law:

$$A(t;\lambda) = -\ln \frac{I_{out}(t;\lambda)}{I_{in}(\lambda)} \overset{\Delta}{=} \mu_a(t;\lambda) \times l. \qquad \textbf{eq.1}$$

Here, 'A' is the absorbance or optical density, which depends on the wavelength λ [nm] of the incident light. It is unitless.

Change in light attenuation is proportional to changes in the concentration of tissue chromophores, mainly HbO and HbR.

If attenuation changes are measures at two or more wavelengths, then concentration changes can be measured.

MBLL is based on two assumptions:
- The absorption of the tissue changes homogenously.
- The scattering lost is constant.

$$\Delta A(t;\lambda) = A(t_2;\lambda) - A(t_1;\lambda) = -\ln\frac{I_{out}(t_2;\lambda)}{I_{out}(t_1;\lambda)} = \Delta\mu_a(t;\lambda)\times l\times d(\lambda), \quad \textbf{eq.2}$$

d (λ): Differential path length factor

$A(t_1;\lambda),\ A(t_2;\lambda)$: the absorbances measured at two time points

$I_{out}(t_1;\lambda), I_{out}(t_2;\lambda)$: the intensitie s of the detected light at two time points

By measuring the absorbance at two wavelength, λ 1 and λ2 (assume that d is constant):

$$\Delta A(t;\lambda_1) = \left[\alpha_{HbO}(\lambda_1)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda_1)\Delta c_{HbR}(t)\right]\times l\times d,$$
$$\Delta A(t;\lambda_2) = \left[\alpha_{HbO}(\lambda_2)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda_2)\Delta c_{HbR}(t)\right]\times l\times d. \quad \textbf{eq.3}$$

Rearranging both equations, we get:

$$\begin{bmatrix}\Delta c_{HbO}(t)\\ \Delta c_{HbR}(t)\end{bmatrix} = \frac{\begin{bmatrix}\alpha_{HbO}(\lambda_1) & \alpha_{HbR}(\lambda_1)\\ \alpha_{HbO}(\lambda_2) & \alpha_{HbR}(\lambda_2)\end{bmatrix}^{-1}\begin{bmatrix}\Delta A(t;\lambda_1)\\ \Delta A(t;\lambda_2)\end{bmatrix}}{l\times d}. \quad \textbf{eq.4}$$

The results from the above equation will give us the concentration value of HbO & HbR.

4 System Architecture

System architecture is the basis of any hardware or software. Before developing any hardware and integrating it with a software, designing its architecture is necessary. System architecture makes it easy to develop a hardware and then its integration with a software for acquiring results. Following is the pictorial representation of the system architecture of our research:

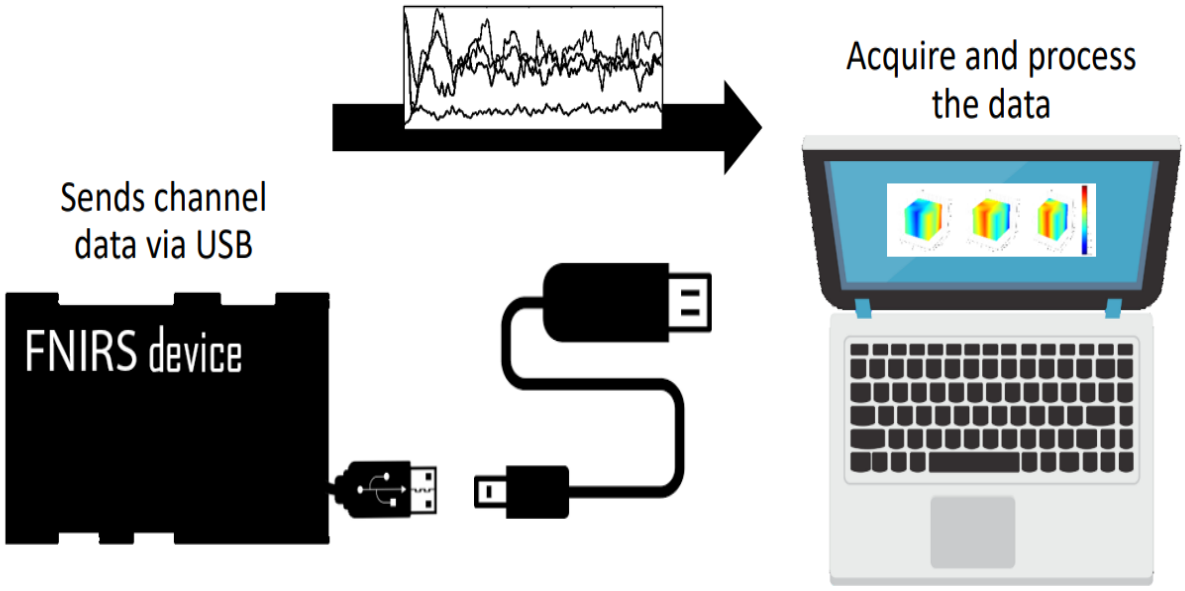

Figure 9: System Architecture

First part of the system is fNIRS device which the hardware in our research. It is a 28 channel fNIRS device with 2 sources & 14 detectors. Detailed explanation of each component being used in the hardware will be discussed in the upcoming chapters.

Second part of the architecture is the interfacing of the hardware with the software. This will be using a USB cable and port. We are using USB port 3. Generation 1. It has a capacity to transmit up to 5 Gigabytes of data per second.

The hardware will be programmed using Arduino IDE & then the data will be transmitted using I2C communication to the Laptop or PC. I2C is a data transmission protocol. I2C stands for Inter-Integrated Circuit & it uses master and slave to send & receive data.

Once the data is transmitted to the Laptop or PC then it will be processed using MATLAB. In MATLAB the data will be first pre-processed then we will apply Modified Beer Lambert Law on the data which will give us the concentrations of HbO & HbR. Once we get the concentrations

then we will filter the outputs for smoothening of signals. After this we will have our desired results.

The computer system used in this research is HP EliteBook 840 G3. System specifications are:

- Windows 10 PRO.
- 6th gen. core i7 2.81 GHz Processor.
- RAM 16Gb
- 256Gb SSD
- 500Gb HDD
- 4 threads.

Following is the complete architecture diagram of the whole process to be carried out:

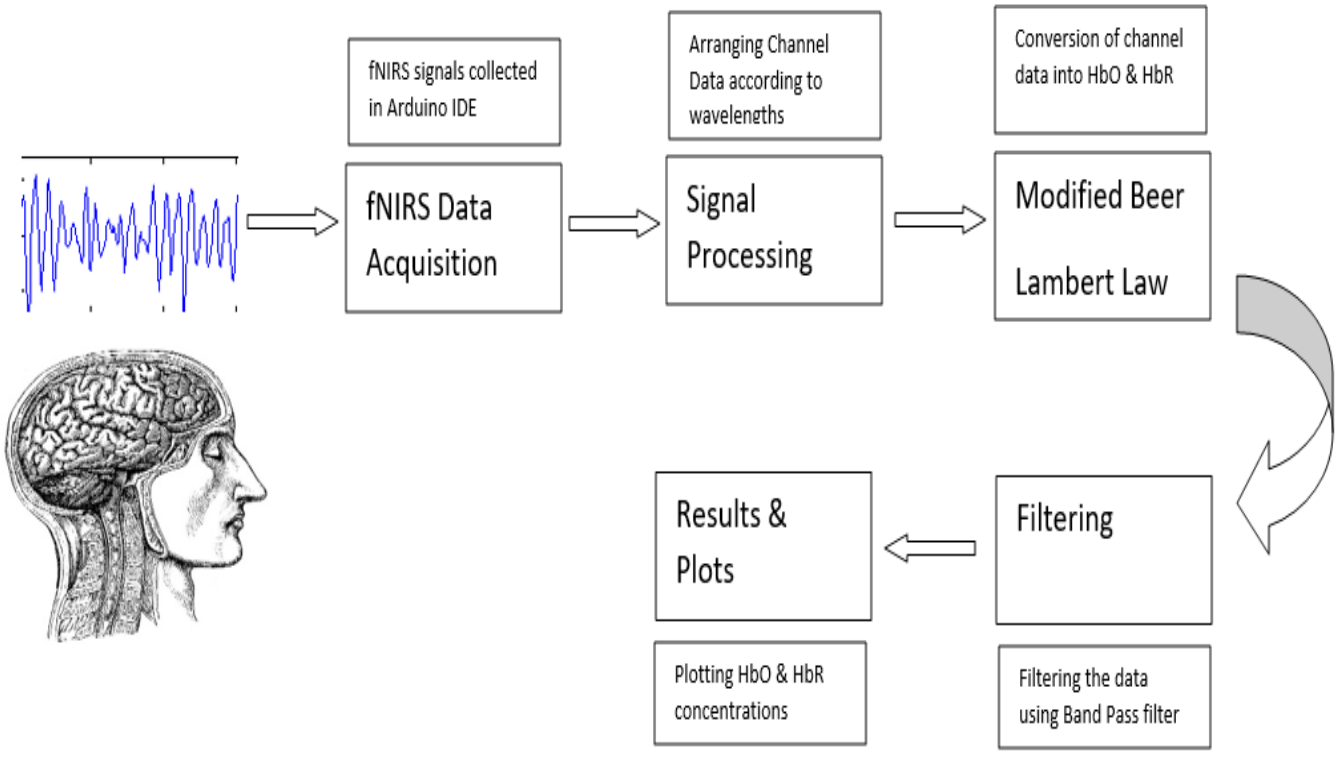

Figure 10: Architecture Diagram

5 Hardware Design

As of now, many fNIRS devices have been made round the world. Some of the common fNIRS devices are as follows:

