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FACULTY OF BIOMEDICAL ENGINEERING

Department of Biomedical Technology

EOG marker for EEG processing

Bachelor Thesis

Study program : Biomedical Technology

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BACHELOR'S THESIS ASSIGNMENT

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II. BACHELOR'S THESIS DETAILS

Bachelor's thesis title in English:

EOG markers for EEG processing

Bachelor's thesis title in Czech:

EOG značky pro zpracování EEG

Guidelines:

EOG is used to classify REM sleep phase, but it is also an artifact that invalidates the EEG. Design an eye movement detector. Use sleep polysomnography recordings to extract EOG signals and design an eye movement or blink detector. Define the output of the detector so that it is synchronized with the EEG signal and can be used for REM phase classification and possibly for artifact elimination. Validate the designed detector using expert-rated recordings.

Bibliography / sources:

[1] Cohen, M.X., Analyzing Neural Time Series Data: Theory and Practice, ed. 1, MIT Press, 2014, ISBN 9780262019873

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[3] SIMOR, P., et al. , The microstructure of REM sleep: Why phasic and tonic?, Sleep medicine reviews, ročník 52, číslo 101305, 2020, Srpen, https://doi.org/10.1016/j.smrv.2020.101305

[4] VAN DEN BERG, N.H., et al. , Eye movements during phasic versus tonic rapid eye movement sleep are biomarkers of dissociable electroencephalogram processes for the consolidation of novel problem-solving skills, Sleep, ročník 46, číslo 8, 2023, Srpen, zsad151 s., DOI: 10.1093/sleep/zsad151

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DECLARATION

I hereby declare that I have completed this thesis having the topic "EOG marker for EEG processing" independently, and that I have attached an exhaustive list of citations of the all used sources.

I do not have a compelling reason against the use of the project within the meaning of Section 60 of the Act No.121 / 2000 Sb., on copyright, rights related to copyright and amending some laws (the Copyright Act).

In Kladno 14.05.2024 …..……………..………………...

Yuzhe Guo

ACKNOWLEDGEMENTS

I would like to thank my supervisor doc. Ing. Marek Piorecký, Ph.D. who worked closely with me throughout the entire thesis. During thesis he helps me a lot and give me nice guide for every step, that is why I can finish this thesis. Then for writing the thesis, he not only did he provide valuable academic advice and guidance, he also provided careful guidance and patient answers in every aspect. I am deeply inspired and encouraged by his rigorous academic attitude, rich knowledge reserve and enthusiasm for students. Thank you for your tremendous influence in my academic and professional life. In this semester, we successfully completed this huge project. It is precisely because of your help that I new knowledge involved in this topic. And I will work harder. Once again, my heartfelt thanks to help with my supervisor.

Sincerely,

Yuzhe Guo

ABSTRACT

EOG marker for EEG processing:

Eye movements during EEG could cause artifacts or in case of sleep are used for scoring of the REM sleep stage. Automatic detection could help with preprocessing and automatic sleep scoring. This project propose analog and digital methodology of eye movement detection. There were construct simple electronic circuit for demonstrating of eye blinking detection. In the future, the analog output can be converted to a binary logic output and save a time-synchronized record of the markers together with the EEG signals. Digital detection is related to eye movements during REM sleep stage. It aims to detect eye movement samples in signal which is measured by polysomnography. Ground truth was set by physicians. We propose eye movements detector based on threshold, amplitude and local maximum detection. Results were described by ROC analysis.

Key words

EOG, eye movement, blinking, REM, polysomnography

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List of symbols and abbreviations

List of symbols

Symbol	Unit	Importance
$+V_{ss}$	V	Positive power supply of comparator
$-V_{ss}$	V	Negative power supply of comparator
V_i	V	Source voltage from power supply instrument channel 2
V	V	Source voltage from power supply instrument channel 1
V_o	V	Output voltage at output channel of comparator LM311
V_1	V	Voltage at non-inverting input channel of comparator
V_2	mV	Voltage at inverting input channel of comparator
R_1	Ω	The resistor used in voltage divider which connected with power source
R_2	Ω	The resistor used in voltage divider which is ground
R_3	Ω	The protective resistor of LED
f_s	Hz	Sampling frequency of A/D converter on open BCI chip
V_{pk}	mV	Peak to Peak voltage of sin wave

List of abbreviations

Abbreviation	Importance
LED	Light-emitting diode
BCI	Brain-computer interface
A/D	Analog to digital
EOG	Electrooculogram
3D	Three dimensions
REM	Rapid eye movement
EEG	Electroencephalogram
PSG	Polysomnography
EMG	Electromyography
ECG	Electrocardiography
PLMD	Periodic limb movement disorder
NREM	Non-rapid eye movement
GIT	Gastrointestinal
ROC	Receiver operating characteristics
AUC	Area under curve
TP	True positive
FP	False positive
TN	True negative
FN	False negative
TPR	True positive rate
FPR	False positive rate
SVM	Support vector machines

1 Introduction

Electrooculography(EOG) is one of the signals which measure electric activity reflecting eyes movement. Sometimes recorded EEG is necessary to isolate time segments with eye movements. It could be done in real-time by analog circuits or in digital way in post processing. The data of eye blink show different states of signal from other time, the amplitude of signal will be much higher or lower than reference so we can identify it in the time-amplitude signal curve. The signal can also be processed digitally using software. Our detection is divided to analog and digital detection. In analog detection we are devoted to make an easy circuit which can compare and display eye blink using LED. All of these is based on LM 311 comparator to compare the threshold and the sine wave voltage. The LED is shine with extinguish during time with a specific frequency.

For digital detection, we deal with data about EOG from polysomnography and used scoring of physician as standard. During monitoring brain activity of sleep there are several different sleep stages, one of them are REM signals showing dominant rapid movement of eyes which happens in so-called REM stage. According to the latest studies, the REM phase is divided into tonic and phasic. Within the phasic part of REM, rapid eye movements occur. In addition to changes in eye movement activity, this phase also includes changes in EEG activity. In order to properly investigate the purpose of this REM phase, it is necessary to isolate it well. For robustness, it is advantageous to use thousands of available PSG records. Here is necessary the automatic detection of the phasic part of REM based on eye movements. This thesis describes a simple but robust tool for the detection of eye movements, which in the future could be springboard for an automatic REM phasic detector.

2 Overview of the current state of the art

EOG:

In 1951 Elwin Marg described and named electrooculogram for a technique of measuring the resting potential of the retina in the human eye. [1]

Electrooculography is a diagnostic method of recording the electrical activity of eyes. It is based on the fact that an eye cornea has positive charge and retina has negative charge (so the eye bulb represents an electrical dipole). This enables the genesis of the potentials which cause changes in electrostatic field when the eye changes its position. The dipole is orientated in accordance with the front-end axis of the eye bulb and its direction minimal deviates from the optic eye axis. During the movements of the eye bulb into sides, the size of the charge changes according to the size of the rotation. The EOG signal is recorded using the electrodes placed around the eyes which can be connected either in bipolar or unipolar positions. [2]

The EOG signal belongs to the group of random (non-stationary) signals, as their spectral activity vary over time [3]. Its frequency ranges from 0.5 to 15 Hz and is characterized with a significant DC component. Values of the amplitude do not exceed mV range, but usually are lower than 2 mV (around 50–3500 μV).The change of the voltage is caused by the 1-degree change in view angle. [4]

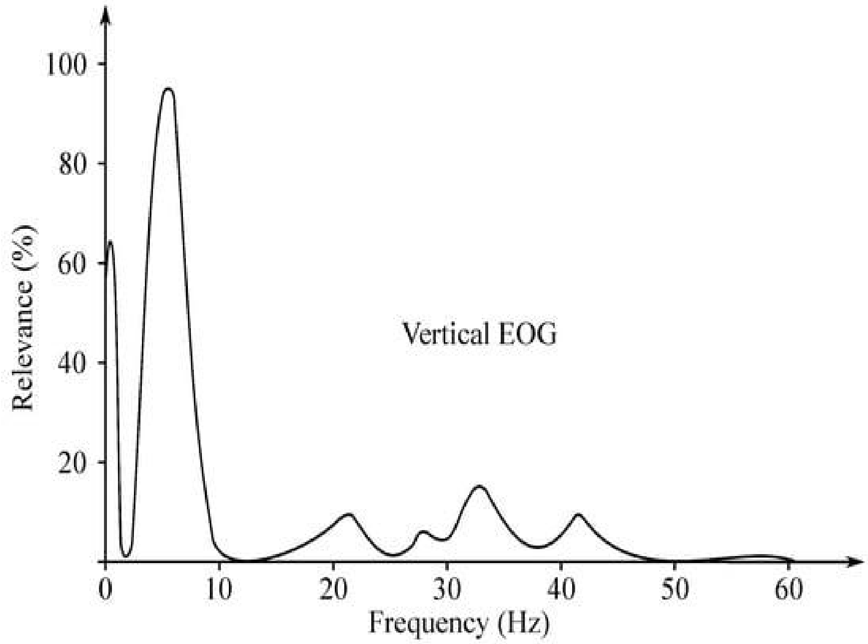

Figure 2.1: example EOG spectrum during relaxation

In some cases, the EOG is a useful tool applied for the diagnostics purposes of inherited muscular diseases [5]. One of the signals that can be detected using the EOG method is the eye blink. In some cases, this signal is considered as the desired one, often used as means of communication with paralyzed individuals. [6,7]

In the EOG signal, the most common artifacts are baseline drift, neck movement (resulting in the low-frequency changes in the signal), muscles potentials around the eyes (having the maximum power in the frequencies above 20 Hz), eye blinking (random potential differences in frequency range of 0.5 to 3 Hz), and saccades. Moreover, the simultaneous activity may cause the electrodes to lose contact or move on the skin surface, which decreases the data quality in a significant way [8,9]. But in some cases we also need specific signal like eye blinks.

Human eye blinks are related to the processing of cognitive tasks in the brain [10]. Thus, this can be used, for example, to determine and monitor attention, fatigue, or stress state of a person [11] or to determine driver and operator fatigue or mental load in vehicles and machines and thus minimize the risk of accidents [12]. Blinking can also provide information about a person's mental or emotional state and thus improve human-machine interaction [13]. In combination with other measurements such as heart rate, blinking can also be used in remote healthcare or telemonitoring apps to support diagnosis. [14]

Comparator:

Eye movement detection can be implemented in analog way or digitally as data post-processing. Since the amplitude during eye blinks have much higher amplitude than the other biological signals on the head, a comparator can be used to compare the reference threshold voltage and eye blinks in EOG signal from EOG detect circuit.

A comparator is an active electronic component. For ideal comparator, there are two leads which can connected with power supply. If we connect both two leads with power supply, these two voltage should be opposite and same value. There are two voltage input in it, one is non-inverting input marked as symbol ‘+’ , the other one is inverting input marked as symbol ‘-’ . This electronic component can compare two input voltage. If we connect two power supply, the output value is equal to positive power supply when non-inverting voltage is higher than inverting voltage, the output value is equal to negative power supply when inverting voltage is higher than non-inverting voltage. The positive power supply is usually marked as $+V_{ss}$ and negative power supply is usually marked as $-V_{ss}$.

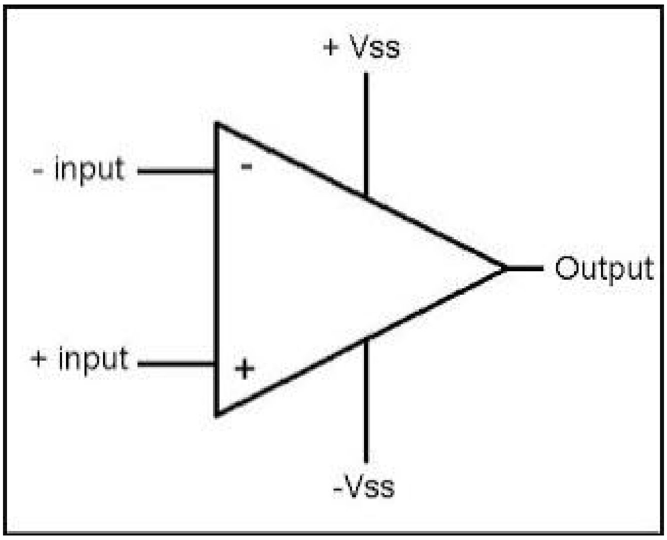

Figure 2.2:symbol of comparator, '-' and '+' is inverting and non-inverting input pin, $+V_{ss}$ and $-V_{ss}$ is positive and negative power supply [15]

There are two configurations to make output voltage, we can use emitter output pin or collector output pin as output voltage, but the connection is different. For emitter output, when inverting input voltage is higher than non-inverting input voltage, the emitter output pin 7 should show positive power supply, otherwise it shows negative power supply.

Polysomnography and sleep:

In sleep polygraph monitoring, comparators can be used to process and analyze signals collected from sleep monitoring equipment. For example, comparators can compare different sensor readings such as brain waves, heart rate, breathing rate to determine sleep stages or diagnose sleep disorders.

Polysomnography (PSG), a type of sleep study [16], is a multi-parameter study of sleep and a diagnostic tool in sleep medicine. The test result is called a polysomnogram, also abbreviated PSG.

