Neuro-NIRS: Analysis of Neural Activities Using NIRS

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Abstract. Analysis method for quick component of NIRS is explained. In order to compare quantitatively the amount of quick component, absolute average operation is applied. The result Q is then formulated as the product of magnitude M and density D. By characteristic differences of M and D functional features of each channel are discussed. The method is applied to text entry task to mobile phone. Most of 34 channels under study D values diverged in rest state, but they converged at task state. 6 channels among 34, showed specific responses to specific task.

Keywords: neural activities, NIRS, quick components, text entry, mobile phone.

1 Introduction

Fruitful sessions on NIRS (near infrared spectroscopy) were organized by Monica Fabiani at HCII 2005 held in Las Vegas. By that time, two Japanese companies have developed general purpose NIRS machines, which are capable of simultaneous measuring of oxy and deoxy hemoglobin concentration in the brain surface tissues. Since NIRS has been used in the field of hemo-dynamic studies until then, the new machines are still used mainly to trace oxy hemoglobin and, so far deoxy hemoglobin is often disregarded. Tamura [1] emphasized need to develop analysis methods considering oxy and deoxy hemoglobin at the same time. In HCII 2007 a method to analyze NIRS data in the two dimensional coordinate plane, taking the total (oxy + deoxy) and difference (oxy - deoxy) variables to the axes. The paper showed the total component consisted of, mainly, slow component, while the difference component consisted of slow and quick components.

The slow and the quick components are separated by applying running average of 2 seconds to the difference component. Slow component normally has continuous waveform, while the quick shows the form of pulse train of variable height. The interests of hemodynamic studies have been in the slow component and the quick component is regarded as noise, and no attentions have been paid to the quick component. Although hemodynamic studies are not interested in quick component, they already know the existence of quick signals and regard it fatal for successful NIRS measurements. Many people tried to decrease noise by taking care of external factors like optical contacts to the skin. But the quick component is large in amplitude, often much larger than the slow. It is not reasonable to regard it noise.

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We are convinced that the quick component is not noise but essential physiological signal. We have made measurement [2] of quick component distributions using 34 to 48 channels NIRS, provided by Shimadzu and applied it to various tasks. It was confirmed that the quick distributions changes according to the task, such as text input, hand up down, finger sign and button selection, etc. Slow component are not stable and effected by various factors, but quick components distributions are stable, although they are varying by conditions.

In this paper, the author presents the model of quick and slow component generation with regard to blood circulation systems. Secondly analysis method to draw neural activities included in each NIRS signals is explained. The quick signal from a single channel of NIRS is results of summative activities of small brain area, and speculative model of activities is introduced in this paper.

2 Quick Components

2.1 NIRS Coordinates

Fig. 1 is showing Oxy, Deoxy, and Total Hb (hemoglobin) recording of 6 channels from NIRS. The upper traces correspond to oxy, the lower to deoxy, and the middle to total Hb. The channel number is indicated at the middle of the left side of each chart, Looking to the channel 26, oxy and deoxy Hb contains big high frequency components, which we call quick components, while total Hb contains less. The traces of 29 and 32 contain less quick components, in both oxy and deoxy, as well as total Hb.

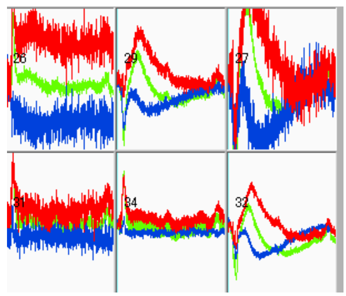


Fig. 1. Raw traces of NIRS

The NIRS variables, oxy and deoxy Hb can be replaced by total and difference Hb as below:

$$\text{Total Hb:} \quad \text{Total=Oxy+Deoxy} \quad (1)$$

$$\text{Difference Hb:} \quad \text{O\_D= Oxy –Deoxy} \quad (2).$$

Fig. 2 is showing traces of above variables. The quick components of oxy Hb and deoxy Hb are in opposite phases, thus by the addition of quick components, they are almost compensated, while by subtraction, the quick component is doubled in amplitude.