- CW-NIRS system **DYNOT-232** of NIRx medical technologies.
- FD-NIRS system **ISS Imagent of ISS Inc,** Champaign, IL, USA
- CW-NIRS system **PortaLite** of Artinis Medical Systems.
- CW-NIRS system made at the Department of Cogno-Mechatronics Engineering, PNU

Following is a list of some of the commercially used fNIRS devices:

	Device	(Manufacturer), country	Time-res. [Hz]	#Emitter	#Detector	MUX	SDS [mm]	E-tech	Wavelengths [nm]	D-tech	Data	Wear	CE
D1	OXYMON MkIII[a]	(Artinis), Netherlands	250	32	16	t	a	Laser	760, 850*	APD	Raw	n	y
D2	PortaLite	(Artinis), Netherlands	50	3	1	t	20 + 25 / 30 + 35 + 40	LED	760, 850*	PD	Raw	y	y
D3	fNIR1100	(fNIR Devices), USA	2	1/1/4	2/4/10	t	20/25/25	LED	730, 850		Hb	n	n
D4	fNIR1100w	(fNIR Devices), USA	2	1	2/4	t	20/25	LED	730, 850		Hb	y	n
D5	ETG-4000	(Hitachi), Japan	10	18	8	f	20/30	Laser	695, 830	APD	Raw	n	y
D6	ETG-7100	(Hitachi), Japan	10	40	40	f	20/30	Laser	695, 830	APD	Raw	n	y
D7	WOT[b]	(Hitachi), Japan	5	8	8	t + f	30	Laser	705, 830	PD	Raw	y	n*
D8	Genie	(MRRA), USA	5.02	4 to16	8 to 32	c	a	LED	700, 830	PD	Raw	y	n
D9	NIRScout	(NIRx), USA	6.25 to 62.5	8 or 16	4 to 24	t + f	a	LED	760, 850	PD	Raw	n	y
D10	NIRScoutX	(NIRx), USA	6.25 to 62.5	48	32	t + f	a	LED	760, 850	PD	Raw	n	y
D11	NIRSport	(NIRx), USA	6.25 to 62.5	8	8	t + f	a	LED	760, 850	PD	Raw	y	y
D12	Brainsight NIRS	(Rogue Research), Canada	100	4 to16	8 to 32	f	a	Laser	685, 830, (808)*	APD	Raw	n	n*
D13	FOIRE-3000	(Shimadzu), Japan	7.5 to 40	4 to 16	4 to 16	t	a	Laser	780, 805, 830	PMT	OD	n	n
D14	OEG-SpO2	(Spectratech), Japan	1.52/12.2	6	6	c	30/25/15–40	LED	770, 840	PD	Raw	y*	n*
D15	CW6	(TechEn), USA	10 to 50	4 to 48	8 to 32	f	a	Laser	690, 830*	APD	Raw	n	y
D16	UCL Optical Topography System[c]	(University College London), UK	10 to 160	16	16	f	a	Laser	780, 850	APD	Raw	n	n
D17	Imagent	(ISS), USA	16 to 60	16 or 32	4 or 8	t	a	Laser	690, 830	PMT	Raw	n	y

Figure 11: Commercially Used fNIRS Devices

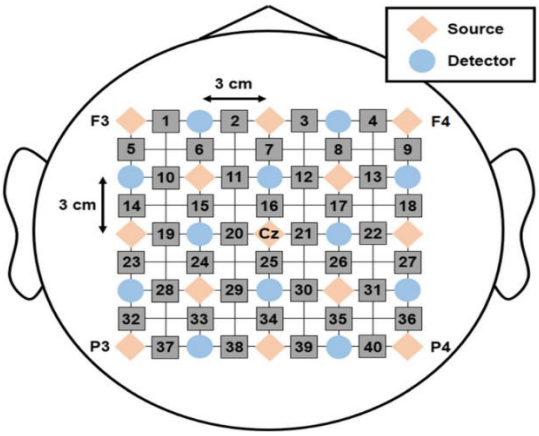

Figure 12: fNIRS Channel Configuration

In the figure above is a most used fNIRS source emitter configuration. In this configuration we can see that each source detector pair is placed at 3cm. When the source and the detector will be placed against the scalp, the source will fire IR radiations and the detector will detect the reflecting radiations. The problem with this configuration it does not cater the problem of artifacts due to skin, bone & tissue.

So, the device I have developed for my research, its design is novel. I have designed it according to the requirement & objectives of the research. This design will cater the problem that artifacts due to skin, bone & tissue. Following is the pictorial representation of the device.

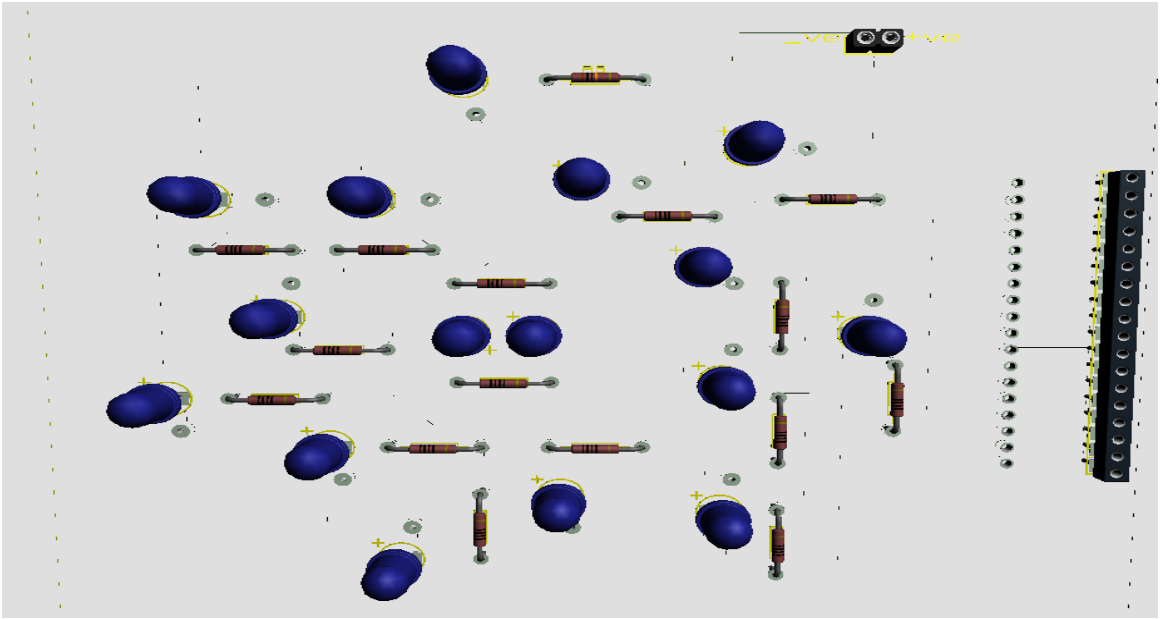

Figure 13: Top View of Proteus Design

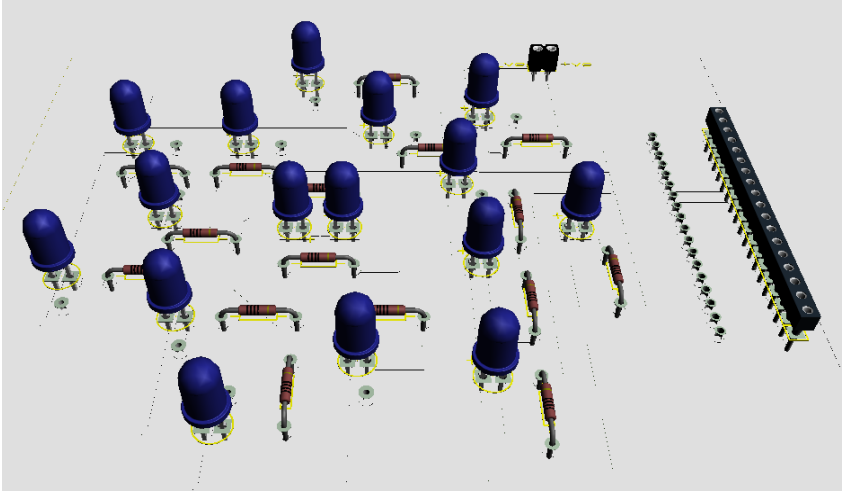

Figure 14: Proteus Design, Front View of Device

Following is a figure to show the scattering and absorption pattern of the IR rays after hitting the scalp. After striking with the scalp they form a banana-shape form.