Polysomnography is used to diagnose, or rule out, many types of sleep disorders, including narcolepsy, idiopathic hypersomnia, periodic limb movement disorder (PLMD), REM behavior disorder, parasomnias, and sleep apnea. Although it is not directly useful in diagnosing circadian rhythm sleep disorders, it may be used to rule out other sleep disorders. The use of polysomnography as a screening test for persons having excessive daytime sleepiness as a sole presenting complaint is controversial.[17,18]

The EOG in polysomnography usually uses two electrodes; One that is placed above 1 cm of the outer canthus of the right eye and one that is placed below 1 cm of the outer canthus of the left eye. These electrodes pick up the activity of the eyes in virtue of the electropotential difference between the cornea and the retina (the cornea is positively charged relative to the retina). This helps to determine when phasic REM sleep occurs, of which rapid eye movements are characteristic, and also essentially aids in determining when sleep occurs.

Sleep is a natural psychosomatic state which, compared to wakefulness, is accompanied by a significant reduction in mental and physical activity, especially the activity of the motor and sensory system. There is a kind of "disconnection" of the brain and psychic activity from external reality [19] . The need and structure of sleep change throughout life.

Sleep can be divided into two basic phases, first is REM (rapid eye movement) phase which is a phase characterized by rapid eye movement. The other one is NREM (non- rapid eye movement) which is a phase without eye movements. About 4 cycles (REM/non-REM) occur during the night. Spontaneous awakening usually occurs in REM sleep.

During sleep in the REM phase, we are accompanied by involuntary eye movements, the recording in the EEG is irregular, given by a combination of delta and beta activity. The muscle tone is lost, sympathetic activity predominates, heart rate and blood pressure increase. On the contrary, GIT (gastrointestinal) motility decreases. We will have faster breathing. The dream phase also appears in REM period. [20]

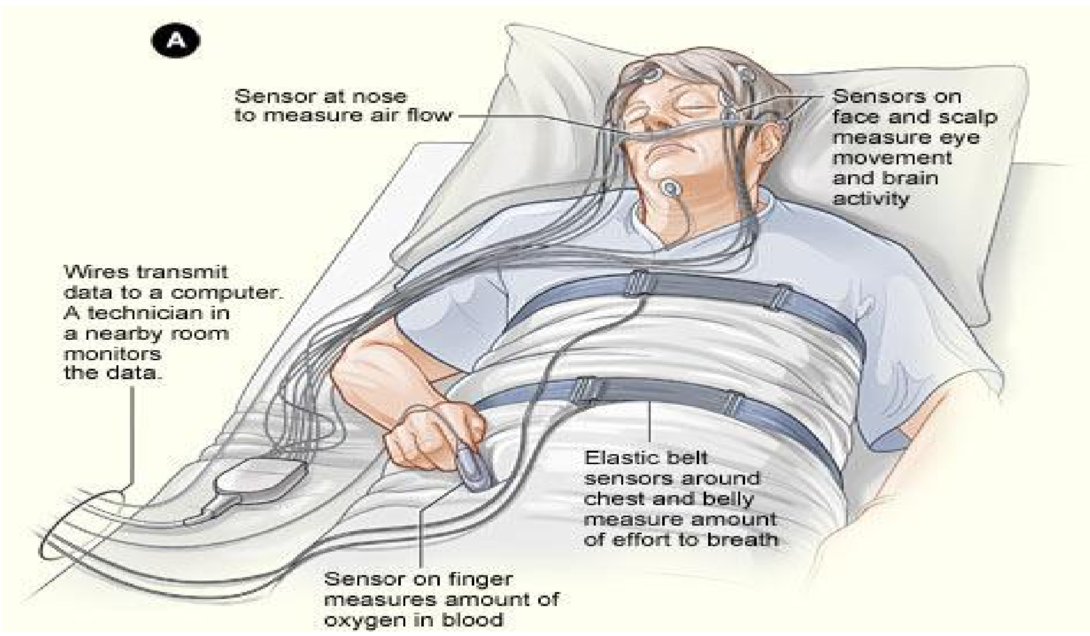

Figure 2.5: sensors placement of polysomnography measuring different signals [21]

Automatic classifier evaluation – ROC analysis:

For a suitable setting of the automatic detector, it is necessary to adjust the value of the parameters, such as the detection threshold. The tool that will allow finding the optimal threshold is ROC analysis. A receiver operating characteristic curve, or ROC curve, is graphical plot that illustrates the performance of a binary classifier model (can be used for multi class classification as well) at varying threshold values.

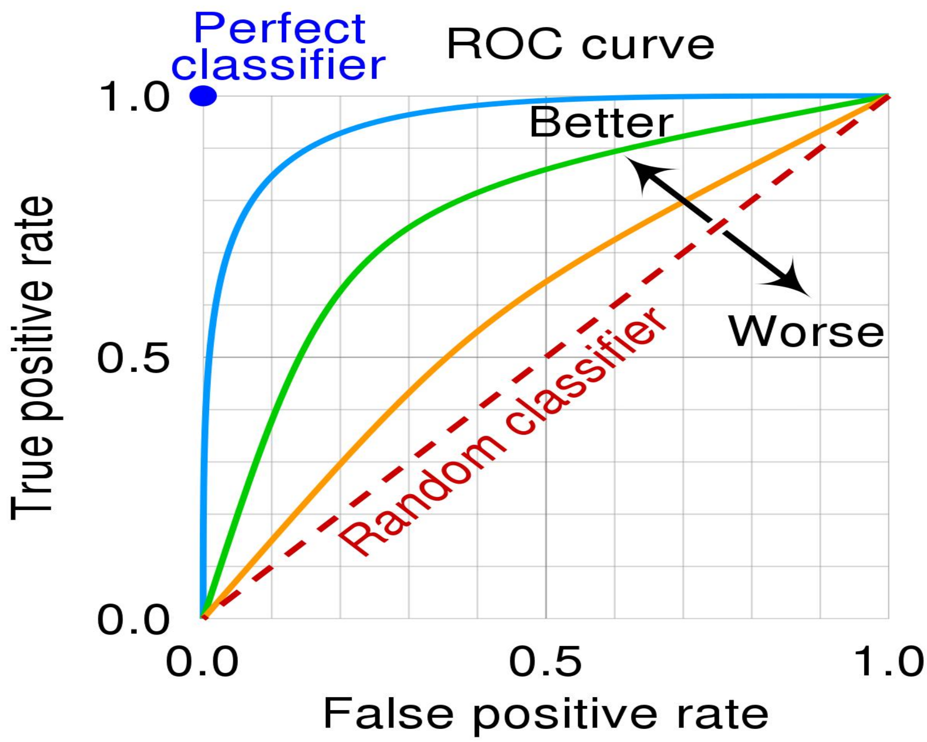

Figure 2.6: example of three ROC curves [22]

In figure 2.6 there are three different blue, orange, green ROC curves and random classifier as diagonal, x axis is false positive rate and y axis is true positive rate, the top left corner is perfect classifier.

3 Aims

The project is divided to analog detection and digital detection. The analog detection aimed to devise a circuit that will enable to detection of eye blinking. Firstly, we find threshold value of eye blinking using software ‘OpenBCI’. Put electrodes connected with OpenBCI chip to correspond position on face and measure EOG signal. Then put the data on ‘Matlab R2023b’ and use a filter then plot a time-amplitude graph to find the threshold voltage of blink. Finally make a circuit using resistors, comparator, leads, and light diode to contribute a circuit which can determine eye blinking.

The digital detection aimed to design a detector which can detect eye movement in EOG signal during REM phase when data are measured during polysomnography. First there were isolated REM sleep stages. Data were preprocessed and then was used designed detector of eye movements. Detector scoring and physician one were compared. Analysis for optimal parameters setting was done. Criterion sensitivity and specificity of our detector should be as high as possible. We do all of process using software ‘Matlab R2023b’.

4 Methods

4.1 Instruments and material

The project is divided into analog detection and digital detection, for digital detection we just use software 'Matlab version R2023b' but no instruments and materials. So, the instruments and material in analog detection are as following.

In the analog detection we use several instruments and components, the following table 4.1.1 shows list of instruments and components used in analog detection and their brand, code or parameters.

Name of instruments or components	Brand, code, parameters of instruments and components
Triple Output DC Power Supply	OWON ODP6033
Bread board	MODEL:ZY-201
Digital multimeter	ProsKit MT-1232
LM 311 comparator	TEXAS INSTRUMENTS
LED	Green light
3 resistors	22 Ω,2200 Ω,100 Ω
wires	
OpenBCI board	chipKIT Cyton
Function generator	RIGOL LXI DG1022
Oscilloscope	OWON XDS3062A

Table 4.1.1: instruments and material used in lab and their information

4.2 Procedures

Analog detection:

For analog detection, firstly we connect 3 electrodes on the face, one electrode on forehead, the other two electrodes are above and below right eye, these three electrodes is connected with 3 wires and these 3 wires is connected to 3 channels of 'OpenBCI' chip Cyton.

To transfer signal to computer we use the software 'Open BCI' and a chip called OpenBCI Cyton boards, there are different types of chips which use different way to transfer data to computer. Cyton shield transfer data to computer through blue tooth protocol. The chip works like A/D converter at sampling frequency 250 Hz.

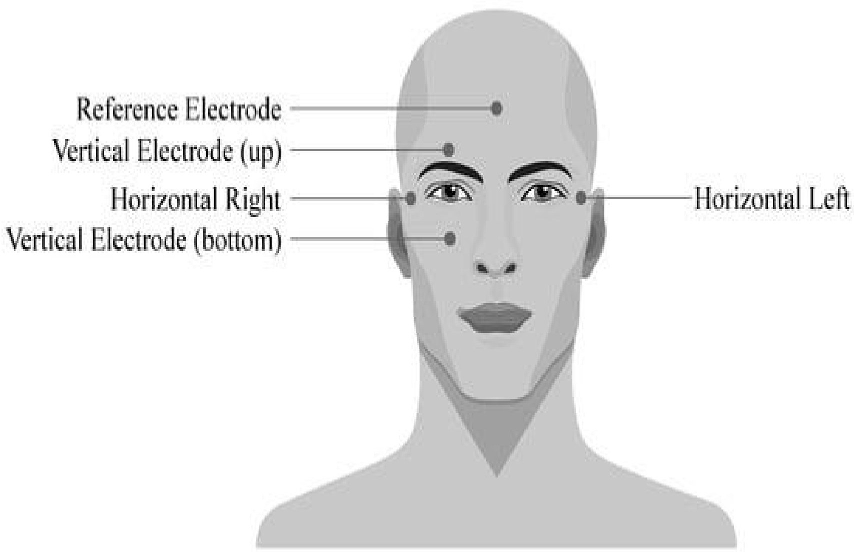

Figure 4.2.1: placement of EOG electrodes

We measured one minute EOG signal for all these three electrodes configuration and make some blinks during this period, then we can get data in a table from it.

Then use software ‘Matlab R2023b’ to plot graph of the data and smooth it by filter. First we import the data table in ‘Matlab R2023b’. Then use digital band-pass filter, the filter is made by colleague Vojtěch Šourek and plot code is made by my supervisor. The setting of sample frequency f_s is 250 Hz and setting of range of curve frequency is between 0.5 Hz and 8 Hz. Choose the 2 columns which are correspond to 2 electrodes above and below right eye. Then plot EOG curve using setting filter. Finally, we get following Figure 4.2.2. The x axis is number of samples from software ‘OpenBCI’ and the table, each gap of sample is 1/250 s. The y axis is voltage amplitude in mV, from the graph we can observe that threshold of eye blinking is higher than positive 50 mV and lower than negative 50 mV. In one blink the positive and negative amplitude is not necessary to be equal and each blink time is not same. In this figure we make 4 blinks.

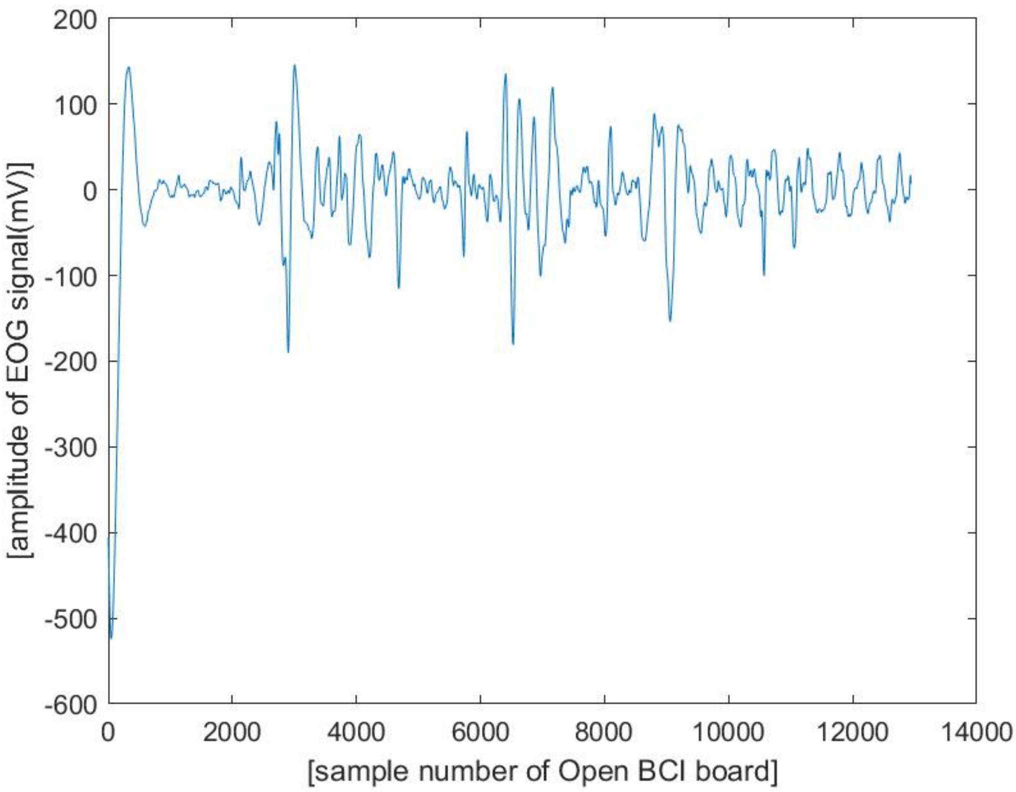

Figure 4.2.2: amplitude of measured EOG signal with blinks

In Figure 4.2.2, we can estimate the amplitude which is higher than 50 mV or lower than -50 mV show blinks. X axis is sample number of Open BCI board, Y axis is amplitude of EOG signal in mV. We can observe that there are several signature eye blinks, they appear at around 500 samples, 3000 samples, 6000 to 7000 samples, 9000 samples. The threshold value of eye blink is almost 50 mV. Sample frequency is 250 Hz.