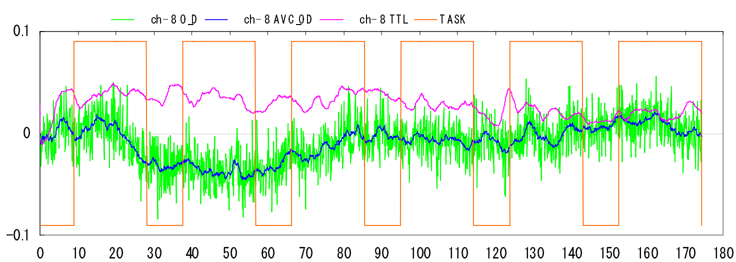


Fig. 2. Total Hb(red) and difference Hb(green) and the slow O_D (blue) among the middle of difference(O_D) trace. Square trace indicates on and off of task.

Applying moving average of 2 second, quick and slow components of Total and O_D can be derived.

Slow total Hb: slow total=Average (Total) (3)

Slow difference Hb: slow O_D= Average (O_D) (4)

Quick total Hb: Quick t= Total -Average(Total) (5)

Quick difference Hb: Quick O_D = O_D − Average(O_D) (6)

Thus the analysis of quick components of NIRS can be concentrated to the quick O_D. The quick components derived from eq. (5) and (6) are shown in Fig. 3. The magnitude of quick total is about 1/10 of quick O_D, the characteristics of the latter are mainly discussed below.

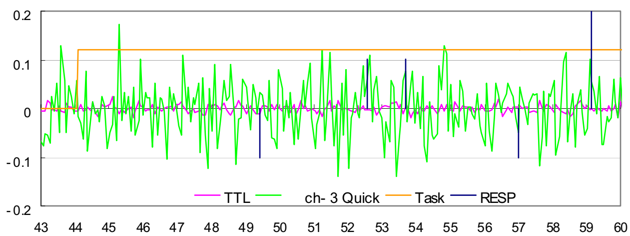


Fig. 3. Traces of Quick O_D and Quick total

2.2 Analysis of Quick Components

For the comparison of quick components, derived from various channels at various tasks, unified quantitative formulation of quick component is necessary. An appropriate function applicable to noise like signal as quick components is Avedev (Microsoft excel function), which is average of absolute difference of data and their mean value. In our analysis, slow component is subtracted from O_D signal, thus the mean value of quick component is assumed to be zero. In short, avedev can be called the time average of absolute value of quick.

In the previous papers [2], long term (>30second) distributions of quick components around different channels and their changes are reported. A distribution proper to the case of this paper is shown in Fig. 9 below.

Avedev is stable in value, when time length is taken 10 seconds or longer. It change considerably as averaging time is shorten, reflecting change of brain activities under the recording. In this paper, a method to evaluate short term change in brain activities is considered by introducing two parameters, M (magnitude)and D (density), related to Q.(avedev of quick component). The relation of these parameters is formulated as below.

$$Q = M * D \tag{7}$$

Here

$$M = \max(\max(\text{member}), -\min(\text{member})) \tag{8}$$

member: data within time span of averaging, and the number of data is denoted by N.

Following the above formulation, relation below is derived.

$$0 < 1/N < D < 1 \tag{9}$$

Inequality (9) states that the density remains with in the bound of 0 and 1. Further studies are concentrated to the change of M and D, in succession of averaging cycles, which are taken 1, 2 and 5 second, for comparison, depending on the tasks.