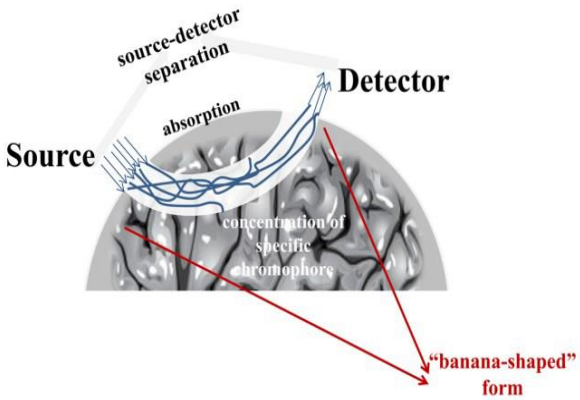

Figure 15: IR Rays Scattering and Absorption

Hardware components:

- 14 Infrared Receiver LEDs
- 2 IR Emitter LEDs
- 16 Resistors
- Arduino Mega 2560
- Jumper wires
- Power Source
- PCB

So, aligning the detectors in a circular configuration close to each other will allow us to capture the maximum number of reflected IR rays. This will result in a high-density brain image which is the primary objective of my research.

5.1 Hardware Components Description

5.1.1 IR LED

This is an infrared light emitting diode used for emitting & detecting IR waves. The source IR LEDs we are using in the project have a wavelength of 830nm & 690nm. The detector IR LEDs have a wavelength of 950nm. This means detector LEDs can detect a wavelength of up to950nm. The source LEDs have a firing angle of 45 degree.

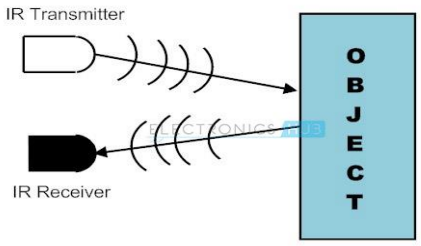

Figure 16: IR Source and Detector

5.1.2 Resistor

A resistor in an electrical component that is used to implement electrical resistance in a circuit. It is a passive electrical component. It is a two-way device. In an electronic circuit resistors are used to reduce the flow of current, divide voltages etc. In this project we are using 1K ohm & 10k ohm resistors.

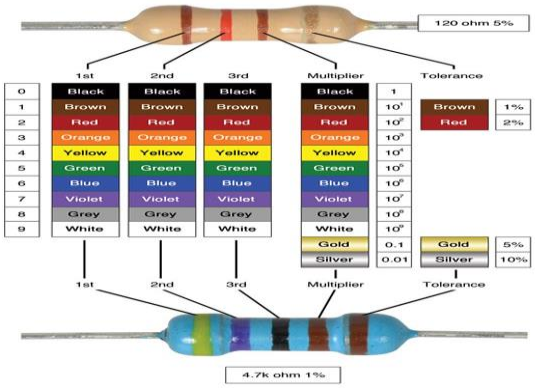

Figure 17: Resistor

5.1.3 Arduino Mega 2560

Arduino mega 2560 or AT Mega 2560 is an electronic circuit board. It is a microcontroller used for interfacing hardware and software. It has 16 Analog input pins, 54 digital I/O pins & 15 PWM pins for output. Along with all these pins it has transmitter receiver pins and voltage pins on it.

For interfacing we must program Arduino first and then the hardware will be able to function as per the programming done on the Arduino IDE.

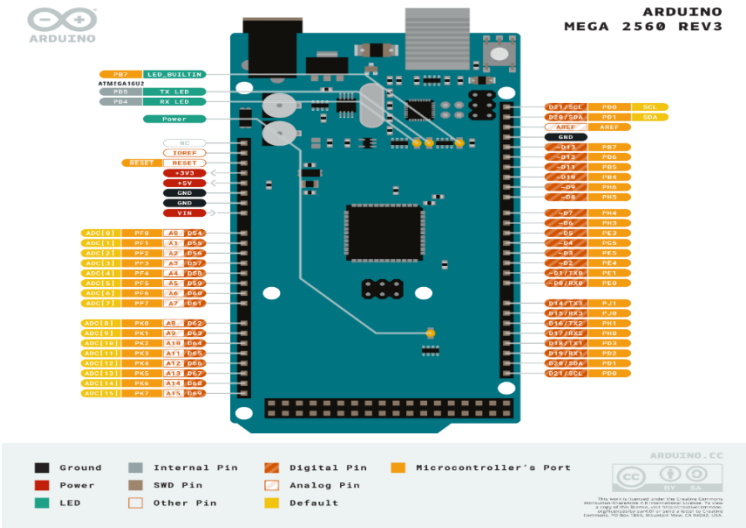

Figure 18: Arduino Mega 2560

5.1.4 PCB or Printed Circuit Board

PCB is used for designing electronic circuits. It has printed circuit lines on it which are used for connecting several electrical and electronic components and for the flow of electricity through the circuit.

For designing a PCB several software are used. In this project we have used Proteus for designing PCB. The soft form of PCB is then printed on the hardware PCB so that it can be used in the project as per requirement.

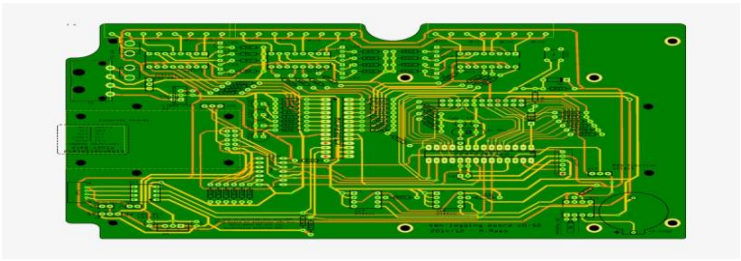

Figure 19: Sample PCB

6 Methodology

Over the years many different methods & techniques have been used in many research studies. fNIRS has no standardized system for collecting and processing of data so we have a lot of liberty to modify the formulas and data recording methods as per the requirement.

In recent years researchers have recorded data with fNIRS using different source & detector channels. They have designed detector configurations and based on their hardware they have come up with different results and accuracies.

The most common configuration is placing a detector LED at 3cm from the source IR LED but there is no standard or rule that we are not allowed to change the distance between source and detector.

The scope of our research requires a deep brain image and for that we will place the source and detector LEDs close to each other so that there is no or minimum loss of information which will result in a deep brain image. The system we have developed for our research is a 28 channel fNIRS system. It has 2 source LEDs & 14 detector LEDs.

The hardware is designed in such a way that the 14 detector LEDs are placed in 2 circles with each circle having 7 IR LEDs in it. In the center of the inner circle, we have placed 2 source LEDs. This configuration will help us in acquiring the maximum information from the circuit and that will result in building a deep brain image.

We have divided this research into four sub-categories:

- Hardware & PCB development
- Programming Software
- Experimental Design
- Pre-Processing of Data in MATLAB.

6.1 Hardware & PCB Development

The first part of this project is to develop a hardware which can be used for acquiring data which can be used further for the formulation of results & outcomes.

The hardware we developed for our research consists of 14 receiver IR LEDs & 2 emitter IR LEDs primarily. The other hardware components used are pullup & pulldown resistors, jumper wires & voltage source.

Once we decided the equipment to be used, we need to make a PCB & for that we have used PROTEUS software for designing a PCB.

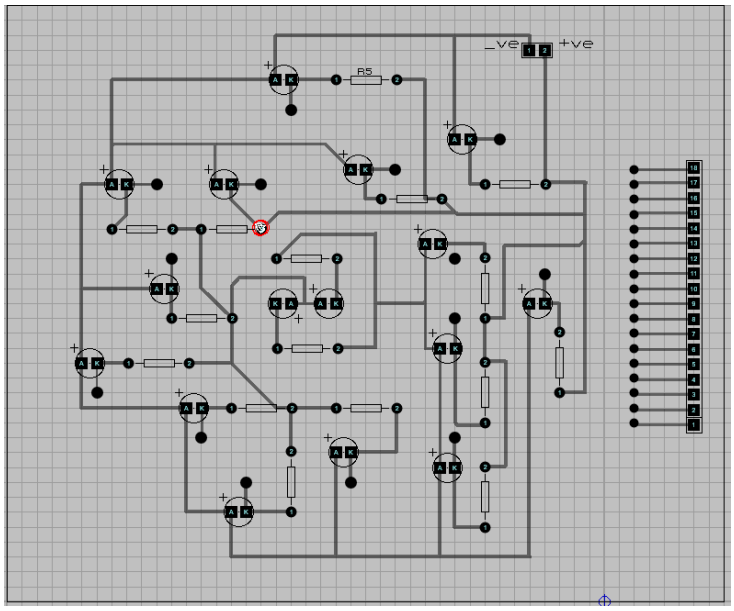

Figure 20: Software Design of PCB

When the PCB is designed on software, we must shift it to hardware where this software design will be implemented practically.