The LM311 are voltage comparators that have input currents nearly a thousand times lower than legacy standard devices. They are also designed to operate over wider range of supply voltages: from standard ±15V op amp supplies down to the single 5V supply used for IC logic. [23]

LM311 is a single-channel comparator. When using it, connect the reference voltage and the compared signal voltage to its non-inverting and inverting input terminals, and its output is the result of the comparison. If you want the forward output result, pin 7 is connected to the positive power supply and pin 1 is the output. If the result is to be output in reverse, pin 1 is grounded and pin 7 is the open collector output. The function of balancing the mirror current of the reverse circuit is realized by connecting a potentiometer in the middle. The comparators are all open-collector outputs, without load resistance, they cannot output voltage signals. Dual power supplies can detect signals lower than 0, and single power supplies can only detect signals higher than 0. [24]

After getting the threshold, we construct a circuit in bread board using comparator LM311. For LM 311, pin 1 is emitter output, pin 2 is non-inverting input and pin 3 is inverting input, pin 8 is positive power supply. Then we use some passive electronic components like resistors, light diode, LM311 comparator to contribute a circuit and connect it with power source, function generator and oscilloscope. Set voltage as 5 V at both channel 1 and channel 2 of power source instrument. Then connect negative port of channel 2 with positive port of channel 1, these two points work as 0 V, negative port of channel 1 work as -5 V, which means we make a symmetrical power supply. Connect the positive port of channel 2 which is 5 V to positive marked column of bread board and connect 0 V to negative marked column of bread board, we can regard 0 V as ground. Each hole at these two columns has same voltage 5V and 0V. In the middle of bread board there are two blocks, each hole in a line of a bock show same voltage, the two blocks ca be also connected.

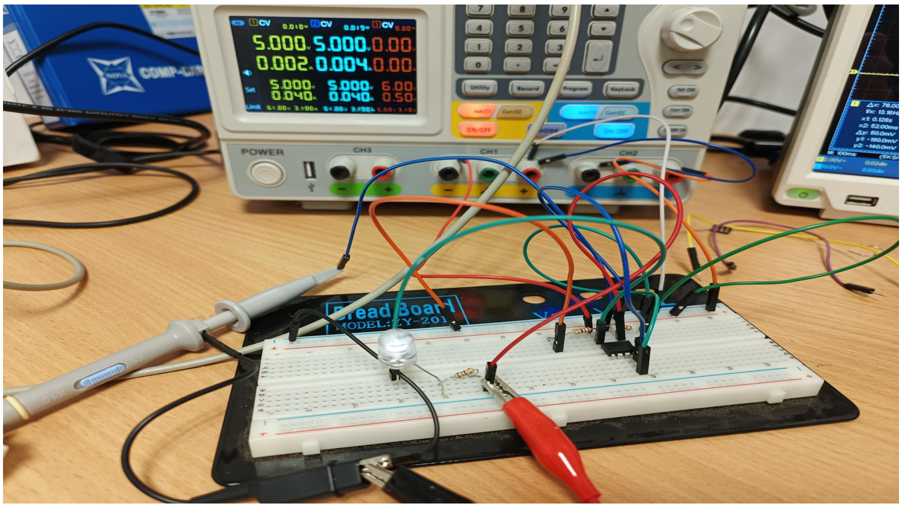

Figure 4.2.3: picture of constructed circuit and symmetrical power supply

Comparator is an active electronic component so it should be connected with power supply, pin 8 and pin 4 are for positive and negative power supply $+V_{cc}$ and $-V_{cc}$. Put 5 V which is at positive marked column of bread board to pin 8 as $+V_{cc}$.Put the wire of -5 V to pin 4 as $-V_{cc}$.

In non-inverting pin we connect to function generator, the setting is 0.2 V peak to peak voltage and 2 Hz sin wave, phase shift is 0. After that we should choose two resistors R_1 and R_2 to make voltage divider which can realize about 50 mV between them. In our lab we choose R_1 =2200 Ω and R_2 =22 Ω. So before inverting input pin we connect with this voltage divider by connecting the part between R_1 and R_2 and the other side of R_2 is connected to negative marked column of bread board which is ground. If putting the voltage at positive marked bread board 5 V to the other side of R_1, a 49.5 mV should generate at inverting port, this is just slightly lower than the threshold. Use digital multimeter to measure voltage at inverting input pin with power source on, the real value is 49.7 mV.

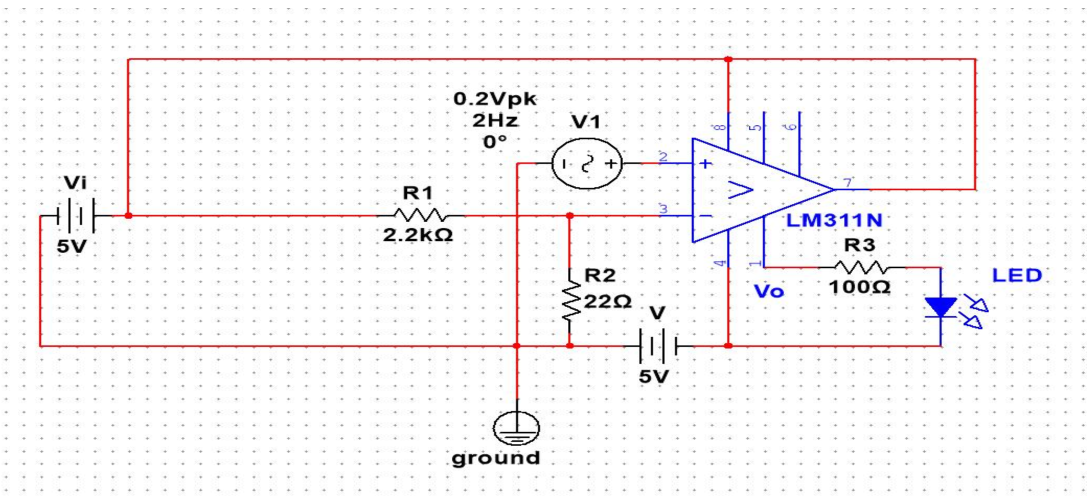

Figure 4.2.4: graph of connected circuit,V_i is power source channel 2 voltage, V is power source channel 1 voltage , V1 is sin signal from function generator, V_o is emitter output voltage of LM311N comparator

According to voltage divider equation:

$$V2 = Vi \frac{R2}{R1+R2} = 5 \frac{22}{22+2200} \text{ V} = 0.0495 \text{ V} = 49.5 \text{ mV} \qquad (4.2.1)$$

Where V2 is voltage at inverting input pin of comparator, R1 is the resistor used in voltage divider which is connected with power source, R2 is resistor connected to ground. A protective resistor R3 is connected after emitter output pin 1. We use resister value 100 Ω and a green light diode is connected with that resistor. The output voltage at emitter output channel is marked as V_o. Finally, the output of light diode should be connected to -5 V and collector output pin 7 should be connected to 5 V. The electronic circuit connection is shown in Figure 4.2.4.

Open the power supply, function generator, oscilloscope and observe the state of light diode, use oscilloscope to monitor output voltage from emitter output pin 1. Keep frequency and peak to peak voltage of function generator, move highest peak and lowest peak and observe state of LED and output signal on oscilloscope.

Digital detection:

For digital detection, we got 10 files from polysomnography in sleeping laboratory which show 10 different sets of EOG signal data of two eyes from whole night and scoring of eye movements from physician. The sampling frequency of measurement was 250 Hz. First step was importing of the polysomnography data and finding the EOG channels.

Next step we index the amplitude samples during REM sleep phase window from whole night EOG data and filter it, then make help vectors of REM and physician. The polysomnography detect REM as a window of 30 seconds, the samples at 15 seconds before and after the detected samples during REM sleep phase are also regarded as REM sleep phase. After getting the final EOG segment during REM sleep phase window, we use filter which filter signal frequency above 6 Hz to smooth the final EOG data during REM sleep phase window and get a filtered EOG data. After this we use filtered data to make a help vector of REM sleep phase, this help vector just shows position of REM sleep phase. And then load scoring of physician and make a help vector of scoring showing period between each REM start and REM end.

Next step we make our own detector and help vector of our own detector. Make threshold from 0.1 to 2 and step is 0.1 multiplying by mean value of absolute value of filtered EOG signal during REM sleep phase, so we get 20 thresholds, from 0.1 to 2 is clear enough to watch the peaks of proper threshold and we can identify the difference in result. Divide filtered EOG data during REM sleep phase window to several data with number of detected windows, then detect peaks which show rapid eye movement during each window, so we can get time sample with number of detected windows. Each of these data start with sample of their window but not original whole night samples, so then we merge all time data together and compensate time shift. After that we can make another help vector of our own detector showing detected eye movement positions.

Then find true positive, true negative, false positive, false negative values at each threshold. From these 4 values we can calculate sensitivity and false positive rate under different thresholds, and plot ROC graph. The following table show description of these 4 values in our detection.

Sample	Own scoring	Physician scoring
TP	YES	YES
TN	NO	NO
FP	YES	NO
FN	NO	YES

Table 4.2.1: Description of TP, TN, FP, FN in our detection

In table 4.2.1 we can see TP is the samples which both our detector and physician detected. TN is the samples which neither our detector nor physician detected. FP is the samples which our detector detected but physician did not detect. FN is the samples which our detector did not detect but physician detected.

To find these 4 values, index data from help vector of physician and our own detector which are just during REM period and get 2 new help vectors. Sum them together and we get a merged help vector. From it we can get true positive because both physician and us detect this sample, and get true negative because neither physician nor us detect this sample. Use rest of samples together with 2 new help vectors we can count false negative and false positive and verify these values.

The ROC curve is the graph of the true positive rate (TPR) with corresponded positive rate (FPR) at each threshold, so the curve is the sensitivity as a function of false positive rate. The true-positive rate is also known as sensitivity, recall or probability of detection. The false-positive rate is also known as probability of false alarm [25] and equals (1 − specificity). The ROC is also known as a relative operating characteristic curve, because it is comparison of two operating characteristics (TPR and FPR) as the criterion changes. [26]

The number of true positive, true negative, false positive, false negative was summed and check it is equal to REM period. Then calculate sensitivity and specificity of each threshold. The sensitivity is calculated by true positive value over sum of true positive and false negative value of corresponded threshold. The specificity is calculated by true negative value over sum of true negative and false positive value of corresponded threshold. Then the false positive rate is calculated by (1 − specificity).

Finally we plot ROC graph, calculate AUC area and then plot a graph of sensitivity and corresponded false positive rate. Plot a green line showing diagonal in the same graph. Find best sensitivity and false positive rate in graph and their corresponded threshold, this threshold is the best threshold for our detector.

5 Results

Analog detection:

For analog detection after finishing the circuit which is constructed by Figure 4.2.4, we open and set all the devices. We can see the LED shine and extinguish with specific frequency. Then change high and low limit of sine wave signal in function generator, the frequency of the sine signal should be always 2 Hz and peak to peak voltage should be always 200 mV. We find 5 pairs limit values when light start shine, 33% duty cycle, 50% duty cycle, 66% duty cycle and shine all the time.

State of LED / Peak voltage limit	LED start to shine	33% duty cycle	50% duty cycle	66% duty cycle	always shine
Highest peak voltage limit (mV)	255	225	150	75	50
Lowest peak voltage limit (mV)	55	25	-50	-125	-150

Table 5.1: high and low limit of sine wave during different states of LED

The following graphs show oscilloscope interfaces of output signal. Regard the dotted line in horizontal as x axis and dotted line in vertical as y axis.