Imagine pulse trains of full, half, quarter, etc density as shown in Fig 4a. Relations of Q and M are shown by the lines of positive slope in Fig.4b. D is larger at the upper side of the slope lines. When quick component data are plotted on Q and M plane, scatter graph as in Fig. 4c is obtained. The data points are scattered around a positive slope line, and the slope is definite to member size, independent of channel. The member size increases in accordance to averaging interval of avedev (Q). Thus the inclination of slope decreases with increase of averaging interval. The degree of scatter is different depending on channel.

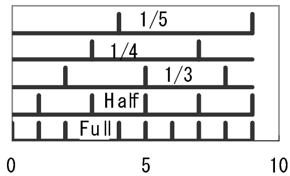


Fig. 4a. Pulse trains

Generally, the channels with large M show big scattering. The slope changes the inclination also depending on the tasks.

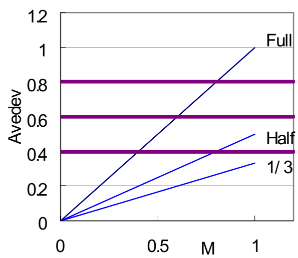


Fig. 4b. Theoretical relationsof Q and M

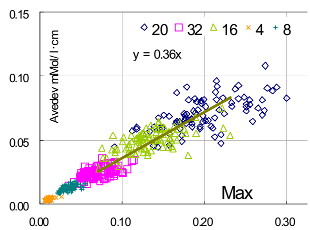


Fig. 4c. Actual distribution of Q and M

Now the scatter plot of NIRS data is considered on density (D) and magnitude (M) plane (Fig. 4d).

The positive slope lines in Fig. 4b are mapped to separate horizontal lines in Fig. 4d. Next the mapping of horizontal lines (Q = constant) in Fig. 4b to Fig. 4d is considered.

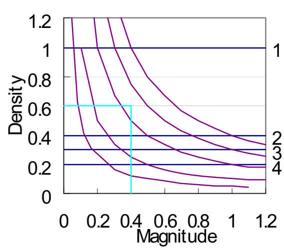


Fig. 4d. Relation of D and M

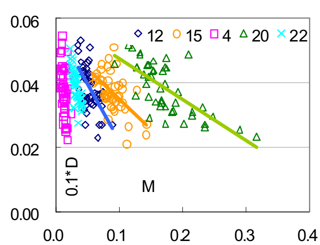


Fig. 4e. Data plot in D and M

They are transformed to hyperbola in Fig. 4d. The scatter graph Fig. 4c is transformed to Fig. 4e. The ordinate is extended in Fig. 4e. The data area of Fig. 4e is the square zone between origin and point 0.4, 0.6) of Fig. 4d.

When D-M data are plotted for one task period, and adjacent dots are connected by lines, trajectory as in Fig. 4f are obtained. The channel 20, shown in green triangles, include active change of M in short interval of time. On the contrary, channel activities are mainly in D change for channel 27 and 12.

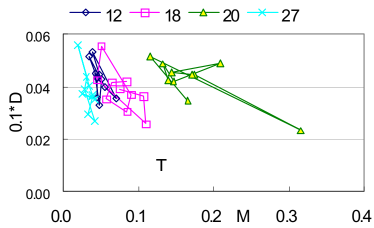


Fig. 4f. D-M trajectory for a Task period. 1019 1454 HIGHX.

3 Sources of Slow and Quick Components

3.1 Hemodynamic Systems

The major NIRS signals, oxy and deoxy Hb, have each the different source. The source of oxy Hb supply is in lung oxygen exchange. Oxy Hb travels a long way up to brain passing through various barriers. Thus the hemodynamic responses are normally slow. The source of deoxy Hb is neural activities in the brain, which is quick in nature. The quick component is gradually smoothed as it goes through cilliary vessel, and finally changes into slow deoxy Hb component. Thus the quick component directly recorded by NIRS is most likely reflecting neural activities of brain.Fig.5 is showing the model of hemodynamic systems related to NIRS.