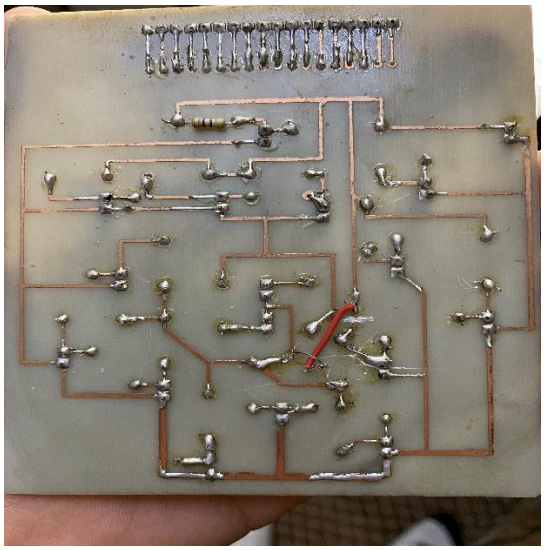

Figure 21: PCB Hardware

6.1.1 Programming Software

Once the hardware is developed, the next step is to program a software through which we can interface hardware and software. We have used Arduino IDE for programming.

The software is programmed in such a way that we are simultaneously switching the emitter LEDs ON/OFF & reading the input from the receiver LEDs respectively. The output is being displayed on a serial monitor in Arduino IDE and shifted to EXCEL afterwards.

B	C	D	E	F	G	H	I	J	K	L
680	680	682	684	684	688	689	687	685	682	680
687	687	687	688	688	688	688	689	688	688	688
686	685	685	686	686	686	686	684	682	682	682
683	681	679	679	679	678	680	681	681	681	681
688	686	685	684	684	682	681	680	679	679	678
688	688	688	688	688	685	684	682	679	679	679
680	684	680	687	687	686	684	681	677	679	682
682	677	679	681	681	680	684	681	676	682	681
677	680	682	677	677	683	678	678	683	679	680
677	676	677	677	677	677	677	677	676	677	677
678	681	683	683	683	675	680	684	683	678	676
677	676	677	678	678	677	677	677	677	677	676
676	677	677	676	676	677	677	677	677	677	676
677	676	677	677	677	677	677	677	676	677	676
677	676	676	677	677	676	676	677	676	677	677
683	677	675	680	680	681	677	680	682	682	677
684	682	677	677	677	683	682	677	679	682	684
677	677	677	677	677	677	676	676	676	677	677
676	677	676	677	677	677	676	676	677	676	677
676	676	677	677	677	677	677	676	677	677	677
682	682	682	680	680	678	678	678	677	676	676
682	682	681	680	680	677	677	677	676	677	679
678	679	680	682	682	683	683	681	681	679	677
683	681	680	679	679	677	676	677	678	679	681
682	682	682	683	683	682	682	681	680	681	680
676	677	676	676	676	678	679	679	678	679	679
686	679	680	688	688	679	681	687	688	681	679
684	687	687	685	685	678	683	687	688	685	681
683	682	681	680	680	682	683	682	682	680	681
684	682	673	687	687	682	688	678	684	681	683

Figure 22: Data Displayed on MS Excel

6.1.2 Experimental Design

This is the part in which we must check that the device we have built is working properly or not & the results are satisfactory or not. So, to check the device we used a technique called occlusion. In occlusion we test the device on our wrist by first blocking the blood flow in the wrist then releasing it. This will give us a data which will provide us with enough evidence that if the device is working properly or not.
In the figure below is the pictorial representation of the experimental design for occlusion.

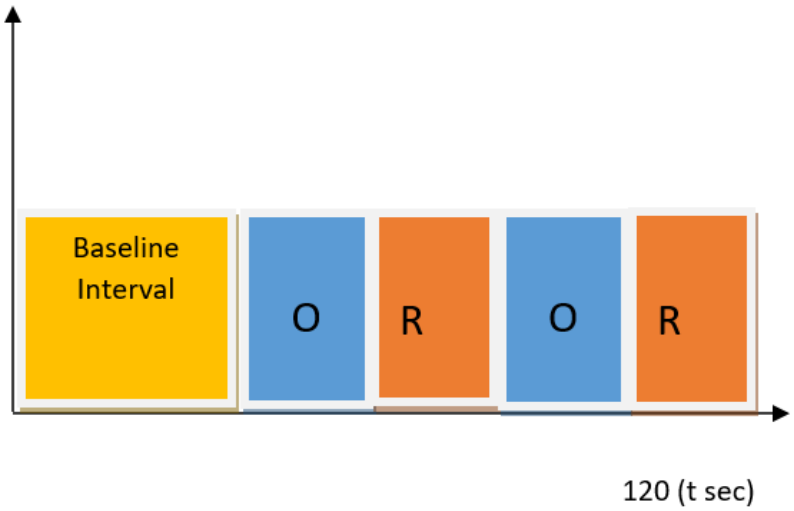

Figure 23: Experimental Design of Occlusion

So, the total length of the experiment was 120 seconds. The starting 40 seconds was the baseline interval in which the device was allowed to settle. The next 80 seconds were divided into four 20 seconds intervals of occlusion & rest respectively.

After testing the device with occlusion, now we will perform the experiment to get the required data set. The device will be placed on the left side of the forehead. While the device being placed on the forehead the subject will reverse count from 100 to 0. The total length of the experiment will be 200 seconds. The starting 40 seconds was the baseline interval in which the device was allowed to settle. The next 120 seconds were divided into six 20 seconds intervals of reverse count & rest respectively.

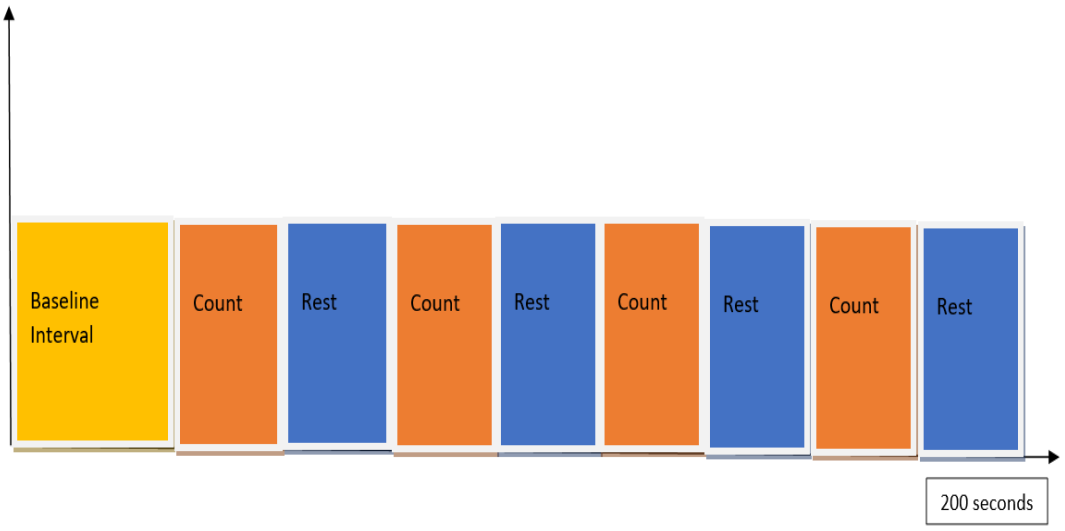

Figure 24: Experimental Design of Reverse Count

6.1.3 Pre-Processing of Data in MATLAB

In MATLAB, the pre-processing of data includes:

- Filtering raw data
- Implementation of MBLL on the data.

Filtering is performed using a bandpass filter. A bandpass filter only allow a set range of data signal to be passed through and rest of the data will be filtered out.

Once the filtering is done, we will apply Modified Beer Lambert Law on the data. MBLL is used for processing the fNIRS data. MBLL has already been discussed in detail in Chapter 3 section 3.3.