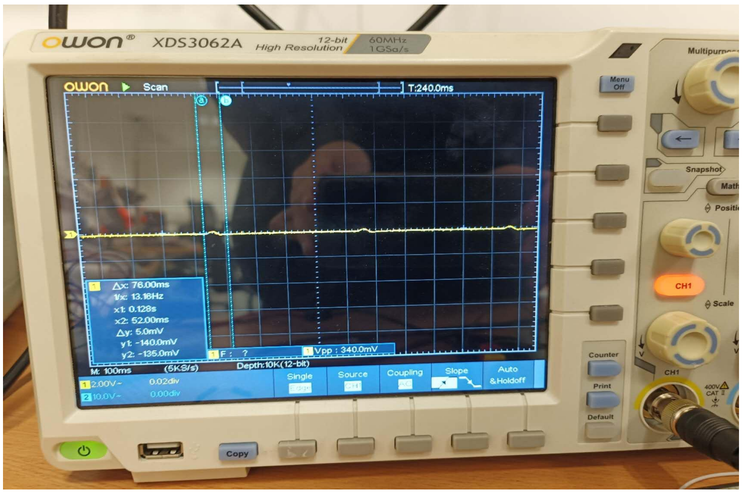

Figure 5.1: oscilloscope interface of output signal when the LED start to shine, one grid is 2 V in y axis and 100 ms in x axis

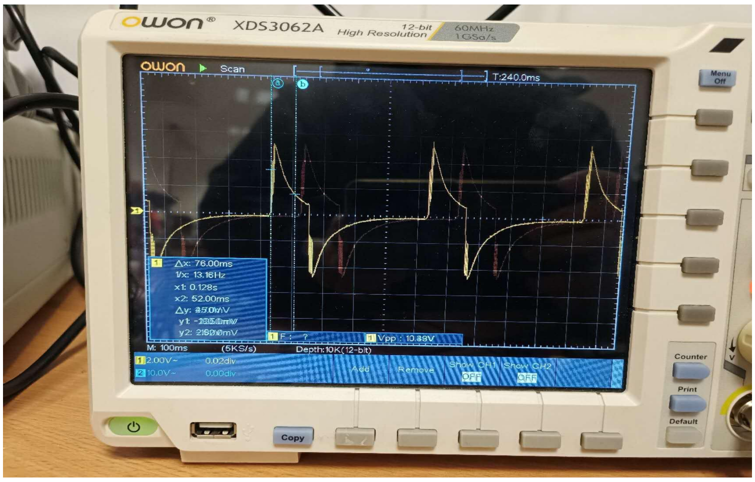

Figure 5.2: oscilloscope interface of output signal when 33% duty cycle, one grid is 2 V in y axis and 100 ms in x axis

Figure 5.3: oscilloscope interface of output signal when 50% duty cycle, one grid is 2 V in y axis and 100 ms in x axis

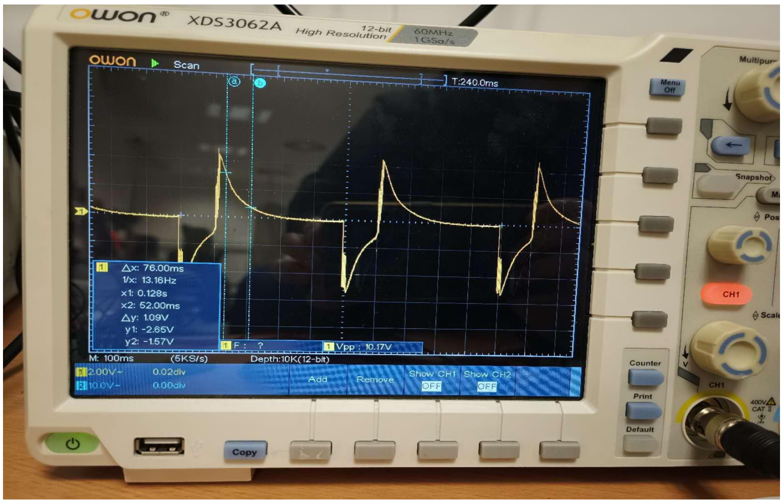

Figure 5.4: oscilloscope interface of output signal when 66% duty cycle, one grid is 2 V in y axis and 100 ms in x axis

Digital detection:

In digital detection, for left eye and right eye of each patient, there are different number of detected rapid eye movement samples, the following table shows the number of detected rapid eye movement samples of our detector and scoring of physician.

patient	Left eye of our detector	Right eye of our detector	Scoring of physician
1	8968	5382	1069
2	10581	9459	11010
3	4600	4500	11690
4	6497	5700	4618
5	1365	1441	4162
6	5813	4994	34326
7	2948	3097	72035
8	3157	3722	41037
9	4170	4185	2384
10	1294	973	5063

Table 5.2: detected rapid eye movement samples of our detector and scoring of physician

According to calculation of table 5.2, for left eye the mean value of number of detected rapid eye movement samples of our detector is 4939.3, for right eye the mean value of number of detected rapid eye movement samples of our detector is 4345.3, the mean value of number of detected rapid eye movement samples of physician is 18739.4. For left eye the standard deviation of number of detected rapid eye movement samples of our detector is 3076.1, for right eye the standard deviation of number of detected rapid eye movement samples of our detector is 2387.1, the standard deviation of number of detected rapid eye movement samples of physician is 23259.0.

From each ROC graph we can find the best point and their corresponded threshold. The following graph is ROC graph of left eye of first patient and its AUC value.

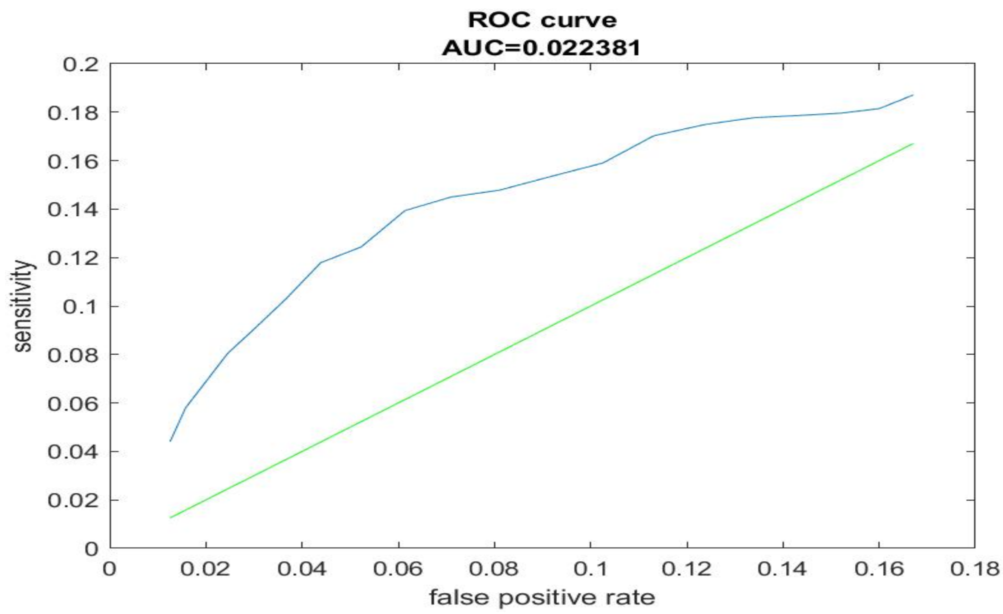

Figure 5.5: ROC graph of left eye of first patient

From figure 5.5 there are some discrete points and we can check their value. We find best point which is the nearest to top left corner. Figure 5.5 have the best point (0.0613, 0.1393) It means the best sensitivity in this graph is 0.1393 and the corresponded best false positive rate is 0.0613. Use sensitivity and false positive rate to find sequence of these two values, it is at twelfth element. Then find threshold of this position which show best threshold of patient of this detector, the threshold value is 44.5345. The title show calculated AUC area and the value is 0.022381. For each patient they have their own threshold value. ROC curves are all available in appendix B.

The following tables show the best sensitivity, best false positive rate, best threshold and its corresponded sequence in threshold vector of left and right eyes of each patient.

Patients	Best sensitivity	Best false positive rate	Best threshold	Sequence in threshold vector
1	0.1393	0.0613	44.5345	12
2	0.0948	0.0218	13.9050	12
3	0.0424	0.0118	17.2389	12
4	0.0864	0.0315	22.5096	12
5	0.1021	0.0290	18.4704	8
6	0.0456	0.0218	25.8057	8
7	0.0320	0.0209	9.8589	7
8	0.0351	0.0089	17.4767	10
9	0.0423	0.0128	12.2582	12
10	0.0341	0.0130	16.0510	8

Table 5.3: the best sensitivity, best false positive rate, best threshold and its corresponded position in threshold data for left eye of each patient

According to table 5.3, for left eye the best sensitivity is 0.1393, the smallest false positive rate is 0.0089, the highest threshold is 44.5345 and the lowest threshold is 9.8589.

Patients	Best sensitivity	Best false positive rate	Best threshold	Sequence in threshold vector
1	0.0346	0.1502	11.6052	4
2	0.0203	0.0583	4.8145	4
3	0.0209	0.0294	6.6388	5
4	0.0309	0.0581	9.8255	5
5	0.0124	0.1038	3.1927	1
6	0.0229	0.0312	19.4488	6
7	0.0279	0.0271	7.2828	6
8	0.0156	0.0282	5.5547	4
9	0.0239	0.0271	5.9196	6
10	0.0142	0.0254	8.8535	4

Table 5.4: the best sensitivity, best false positive rate, best threshold and its corresponded position in threshold data for right eye of each patient

According to table 5.4, for right eye the best sensitivity is 0.0346, the smallest false positive rate is 0.0254, the highest threshold is 19.4488 and the lowest threshold is 3.1927.

6 Discussion

Analog detection:

In analog detection, positive threshold value and negative threshold value appear within very fast time. The highest value is about 150 mV and the lowest value is about -200 mV, but in the device, the LED cannot shine with negative voltage, so we do not consider negative signal. According to figure 4.2.2, it is obvious that the blink voltage is higher than 50 mV, so we choose this value as a reference voltage.

In our configuration, the collector output pin should also be connected with the positive source voltage and we use the emitter output pin to detect the result. Because the two output pins are the collector and emitter of an NPN type bipolar transistor. This bipolar transistor serve as an open circuit when there is no current flow through the collector, so the emitter output pin does not work if the connector output pin does not be connected with a source, that is why we connected pin 7 to 5 V. For our lab, we just need to qualitatively compare inverting input voltage and non-inverting input voltage, so the LED state will show which input voltage is higher.

When keep the amplitude and frequency of the sine wave signal stable from function generator, we change just highest and lowest peak values. From the result, we can observe that the LED is always extinguished when an input sine wave is always higher than reference voltage 50 mV and the LED is always shines when input sine wave is always lower than reference voltage of 50 mV. Between these two ranges, the output signal can have different duty cycle.

The EOG detection we made just compare the voltage with 50 mV. There are some noise which will influence the result on real EOG signal, false positive and false negative results may appear, it is maybe caused by muscle activity, and there are also some delay in result because of slew rate of comparator.

Digital detection:

For digital detection, all of the left eye all have ROC curve above the reference diagonal green line. The best results we found are between the seventh and twelfth position of the threshold. That means these best threshold values are all between 0.7 to 1.2. These are used for multiplying by mean value of absolute value of corresponded EOG amplitude data during REM sleep phase. As they are really different, we can see for threshold of rapid eye movement in EOG signal of left eyes, each person has really big difference but has similar statistic characteristic, and all of thresholds are under 50 mV. The best sensitivity and best false positive rate for left eye of these patients are also have really big difference, so the detector has different performance for different left eye of patients. Therefore, the quality of the signal significantly affects the detector.

Most of right eye have ROC curve under the reference diagonal green line, some have half of ROC curve under and half of ROC curve above the reference diagonal green line, which means not good result. During REM sleep, eye tracings reveals rapid eye movements. These sharply peaked conjugate eye movements occur from both the right and left eyes during REM sleep, meaning both eyes move together in the same direction [27]. The bad result maybe was caused by different polarity of left eye EOG and right eye EOG during measurement of polysomnography, so the EOG signal had opposite sign relative to reference potential.

For one eye it usually moves in both directions, so it does not matter so much if we detect left or right movement. Our result just aims to show tendency of detector with different thresholds of minimum peak height, the result is not accurate maybe because of different electrode position or PSG references. In real detection of eye movement in EOG, there are several components like filter. For filtering it apply a band-pass Butterworth filter to isolate frequencies between 1 and 5 Hz. [28]

Compared with other detector, the result will be better if using more complex algorithm and technology. Researchers extract statistical features from filtered EOG signals common classifiers evaluated for eye movement detection include: K nearest neighbor, linear discriminant analysis, multinomial logistic regression, Naïve Bayes, decision trees, support vector machines (SVM). SVM has shown superior performance in terms of average accuracy. [29]

7 Conclusion

Our purpose of eye movement detection is divided into analog detection and digital detection. From analog detection, a circuit that can potentially show eye blinking was constructed. We observed after preprocessing of the EOG data the threshold voltage was about 50 mV.