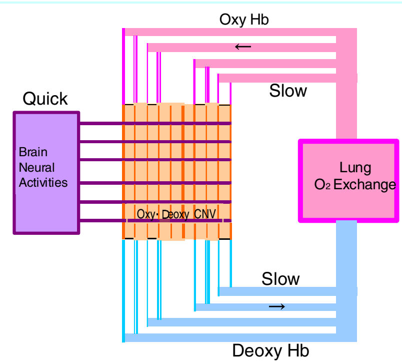
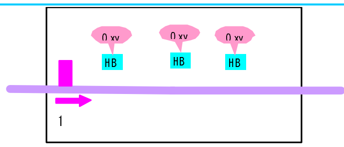


Fig. 5. Hemodynamic model of O_2 circulation

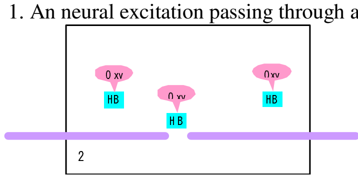
3.2 Oxy/ Deoxy Conversion in Neural Net

Fig. 6 explains the process converting oxyHb into deoxy Hb after arrival of an neural excitation using the quantum model. After the conversion process one unit of oxyHb decreased and one unit of deoxyHb increased. Resultantly, double unit of deoxyHb increase is observed by one neural excitation. The model is in accordance to the quick component increase of O_D.

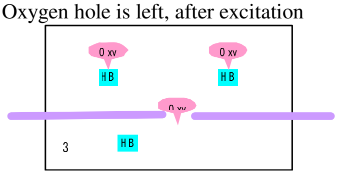
Neural excitation is energy consuming process. The neural system has to supply energy by support of ATP cycle immediately after excitations. In the recovery process after excitation, certain autofluorescence is reported [8]. One possibility of quick optical activities sensed by NIRS is after effect of neural excitations.



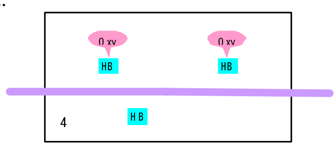
1. An neural excitation passing through axon



2. Oxygen hole is left, after excitation



3. oxyHb supplies oxygen to neuron, Hb is released.



4. local population after recovery of excitation.

Fig. 6. Quantum model of deoxidization of oxyHb after neural excitation

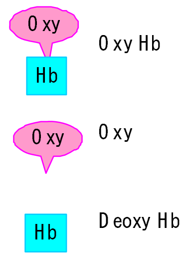


Fig. 7. Notations of O_2 carriers

Two types of general purpose NIRS machine are in market. One provided by Hitachi makes use of continuous modulation of infra red light, while the other provided by Shimadzu, makes use of sampling method. The latter looked annoying at first glance, because of prominent noise like responses. Now we convinced that they are providing significant physiological data. In case of machine using continuous modulation light, in order to cut modulation signal component at output stage, strong high cut filter is necessary. The filter might cut quick component considerably. But careful analyzer might detect quick component as well.

4 Text Entry Task

Text entry task to mobile phone is analyzed in this chapter. The user participated in experiments were female students of university, informed consented in written form. The students are accustomed to enter in multi-tap telephone key entry, and predictive Kanji conversion method.

The subject sat in front of CRT, where text of up to 20 characters are shown on the task phase, and on rest phase, colored picture of nature are shown. Subject held the mobile phone even in rest phase and stayed ready to start. Task and rest phases are 20 and 10 seconds, and the task rest cycle repeated 6 times. Types of text are different cycle by cycle, so that mental effort might be different at each cycle.