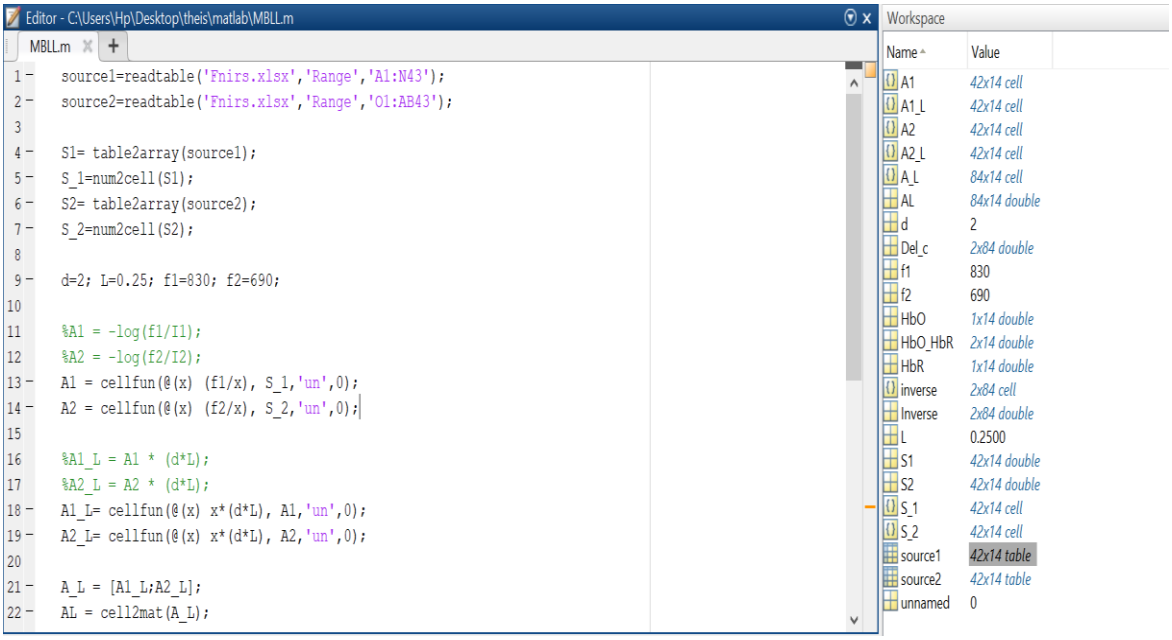

Figure 25: MATLAB Editor

7 Results

The device is designed to acquire deep brain signals using fNIRS. This section will be comprised of the results of the two different experiments performed. First the results of the test experiment will be shown & then the results of the brain signals will be shown.

7.1 Results of Occlusion

The experimental design of occlusion has been discussed in the section above. The figure below represents the optical data captured by the device from two different sources on 14 different channels during occlusion.

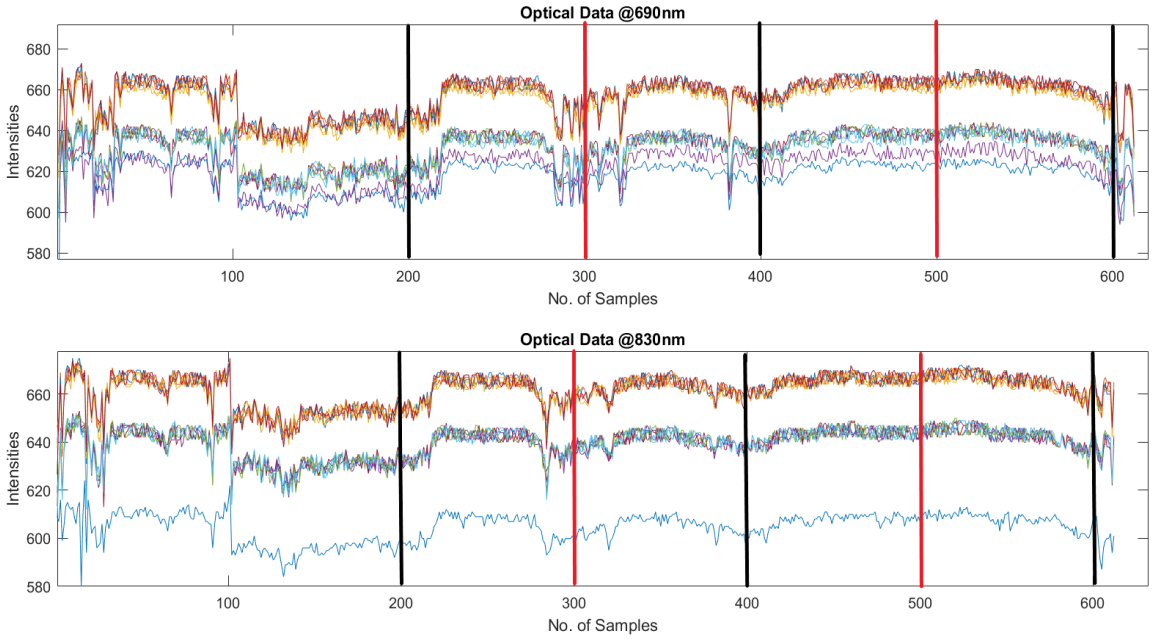

Figure 26: Optical Data of Occlusion from fNIRS Device

After acquiring the optical data, first we will calculate the absorbance of the light from source IR LEDs into the blood & then we must apply Modified Beer Lambert law on it so that we can calculate the HbO and HbR concentrations. The figure below represents the calculated absorbance.

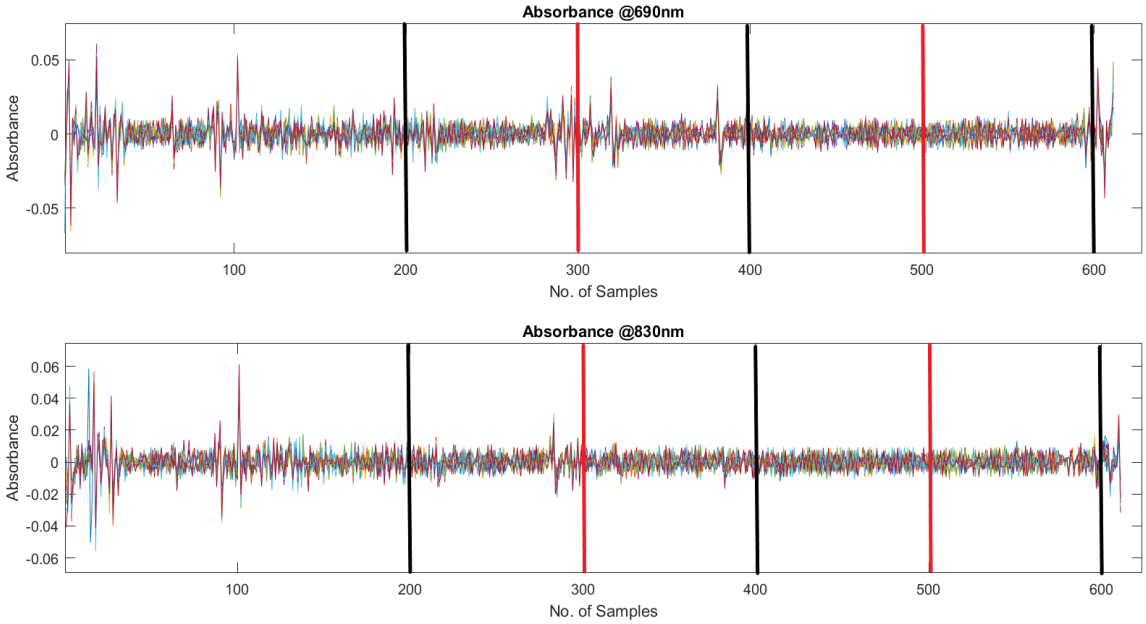

Figure 27: Absorbance with Occlusion

After the absorbance calculation we will use the data for the HbO & HbR concentrations. Following figure represents the graphical data of HbO & HbR concentrations.

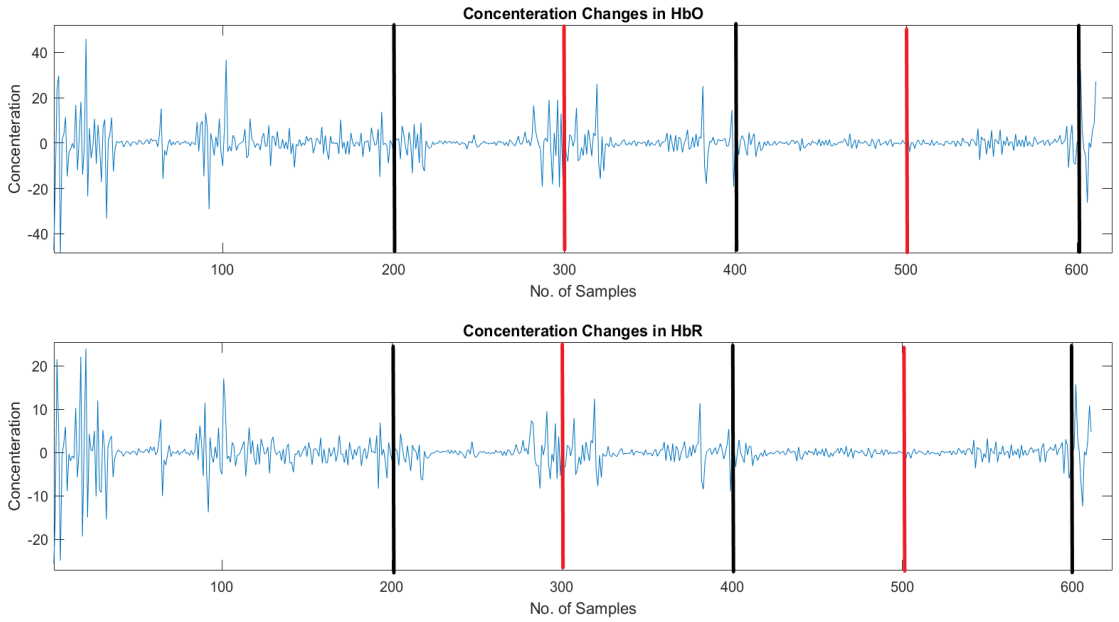

Figure 28: HbO & HbR concentrations with Occlusion

We produced the hemodynamic response function using two gamma function for occlusion. The figure below represents the two-gamma function, stimulating paradigm & hemodynamic response function.