In digital detection, we dealt with 10 files from polysomnography from the sleep laboratory. Each file represented a patient and could be divided into left eye and right eye. There were tested 20 thresholds for proposed detector of eye movements. Detector has parameters fixed minimum peak distance set to one second and minimum peak height constructed from these 20 thresholds. The ground truth was physician scoring. ROC analysis was used for the evaluation of our detector accuracy and estimate of threshold value. The detector had a different accuracy for each left eye of patients and each right eye of patients, the best sensitivity for two eyes and best false positive rate for two eyes were also different because EOG of two eyes had different polarity, the best result of left and right eyes may on different patients. In the future, it is advisable to focus on the montage of EOG channels and to design, for example, a semi-automatic detector that would better adapt to large intra-individual variability.

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Appendix A code for plot ROC graph of left and right eye

The following two files are code for plotting ROC curve of left and right eye:

final_thesis_code
1.m

final_thesis_code
2.m

Appendix B ROC graph of different patients and different eyes

Here are ROC graph of different patients and different eyes:

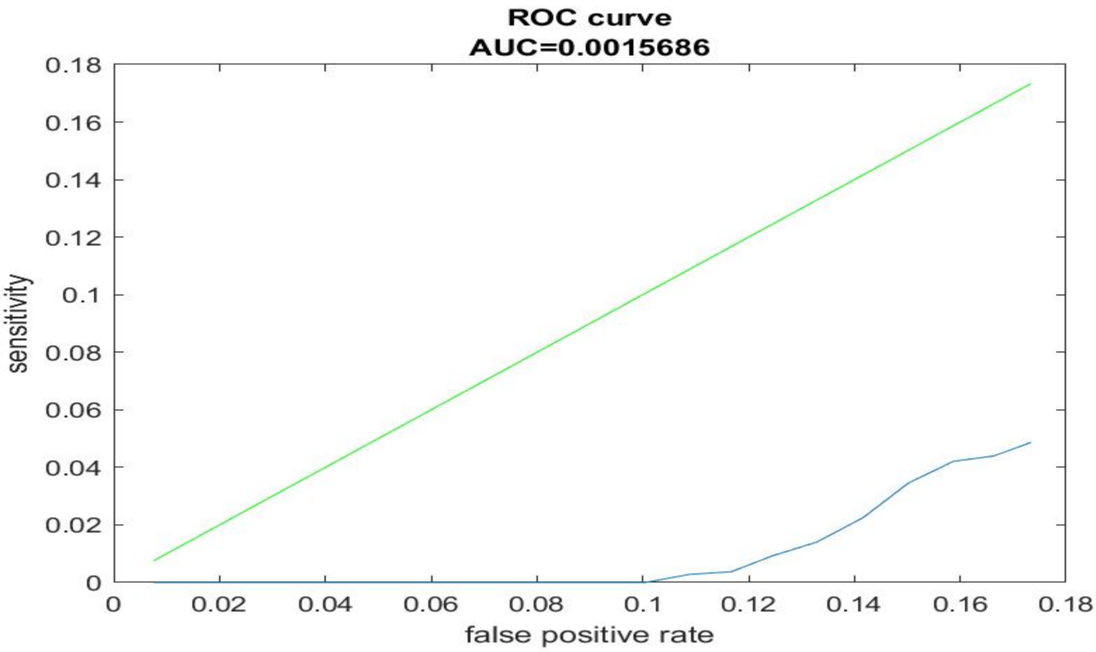

Figure B.1: Right eye of the first patient

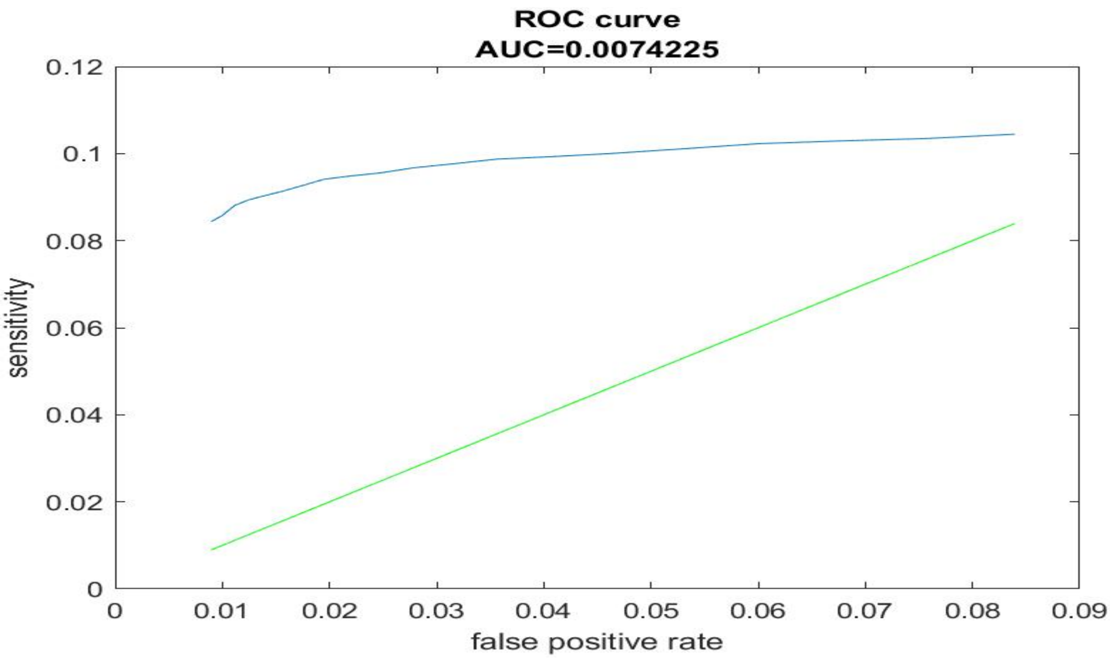