4.1 Task Description

Text types of 6 task cycles are listed below:

1. iroha	いろはにほへと	Japanese alphabet like ABC
2. reverse iroha	とへほにはろい	reverse order (meaningless) text
3. Kanji conversion	色は匂へど 散りぬるを	classic sentence, not fully fit to
4. kanji conversion	我が世誰そ 常ならむ	predictive conversion
5. number entry	119999965566666	same key location as task 1
6. number entry		same key location as task 2

Task 1 is starting part of Japanese alphabet like ABC, which has deep meaning. Task 2 is to enter reverse order text which has no meaning. Text entry speed is not different whether the text is with or without meaning. Task 3 and 4 are text entry with predictive Kanji conversion. But the text are somewhat different from present-day lettering, subject has to think about to overcome the difference. Task 5 and 6 are number entry, the key location and the number of key presses is equal to task 1 and 2. Conversion of letter to multi-tap operation is not required.

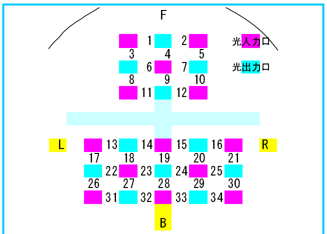


Fig. 8. Optode arrangement (34ch)

4.2 Optode Arrangement

Optode arrangement for present experiment is shown in Fig.8. The red optode indicate light emitting and blue light sink. The number between optodes indicates channel number. The sampling frequency for the arrangement was 100ms. Trace of O_D and total Hb for channel 8 is shown in Fig. 2 together with task/ rest signal.

The quick component recorded in each channel is compared by taking avedev channel by channel , averaging time 180sec.

The result is shown in Fig.9. The highest beak is observed at channel 20, and a sub peak at channel 16. At the 5 channels in the front most, quick components were low.

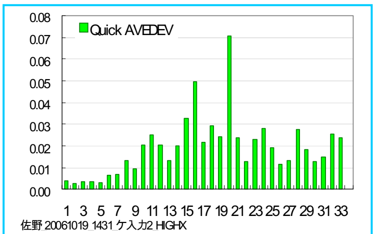


Fig. 9. Quick component distribution around the channels (180sec., ordinate in mMol/lcm)

4.3 Time Course of Magnitude and Density

Quick component are clustered by 2 second, and 2 second avedev was applied for each data. Then M by using eq.(8), and D by using eq.(7) is determined to each cluster.

M and D change their value by time. Because D is 10 times larger in value, in drawing graph, 0.1D is adopted. Fig 10 is showing 0.1D, M, Q and task on/off signal in time. It is interesting, M and Q changes considerable by channel and task, 0.1D is changing in definite range.

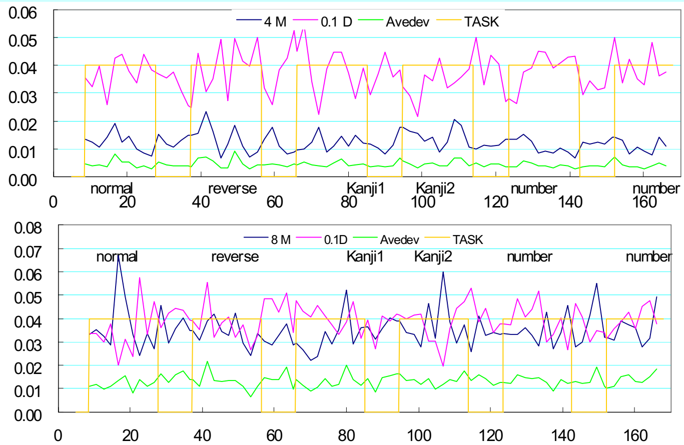


Fig. 10. Change of cluster parameters Q, M, and 0.1*D in time sequence

The variations of D and M are showing the neural processing in task and rest intervals in the channels.

5 Density Relations in Task and Rest Interval

For simplicity of discussion, average of 0.1D values of all the channels is compared in the course of 6 tasks/rest intervals (Fig. 11). Interesting finding is that density of many channels diverges (increase or decrease) at rest, while it converges at task state. Most of the channels show the feature.

In order to confirm the relations, density of all the 34 channels is averaged, and standard deviation of densities is calculated at each task and rest state.

