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A Linear Regression Model for Estimating Anxiety Index Using Wide Area Frontal Lobe Brain Blood Volume

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Abstract**—**Major depressive disorder (MDD) is one of the most common mental illnesses today. It is believed to be caused by a combination of several factors, including stress. Stress can be quantitatively evaluated using the State-Trait Anxiety Inventory (STAI), one of the best indices to evaluate anxiety. Although STAI scores are widely used in applications ranging from clinical diagnosis to basic research, the scores are calculated based on a self-reported questionnaire. An objective evaluation is required because the subject may intentionally change his/her answers if multiple tests are carried out. In this article, we present a modified index called the "multi-channel Laterality Index at Rest (mc-LIR)" by recording the brain activity from a wider area of the frontal lobe using multi-channel functional near-infrared spectroscopy (fNIRS). The presented index aims to measure multiple positions near the F_{pz} defined by the international 10-20 system positioning. Using 24 subjects, the dependencies on the number of measuring points used to calculate the mc-LIR and its correlation coefficients with the STAI scores are reported. Furthermore, a simple linear regression was performed to estimate the STAI scores from mc-LIR. The cross-validation error is also reported. The experimental results show that using multiple positions near the Fpz will improve the correlation coefficients and estimation than those using only two positions.

Keywords**—**Stress, functional near-infrared spectroscopy, frontal lobe, state-trait anxiety inventory score.

I. Background

TODAY, MDD is widely known as a common mental illness in the world. Although many causes are reported to trigger MDD, one of the factors is believed to be stress [1]. To quantitatively evaluate stress, one of the most widely used methods from clinical diagnosis to basic research is STAI. The STAI test is a self-reported questionnaire and the anxiety level could be easily obtained by adding up the scores given for each question. Although a self-reported questionnaire is simple way to evaluate anxiety, if the test is carried out multiple times, the subject may intentionally change the answer to obtain inaccurate result. Therefore, an objective evaluation is required. Several studies have estimated STAI scores based on brain activity. For example, Ishikawa et al. proposed Laterality Index at Rest (LIR) using near infrared spectroscopy (NIRS) [2], [3], Fukuda et al. created a Bayesian method to estimate the anxiety index [4], and Matsumoto et al. reported the correlation between LIR and STAI score using young and elderly subjects [5]. However, in [2]-[5], the left and right channels of NIRS are used to obtain LIR, and a wide range of frontal lobe brain activity is not considered. In this study, we present an index using multi-channel NIRS and identify a combination of channels with high correlation with the STAI score by searching the frontal lobe for regions related to the stress index. Then, we present a stress index weighted on multiple channels and aim to estimate the STAI score by performing regression using the index with the highest correlation coefficient between the index and the STAI score.

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II. Proposed System

Let $\boldsymbol{X}_L(t)$:= [$X_{L1}(t),\ldots, X_{LN}(t)$] and $\boldsymbol{X}_R(t)$:= [$X_{R1}(t),\ldots, X_{RN}(t)$] be the measured oxy-hemoglobin concentration at the left and right $LN = RN = N$ positions around F_{pz} defined by the 10-20 method. Here, t denotes a discrete time index.

In this study, we propose the mc-LIR Y defined by:

$$Y = \frac{\sum_t\{\sum_{i=1}^{RN}(X_{Ri}(t)-\min_t(X_{Ri}(t)))-\sum_{i=1}^{LN}(X_{Li}(t)-\min_t(X_{Li}(t)))\}}{\sum_t\{\sum_{i=1}^{RN}(X_{Ri}(t)-\min_t(X_{Ri}(t)))+\sum_{i=1}^{LN}(X_{Li}(t)-\min_t(X_{Li}(t)))\}}$$

where $\min_t(\boldsymbol{X}(t))$ returns the smallest value in the given vector with respect to t. Note that the proposed mc-LIR is a generalized index of LIR proposed in [2] where N=1.

The estimated STAI score $\hat{Z}$ was calculated by a linear regression model given the obtained mc-LIR Y as

$$\hat{Z} = aY + b.$$

III. Experimental Method

Wearable optical topography (WOT-100) from Hitachi Kokusai Electric Service Corporation was used for the measurements. The blood volumes of 10 measuring positions, as shown in Fig. 1, were obtained with a sampling rate of 5 Hz. Among the 10 measuring positions, N positions were selected as $\boldsymbol{X}_L(t)$ and $\boldsymbol{X}_R(t)$. $\boldsymbol{X}_L(t)$ was selected from positions 5 to 10 whereas $\boldsymbol{X}_R(t)$ was selected from positions 1 to 6. The number of all possible combinations of $\boldsymbol{X}_L(t)$ and $\boldsymbol{X}_R(t)$ given the number of positions N was $\left(\frac{6!}{N!(6-N)!}\right)^2$. Note that central positions 5 and 6 might be included in both $\boldsymbol{X}_L(t)$ and $\boldsymbol{X}_R(t)$.