Figure B.2: Left eye of the second patient

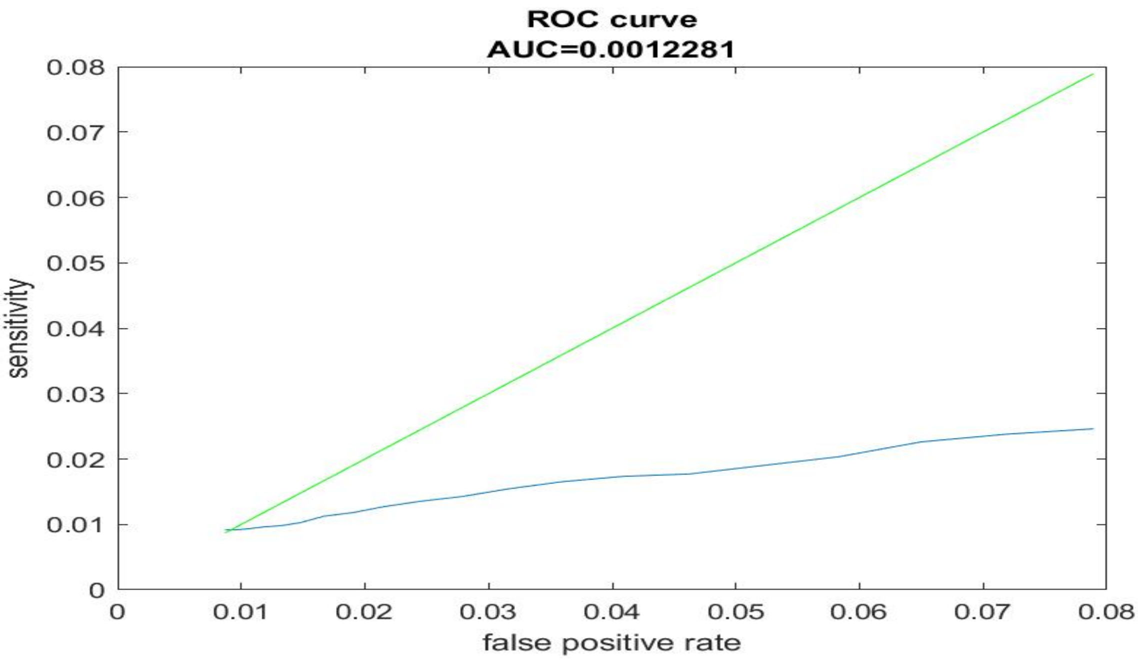

Figure B.3: Right eye of the second patient

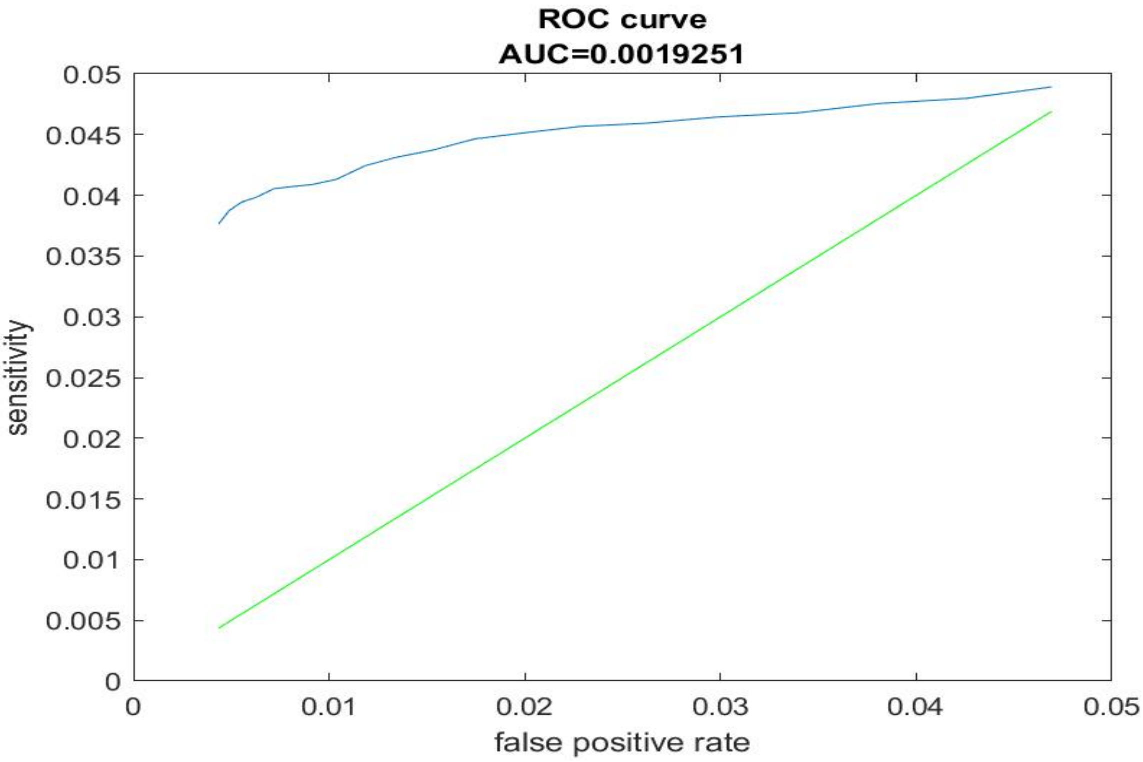

Figure B.4: Left eye of the third patient

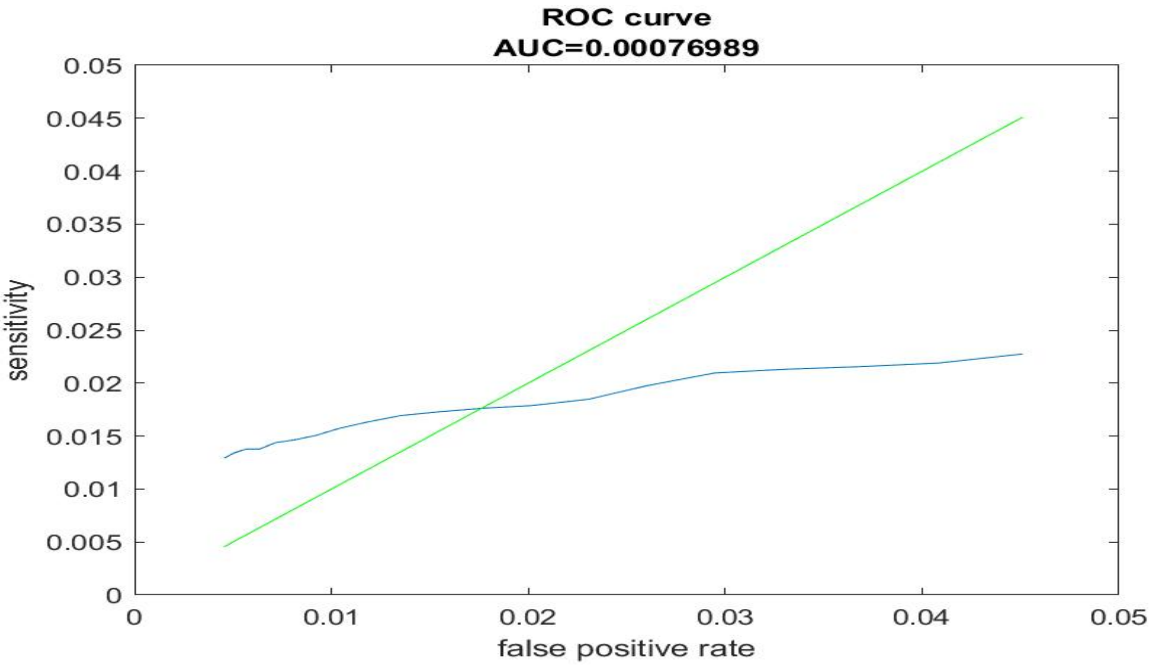

Figure B.5: Right eye of the third patient

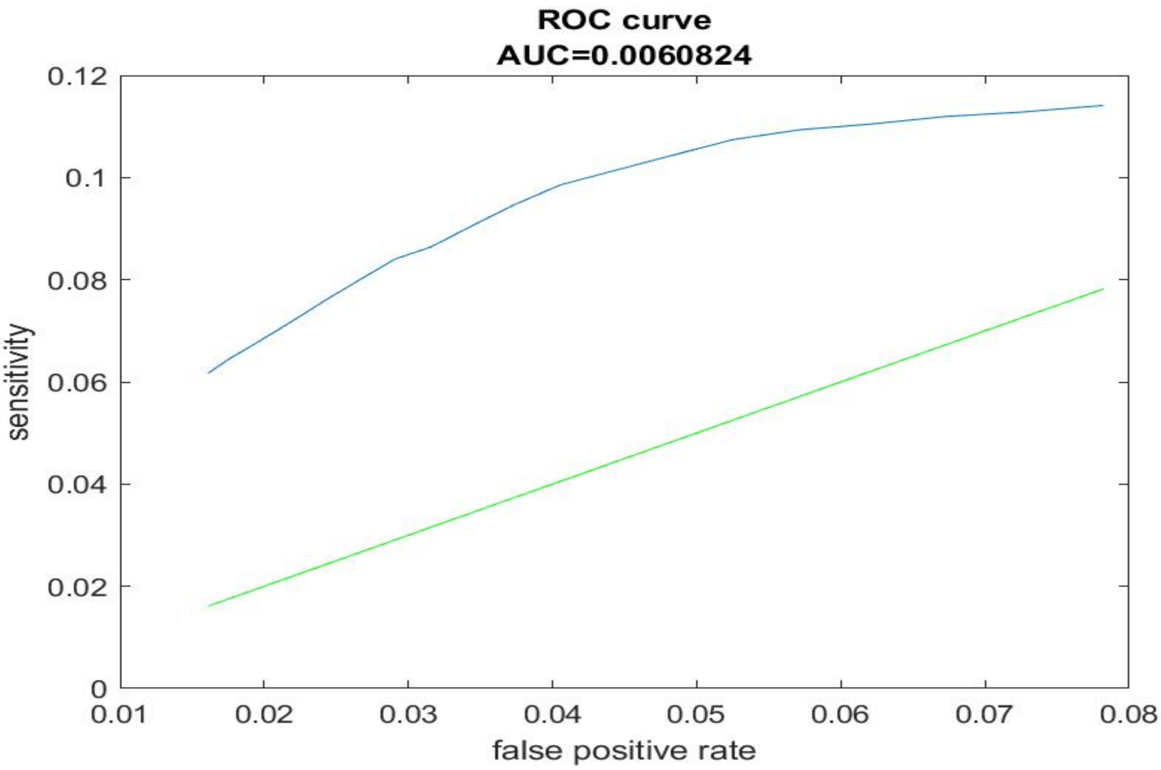

Figure B.6: Left eye of the forth patient

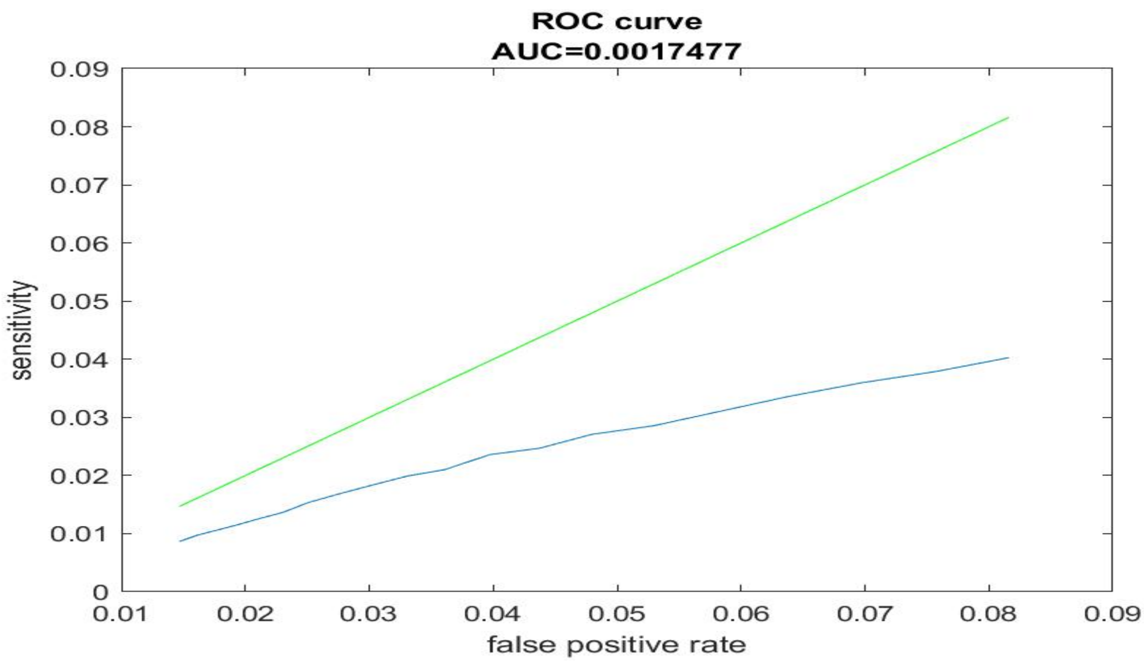

Figure B.7: Right eye of the forth patient

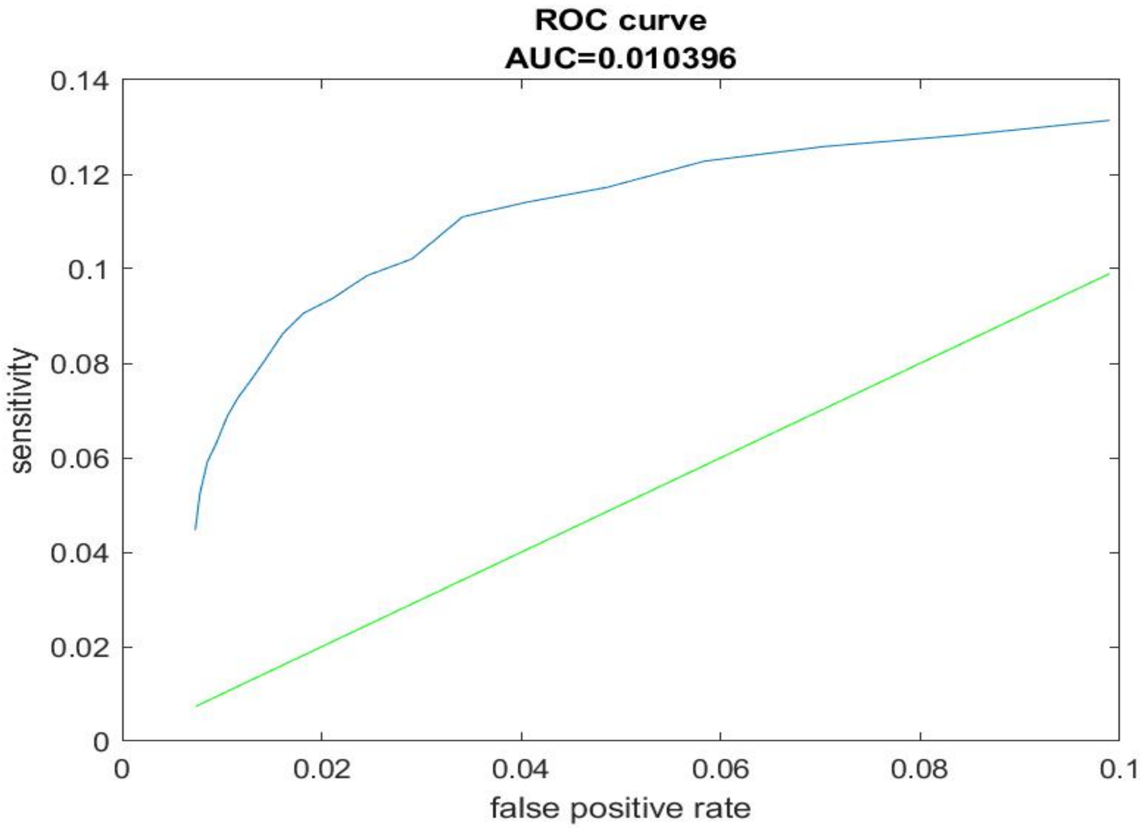

Figure B.8: Left eye of the fifth patient

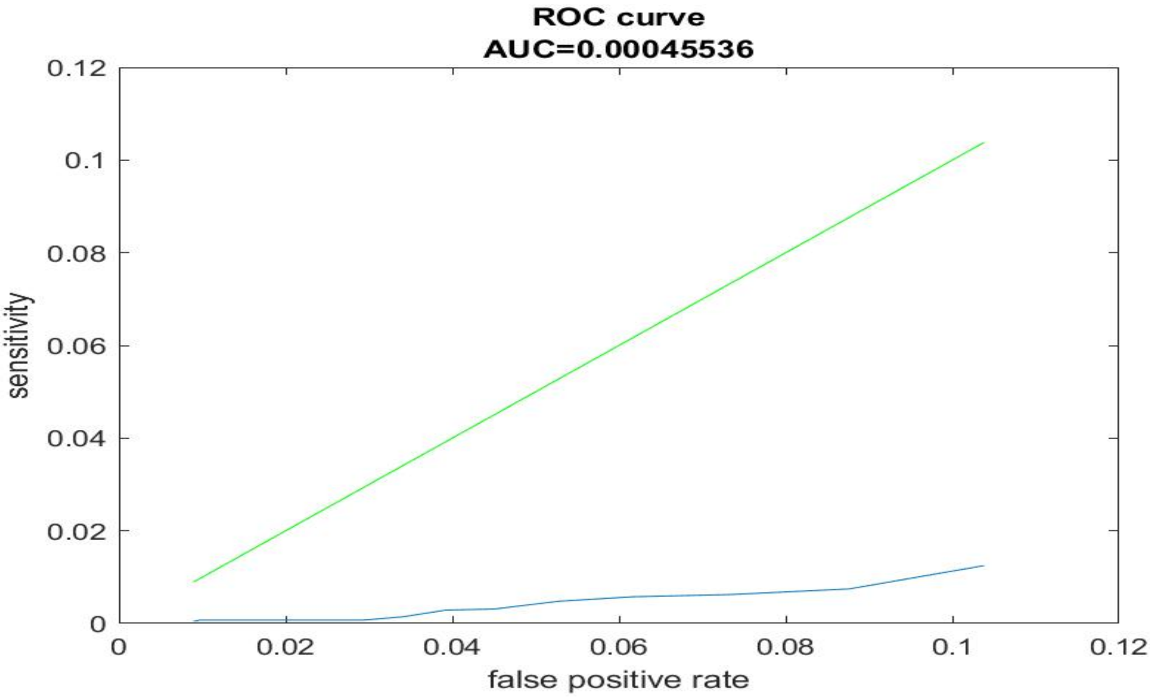

Figure B.9: Right eye of the fifth patient

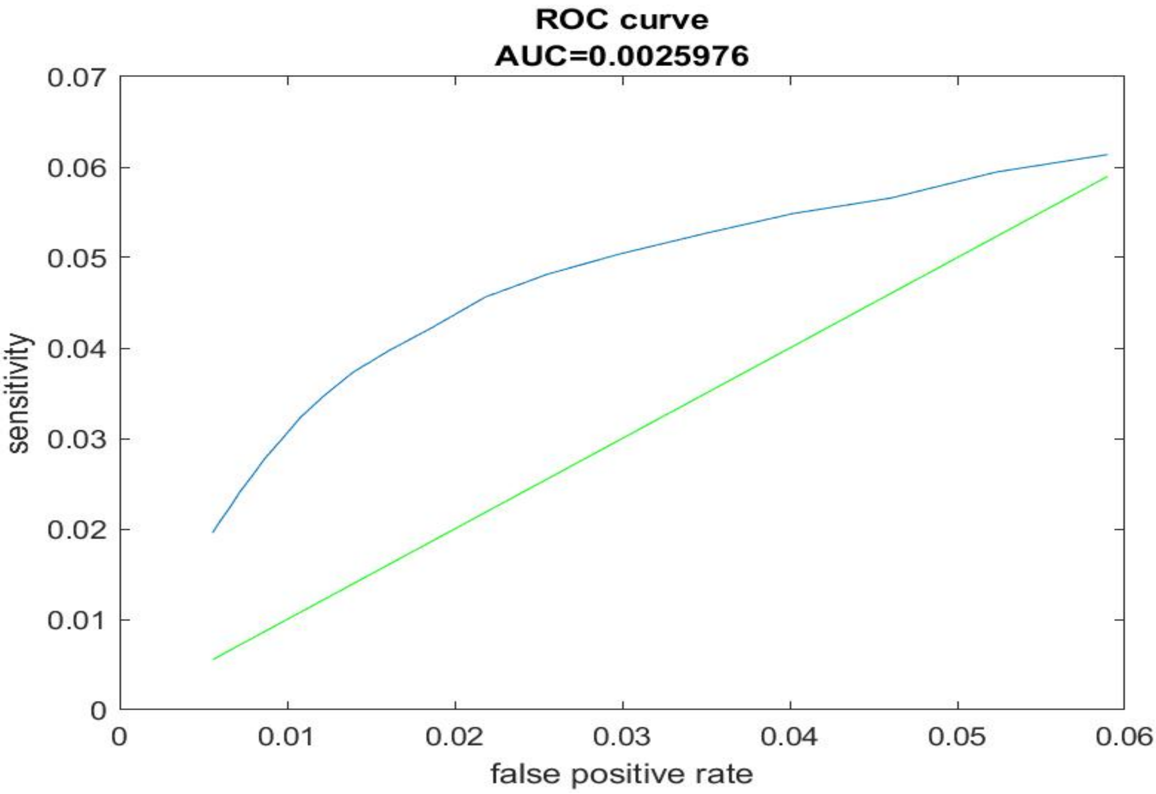

Figure B.10: Left eye of the sixth patient

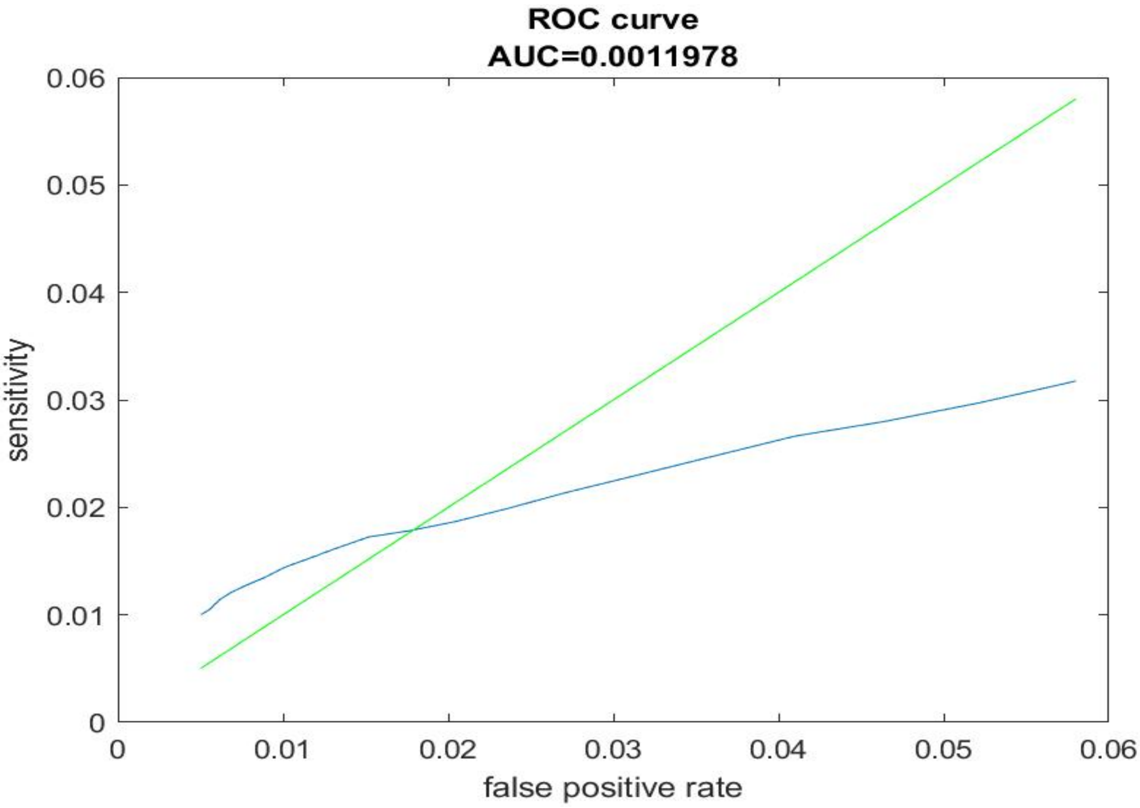