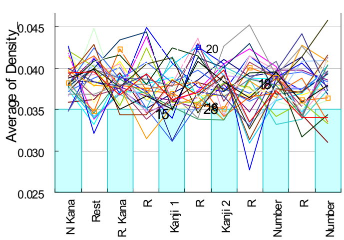


Fig. 11. Density variation at task and rest, comparison of 34 channels 1019 1454 HIGHX

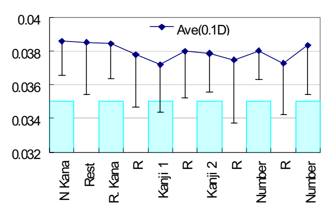


Fig. 12. Average and standard deviation density at task and rest

The results are shown in Fig. 12. The blue line shows the average and the ladder extended from the average is indicating the standard deviation. The standard deviation is lager at rest than at task, at most of the intervals.

6 Density Characteristics at Different Locations

Different locations of brain might have different density characteristics. As shown in Fig. 8, 34 channels are located in three parts of brain. One is in frontal, the second in left apical, and the last in right apical area. Density characteristics with task/rest interval for the channels in each area are illustrated in Fig. 13. The channel location is illustrated by the location maps associated to density graph.

In frontal area, density of most of the channels increases at rest, except for channel 7 and 12. In the apical area also, most channels are density increasing at rest. Some channels which are density increasing at task, 18and 27in left, and 20, 28, 33 in right apical area are accumulated Fig. 14. Each channel seems to have specific task at which it might show high density.

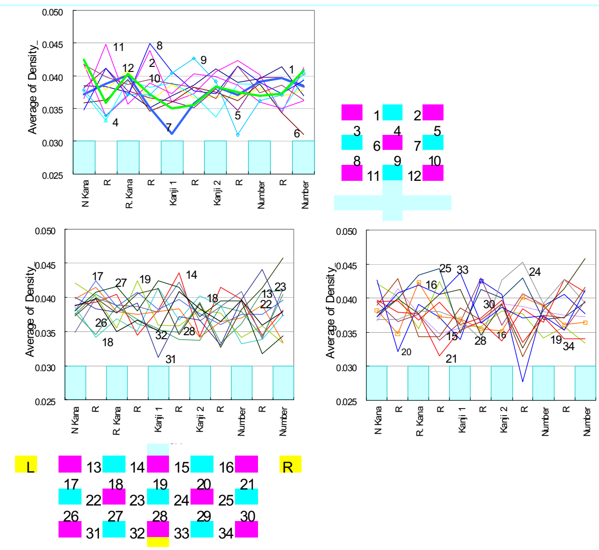


Fig. 13. Average of density within task/rest for all channels

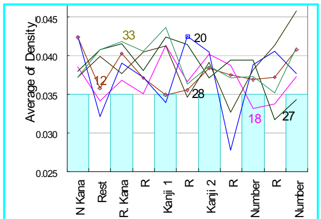


Fig. 14. Density increasing at task

7 Conclusion

Extended analysis method for NIRS quick component is presented. Quick component analysis is going to be most promising to study working brain.

Finally, influences of quick brain activities are partly represented to NIRS trajectories which are derived from slow components. By comparing NIRS trajectories, people might realize, there are channels which increase in oxy or total hemoglobin but less in neural activities. On the contrary, in some channels total or oxy Hb remains steady while the channels are busily functioning,

Hemodynamic studies expect the working brain needs more oxygen supply. Thus the areas supplied with rich oxygen are tentatively working. But this is only the expectation, but not evidence. We have to find evidences related to parts of the brain actually functioning.

Hemodynamic and neural functions are both significant aspects of brain studies. Cerebral infarction might cause hemodynamic problems, which might result in neural dysfunctions. Rehabilitation is the process of recovering hemodynamics and neural function. Neuro-NIRS is a new significant aspect of NIRS studies.

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