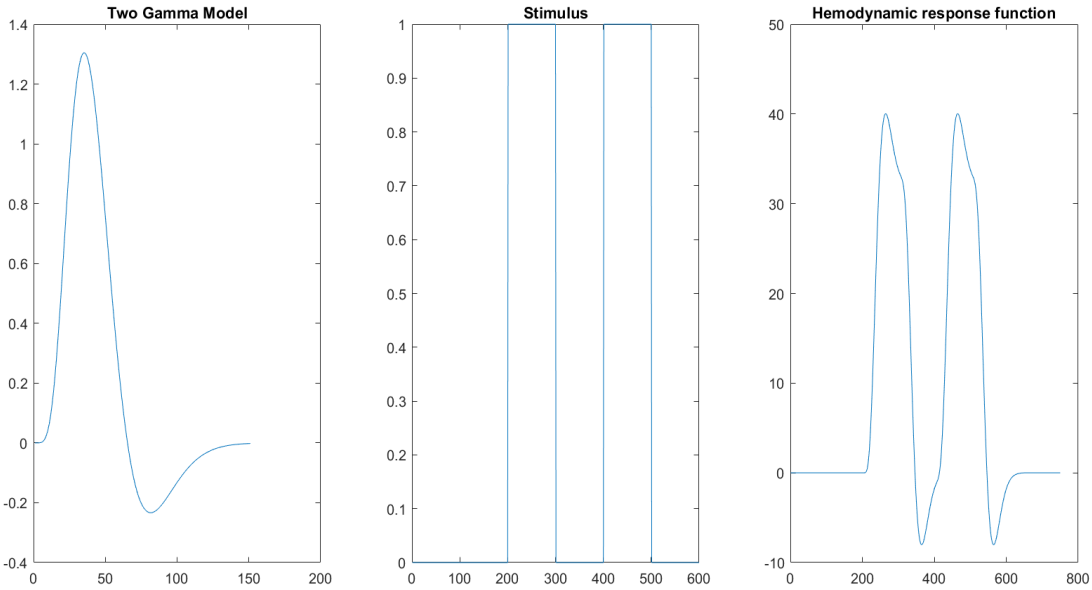

Figure 29: Hemodynamic response function for Occlusion

7.2 Results of Reverse Count

The experimental design of reverse count has been discussed in the section above. The figure below represents the optical data captured by the device from two different sources on 14 different channels during occlusion.

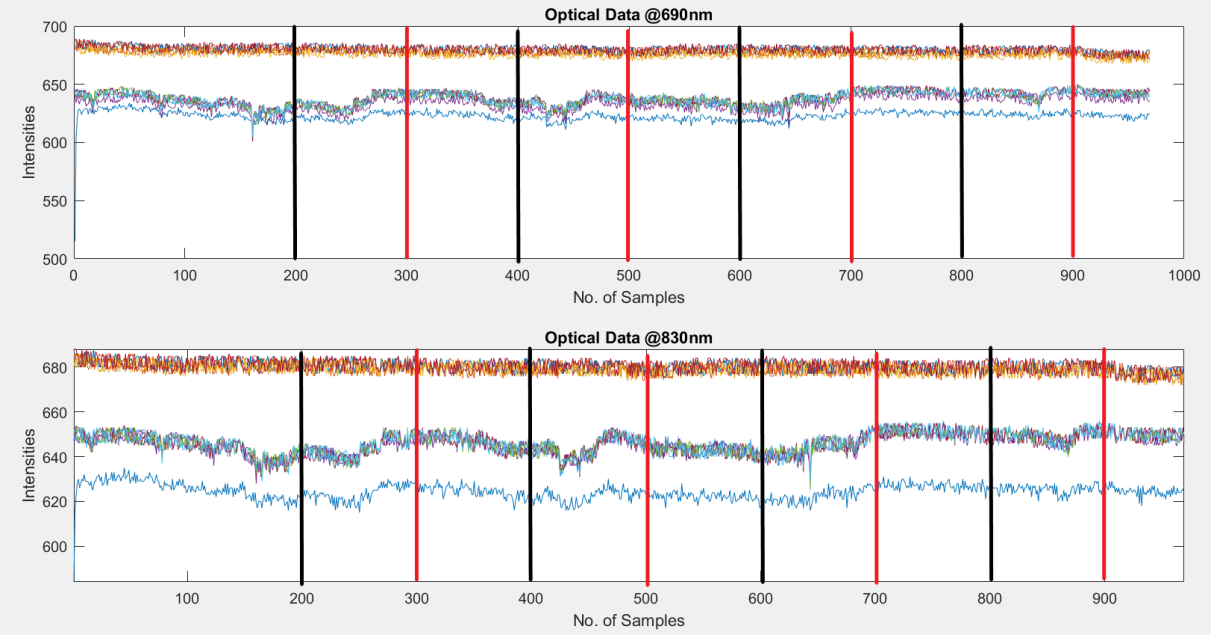

Figure 30: Optical Data of Reverse Count

After acquiring the optical data, first we will calculate the absorbance of the light from source IR LEDs into the blood & then we must apply Modified Beer Lambert law on it so that we can calculate the HbO & HbR concentrations. The figure below represents the calculated absorbance.

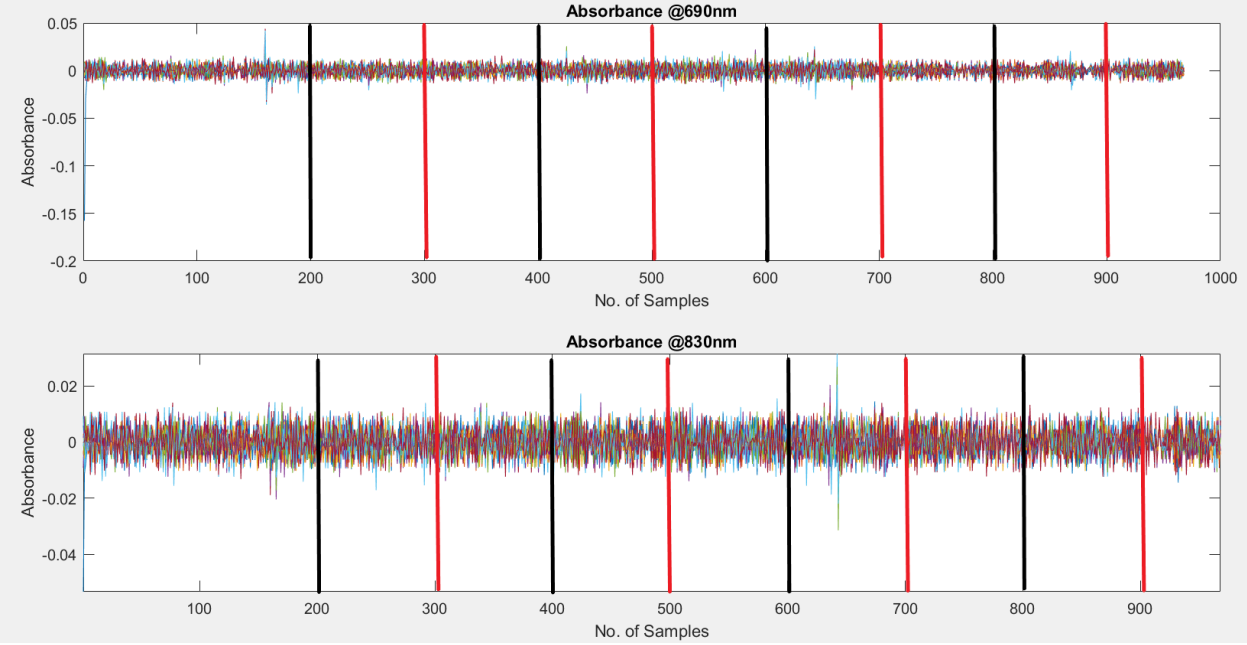

Figure 31: Absorbance with Reverse Count

After the absorbance calculation we will use the data for the HbO & HbR concentrations. Following figure represents the graphical data of HbO & HbR concentrations.