Figure B.11: Right eye of the sixth patient

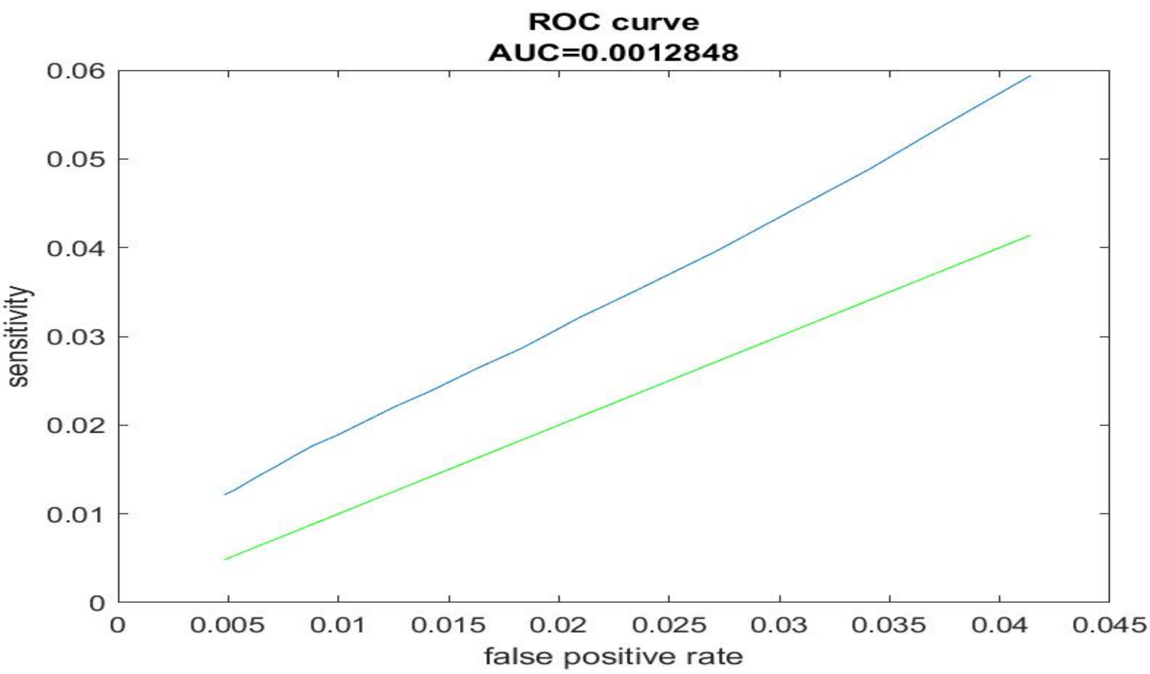

Figure B.12: Left eye of the seventh patient

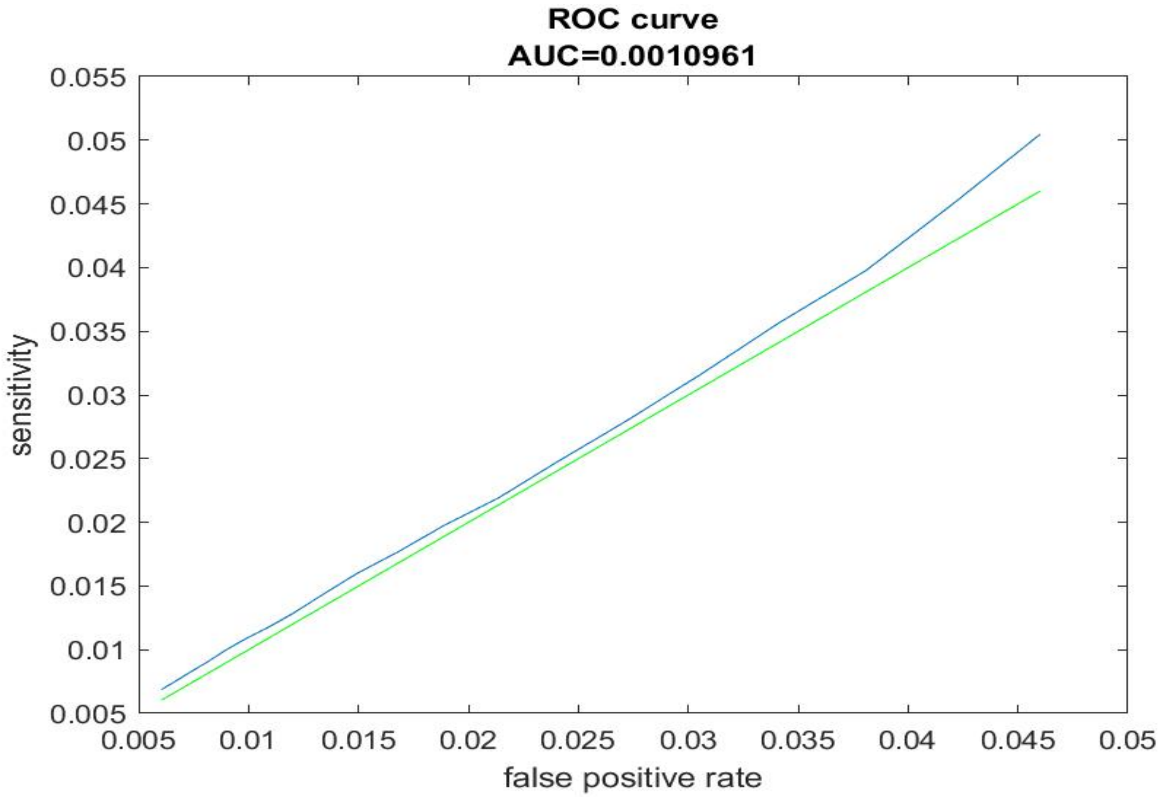

Figure B.13: Right eye of the seventh patient

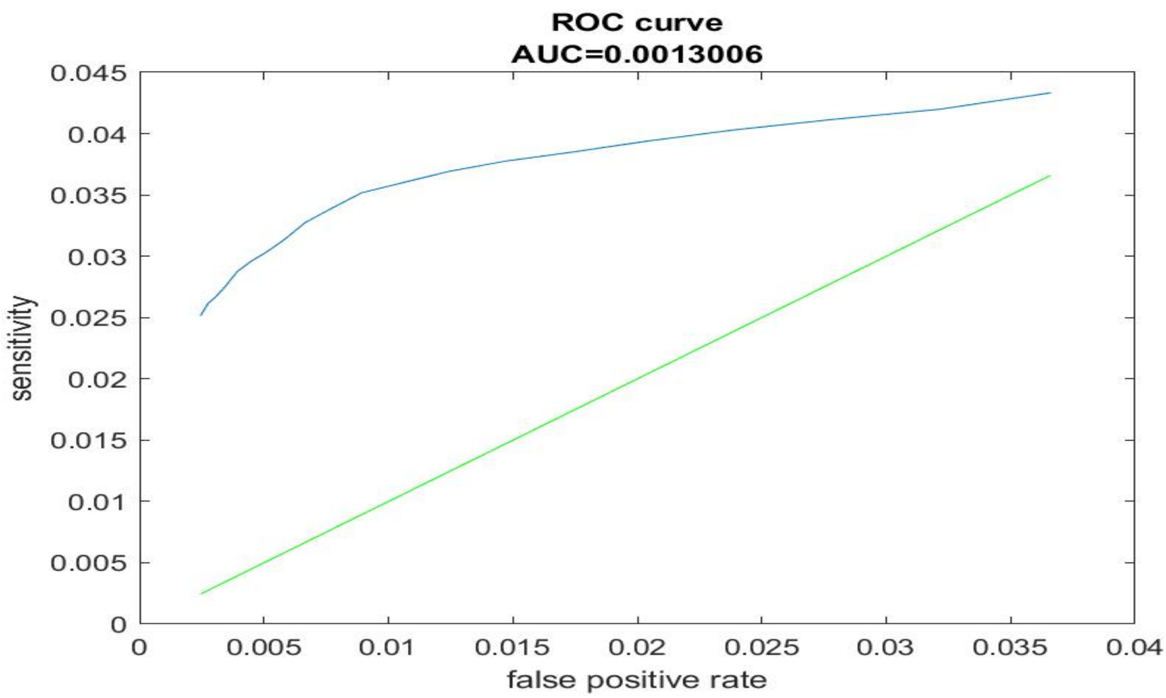

Figure B.14: Left eye of the eighth patient

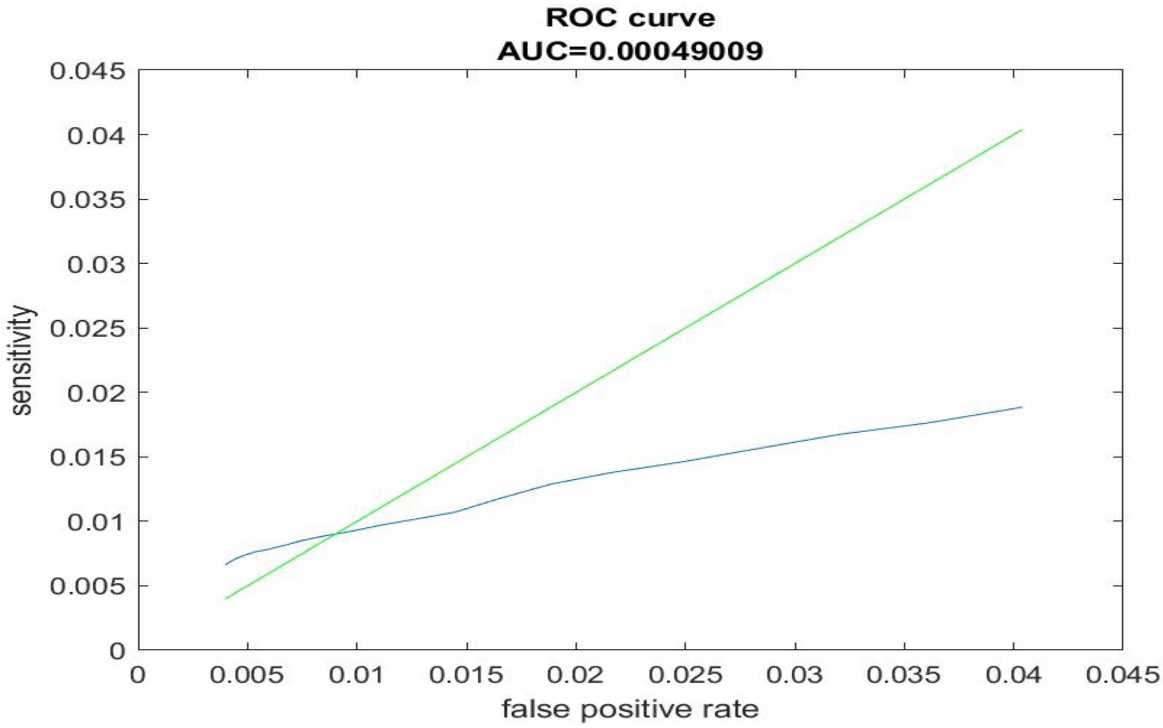

Figure B.15: Right eye of the eighth patient

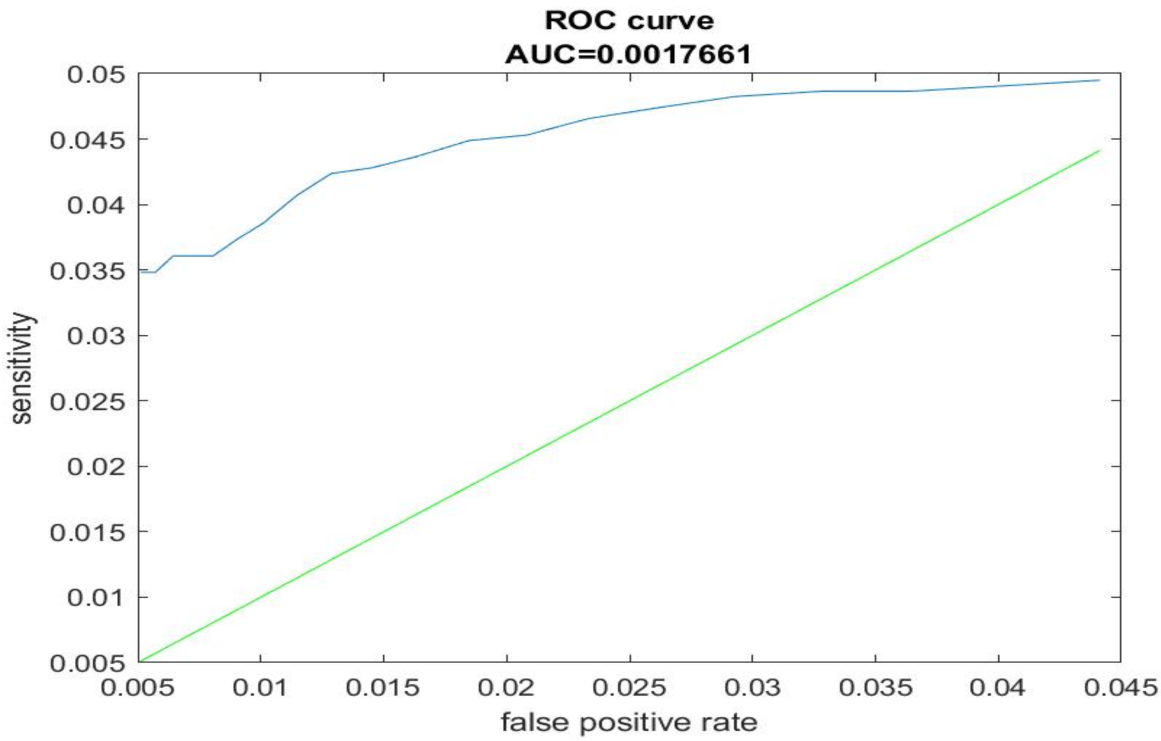

Figure B.16: Left eye of the ninth patient

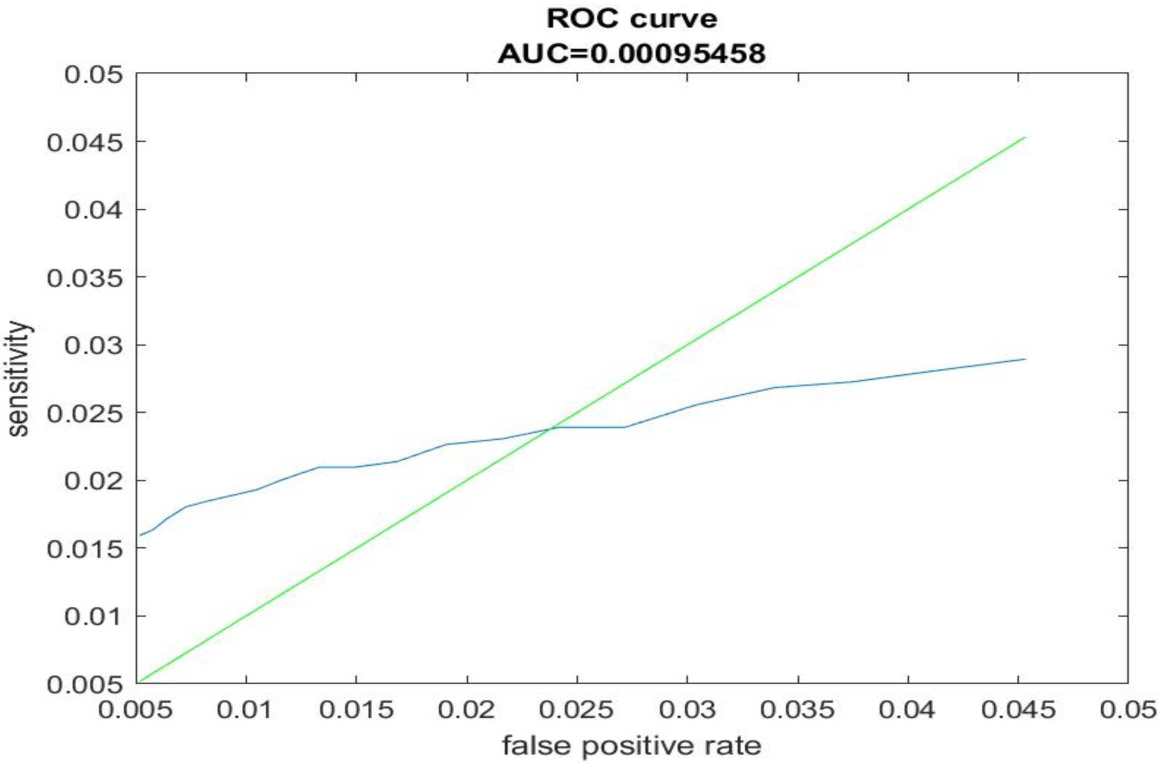

Figure B.17: Right eye of the ninth patient

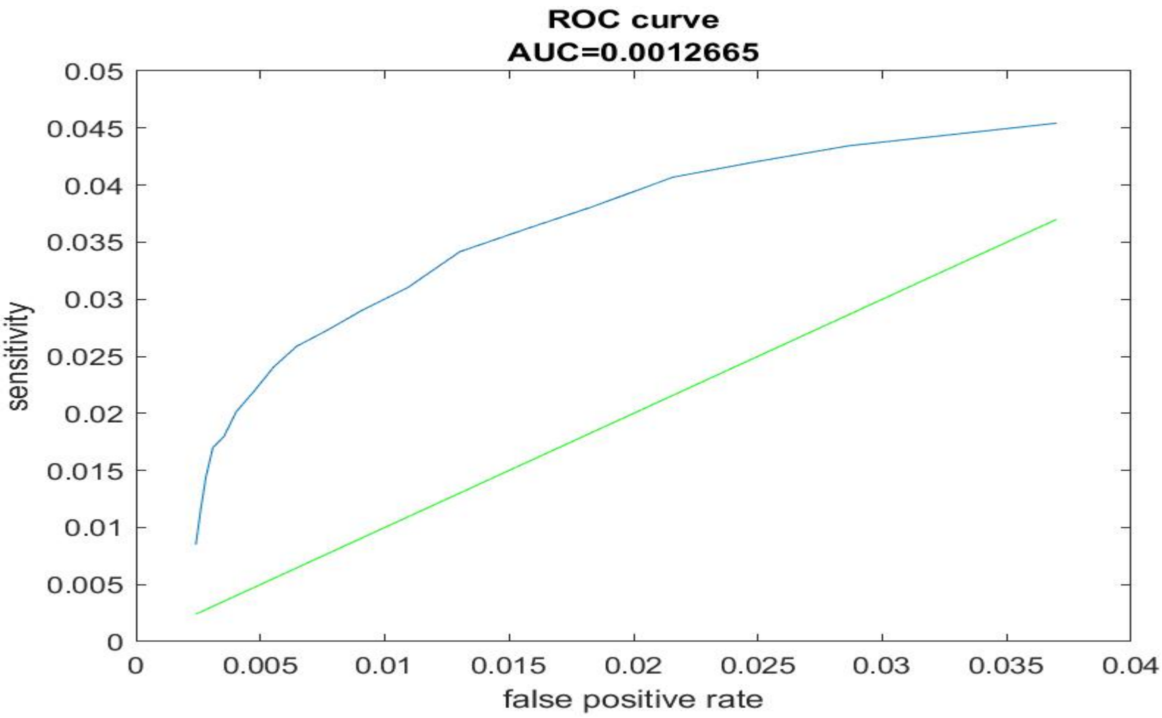

Figure B.18: Left eye of the tenth patient

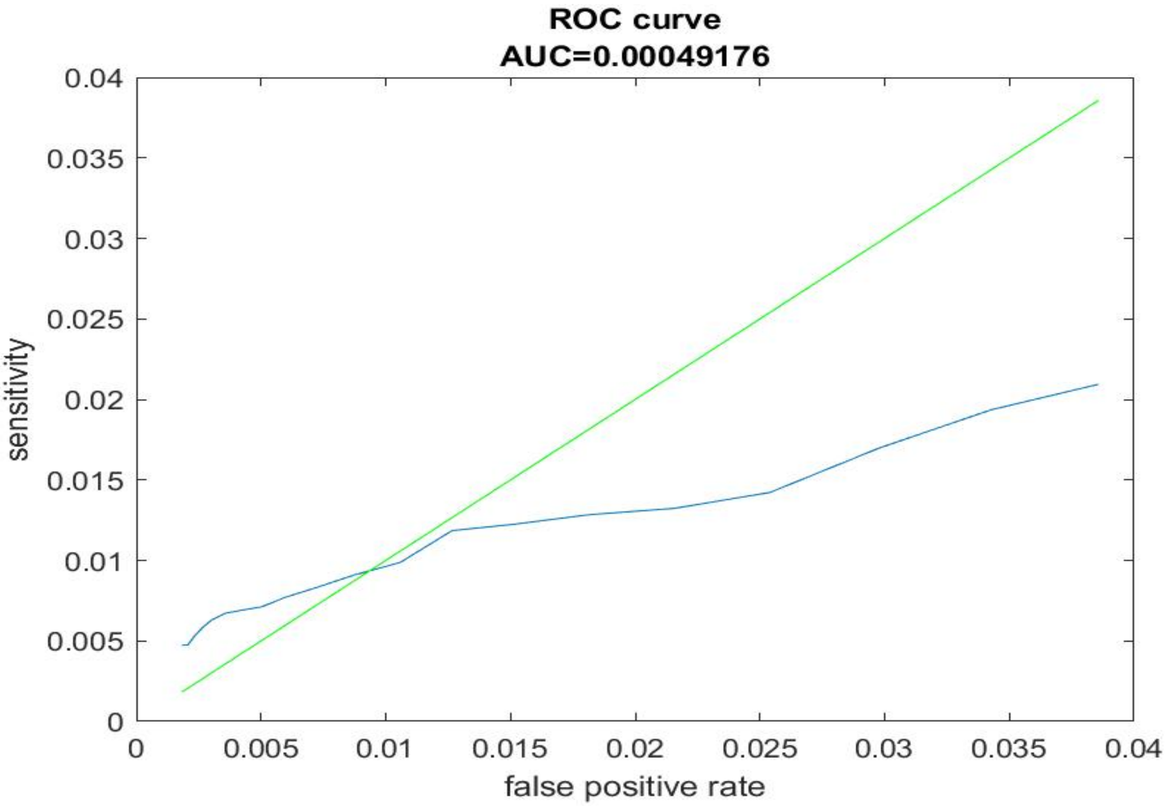

Figure B.19: Right eye of the tenth patient