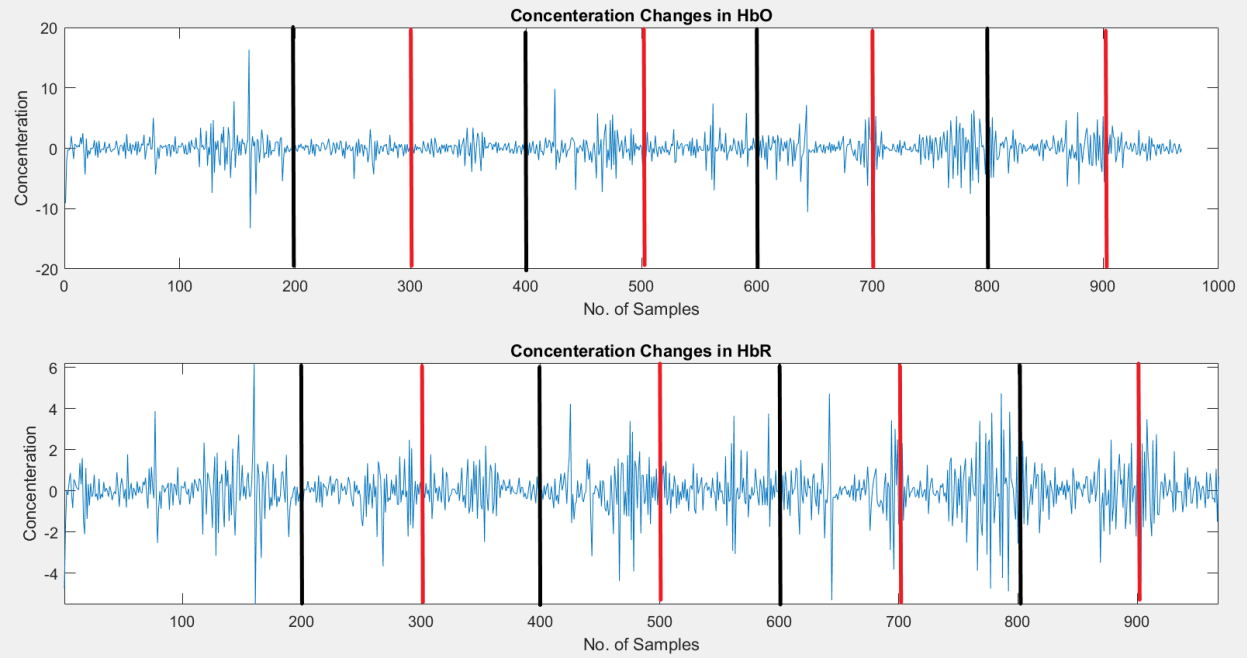

Figure 32: HbO & HbR Concentrations with Reverse Count

We produced the hemodynamic response function using two gamma function for reverse count. The figure below represents the two-gamma function, stimulating paradigm & hemodynamic response function.

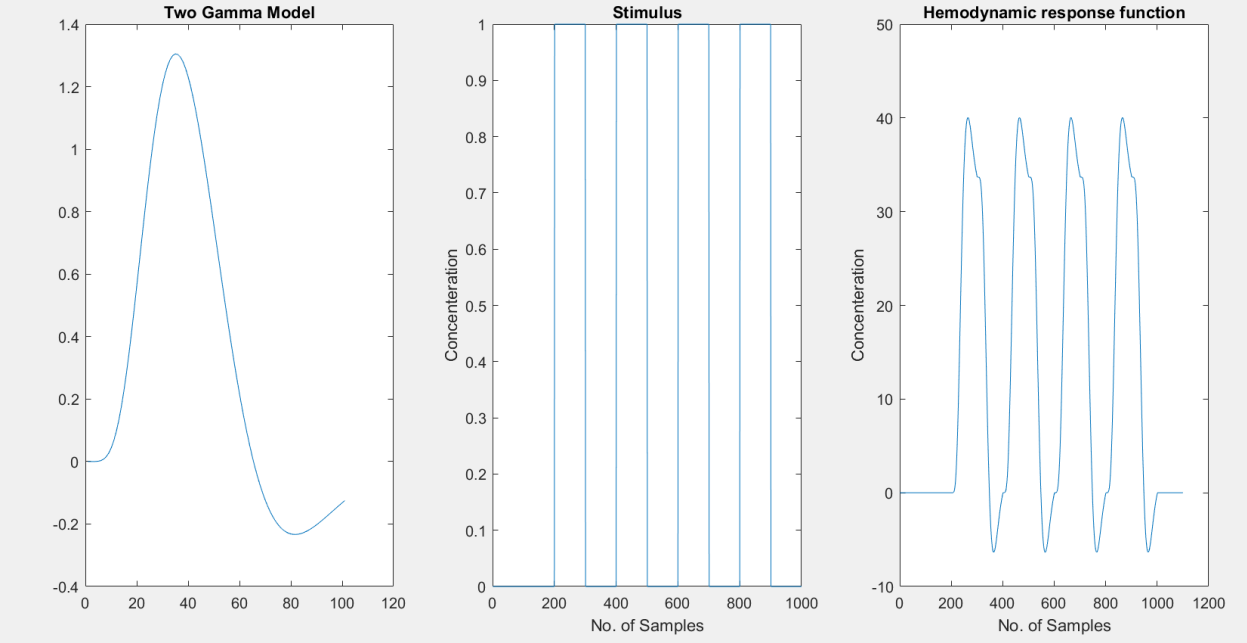

Figure 33: Hemodynamic response function for Reverse Count

After HRF, we have also calculated the *t*-values & have made color maps of both HbO & HbR chromophores. In the figure 34-37, *t*-values & color maps will be shown.

-1.1425 e-5	-1.1389 e-5	-1.1389 e-5	-1.1385 e-5
-1.1389 e-5	-1.1389 e-5	-1.1408 e-5	-1.1390 e-5
-1.1380 e-5	-1.1385 e-5	-1.1395 e-5	-1.1388 e-5
-1.1389 e-5	-1.1384 e-5	-1.1382 e-5	-1.1387 e-5

Figure 34: t-values of HbO

-1.1441 e-05	-1.1388 e-05	-1.1387 e-05	-1.1386 e-05
-1.1390 e-05	-1.1389 e-05	-1.1410 e-05	-1.1389 e-05
-1.1378 e-05	-1.1387 e-05	-1.1397 e-05	-1.1386 e-05
-1.1387 e-05	-1.1386 e-05	-1.1384 e-05	-1.1384 e-05

Figure 35: t-values of HbR

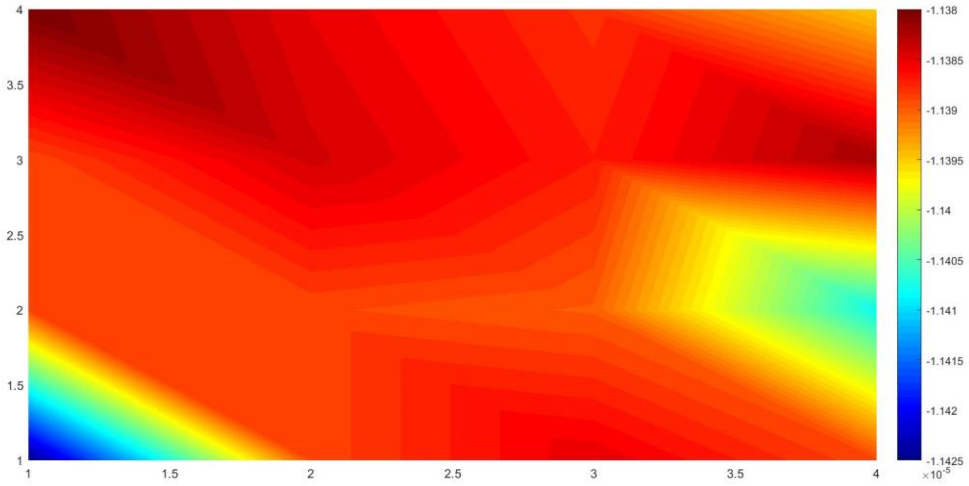

Figure 36: Color map of HbO

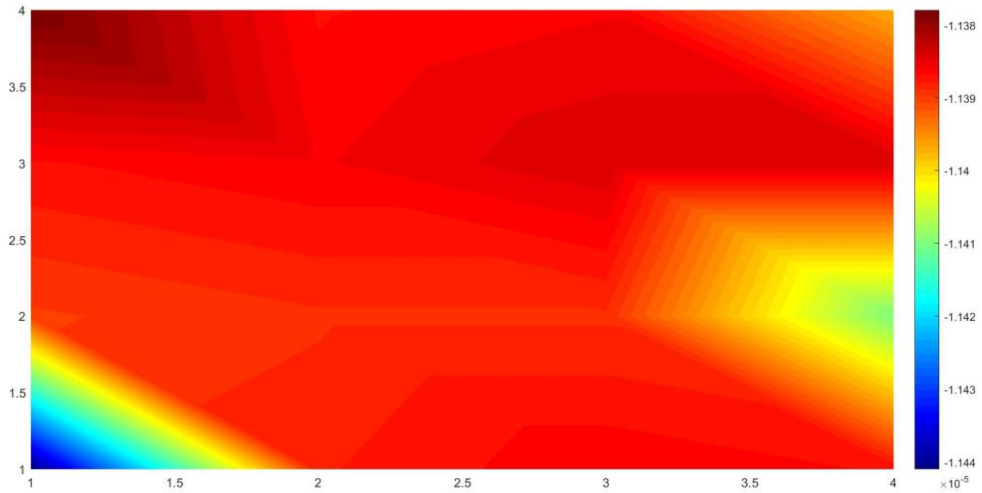

Figure 37: Color Map of HbR

8 Conclusions

In this research study, I presented a high-resolution imaging system for blood activity monitoring in the brain using functional near infrared spectroscopy (fNIRS).

In chapter 1 & 2, I discussed the problem statement, objectives, the previously available literature, the history of fNIRS and its use in the brain imaging.

In chapter 3, I elaborated on the imaging techniques other than fNIRS such as EEG, EMG, PET, FMRI etc., how we record the hemoglobin concentrations, discussed fNIRS in detail including its types and which fNIRS technique is used by us in this research.

Chapter 4& 5 are about the system architecture & hardware design. Hardware design in this research is novel. In the first step, the design was developed on software and then it was implemented on the hardware. In chapter 5, I discussed different hardware components being used.

After the development of the hardware, next step is to test it and for that there needs to be a methodology. So, in chapter 6 the whole methodology is discussed & then in chapter 7 the results are shown.

The results showed an improvement than the ones presented before. It shows that the design is an improve done than before. The results can be improved further by using the high-power IR LEDs. The reason for not using the high-power LEDs is their procurement being a problem. They were not available locally and to procure them from an international vendor, it was not viable financially.

This research shows that fNIRS being non-invasive is the future of brain's clinical diagnostics, but it certainly needs to improve further so that the diagnostic can be done with much higher accuracy.

To make improvements in the technique, following work can be done in future:

- Use of high-power LEDs for better penetration & to improve the results.
- Real time processing of the fNIRS data instead of offline processing.
- Increased number of channels for a larger data set.
- Different placement of source & detector channels.
- Development of hardware using multi-layer PCB to make the system compact.
- Use of wireless system to make it more portable.

9 References

1. J. Carlos Meléndez, Ernest McCrank, MD, FRCP. Anxiety-Related Reactions Associated with Magnetic Resonance Imaging Examinations. JAMA. 1993; 270(6):745-747.

2. McIsaac, H.K., Thordarson, D.S., Shafran, R. *et al.* Claustrophobia and the Magnetic Resonance Imaging Procedure. *J Behav Med* 21, 255–268 (1998).

3. van Minde, D., Klaming, L. & Weda, H. Pinpointing Moments of High Anxiety During an MRI Examination. *Int.J. Behav. Med.* 21, 487–495 (2014)

4. Salem Ah Sing Koh, Weiling Lee, Rosherinna Rahmat. Interethnic variation in the prevalence of claustrophobia during MRI at Singapore General Hospital: does a wider bore MRI scanner help? Volume: 26 issue: 4, page(s): 241-245(2017)
5. Artifacts in Magnetic Resonance Imaging ,Katarzyna Krupa and Monika Bekiesińska-Figatowska Brain MRI Shows Patterns in Patients with Depression, Anxiety RSNA,2017

6. Zyad Mansour Almutlaq. Discussion of the Causes, Effect and Potential Methods of Alleviating Patient Anxiety When Undergoing Magnetic Resonance Imaging (MRI). Volume 72, Issue 5, Summer 2018, Page 4473-4477(2018)

7. Dziuda, Ł., Zieliński, P., Baran, P. *et al.* A study of the relationship between the level of anxiety declared by MRI patients in the STAI questionnaire and their respiratory rate acquired by a fiber-optic sensor system. *Sci Rep* 9, 4341 (2019).

8. Victoria Tischler Tim Calton Michael Williams Anna Cheetham. Patient anxiety in magnetic resonance imaging centers: Is further intervention needed? Radiography 14(3):265-266(2008)

9. Ahlander BM, Årestedt K, Engvall J, Maret E, Ericsson E. Development, and validation of a questionnaire evaluating patient anxiety during Magnetic Resonance Imaging: The Magnetic Resonance Imaging-Anxiety Questionnaire (MRI-AQ). J Adv Nurs. 2016 Jun;72(6):1368-80

10. Dewey, M., Schink, T. & Dewey, C. F. Claustrophobia during magnetic resonance imaging: cohort study in over 55,000 patients. *J. Magn. Reson. Imaging* 26, 1322–1327(2007)

11. Enders, J. *et al*. Reduction of claustrophobia with short bore versus open magnetic resonance imaging: a randomized controlled trial. *PLoS One* 6, e23494(2011)

12. Eshed, I., Althoff, C. E., Hamm, B. & Hermann, K. G. Claustrophobia, and premature termination of magnetic resonance imaging examinations. *J. Magn. Reson. Imaging* 26, 401–404(2007)

13. Frank A. Fishburn, Megan E. Norr, Andrei V. Medvedev and Chandan J. Vaidya. Sensitivity of fNIRS to cognitive state and load. Front. Hum. Neurosci., 20 February 2014

14. Hasan Ayaz, Patricia A. Shewokis, Scott Bunce, Kurtulus Izzetoglu, Ben Willems, Banu Onaral, Optical brain monitoring for operator training and mental workload assessment, Neuroimage, Volume 59, Issue 1, 2012, Pages 36-47, ISSN 1053-8119.

15. Xu Cui, Signe Bray, Daniel M. Bryant, Gary H. Glover, Allan L. Reiss, A quantitative comparison of NIRS and fMRI across multiple cognitive tasks, Neuroimage, Volume 54, Issue 4, 2011, Pages 2808-2821, ISSN 1053-8119.

16. Herold F, Wiegel P, Scholkmann F, Müller NG. Applications of Functional Near-Infrared Spectroscopy (fNIRS) Neuroimaging in Exercise–Cognition Science: A Systematic, Methodology-Focused Review. *Journal of Clinical Medicine*. 2018; 7(12):466.

17. Hu Xin, Zhuang Chu, Wang Fei, Liu Yong-Jin, Im Chang-Hwan, Zhang Dan. fNIRS Evidence for Recognizably Different Positive Emotions. Frontiers in Human Neuroscience, VOLUME 13, 2019, ISSN 1662-5161

18. Fen Zhang, Herbert Roeyers, Exploring brain functions in autism spectrum disorder: A systematic review on functional near-infrared spectroscopy (fNIRS) studies, International Journal of Psychophysiology, Volume 137, 2019, Pages 41-53, ISSN 0167-8760.

19. Near Infrared Measurements: How do they work ? , Accessed 2nd March 2022, <https://bbpsales.com/near-infrared-measurements-how-do-they-work/>

20. Keum-Shik Hong, Noman Naseer 2015, Example of emitter detector pairs showing the banana shaped paths of light, Accessed 2nd March 2022, <https://www.researchgate.net/figure/Example-of-emitter-detector-pairs-showing-the-banana-shaped-paths-of-light_fig5_270282618>

21. Absorption spectra for Oxy-Hb and deoxy-Hb for near-infrared wavelengths, Accessed 2nd March 2022, <http://www.wikiwand.com/en/Functional_near_infrared_spectroscopy>

22. IR Sensor 2015, Accessed 3rd March 2022, <https://www.electronicshub.org/ir-sensor/>

23. Resistor Color Chart, Accessed on 3rd March 2022, <https://www.jameco.com/Jameco/workshop/CircuitNotes/circuit-notes-resistors.html>

24. Positron Emission Tomography, Accessed on 3rd March 2022, <https://www.torrancememorial.org/medical-services/radiology-imaging/tests/pet/>

25. Sebastian Nagel 2019, Sketch of how to record an electroencephalogram, Accessed on 3rd March 2022, <https://www.researchgate.net/figure/Sketch-of-how-to-record-an-Electroencephalogram-An-EEG-allows-measuring-the-electrical_fig1_338423585>

26. Pinout Diagram, Accessed on 3rs March 2022, <https://store-usa.arduino.cc/products/arduino-mega-2560-rev3>

27. Printed Circuit Board & PCB assembly- Electronic Component, Accessed 3rd March 2022, <https://www.nicepng.com/ourpic/u2w7a9o0e6w7a9o0_printed-circuit-boards-pcb-assembly-electronic-component/>

28. CT scans 2019, Accessed on 4th March 2022, <https://www.nbcnews.com/storyline/smart-facts/what-ct-scan-what-test-detects-how-it-works-n988601>

29. Traci Pederson 2021, Signal Photos/Alamy stock photos, Accessed on 4th March 2022, <https://psychcentral.com/lib/what-is-functional-magnetic-resonance-imaging-fmri>