24 undergraduate students participated in the experiment after providing their written informed consent (12 male and 12 female subjects, aged 18-22 years old). The subjects were asked to complete the STAI questionnaire format followed by a 1-min

calibration phase and 3-min actual measurement phase. The subjects were asked to sit still without thinking anything throughout the measurement phase.

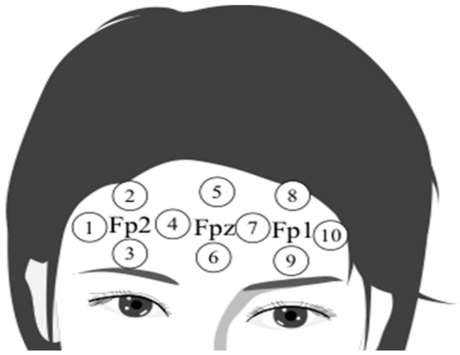


Fig. 1 Measurement positions and F_{pz} in the 10-20 method: The numbers denote the position numbers

The presented index was evaluated using two measures. First, the correlation coefficients ρ between the proposed index and the actual STAI score Z was evaluated. The dependencies of the correlation coefficients on the selection of the $\boldsymbol{X}_L(t)$ and $\boldsymbol{X}_R(t)$ were evaluated. Next, the absolute error of the estimated STAI score using the proposed index and the actual STAI score was evaluated.

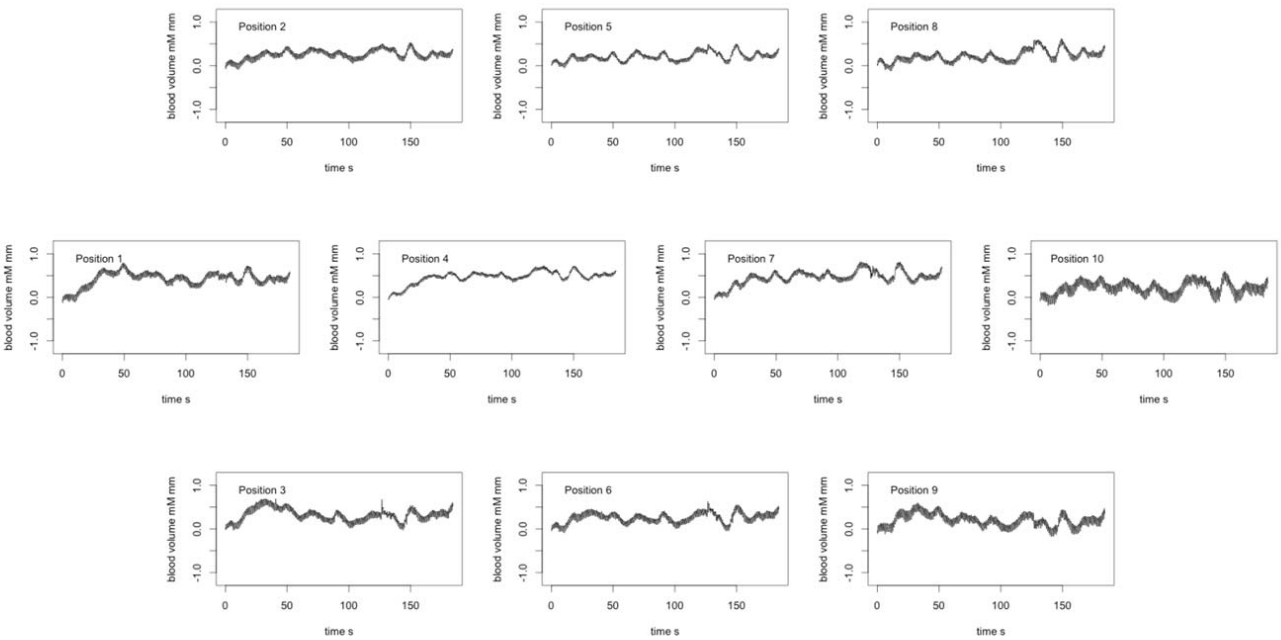
IV. Result

The actual STAI score ranged from 28 to 57. Fig. 2 (a) shows the blood volume time series data where STAI score was high. On the other hand, Fig. 2 (b) shows the blood volume time series data where STAI score was low. It is extremely difficult to estimate the STAI score only from these time series data.

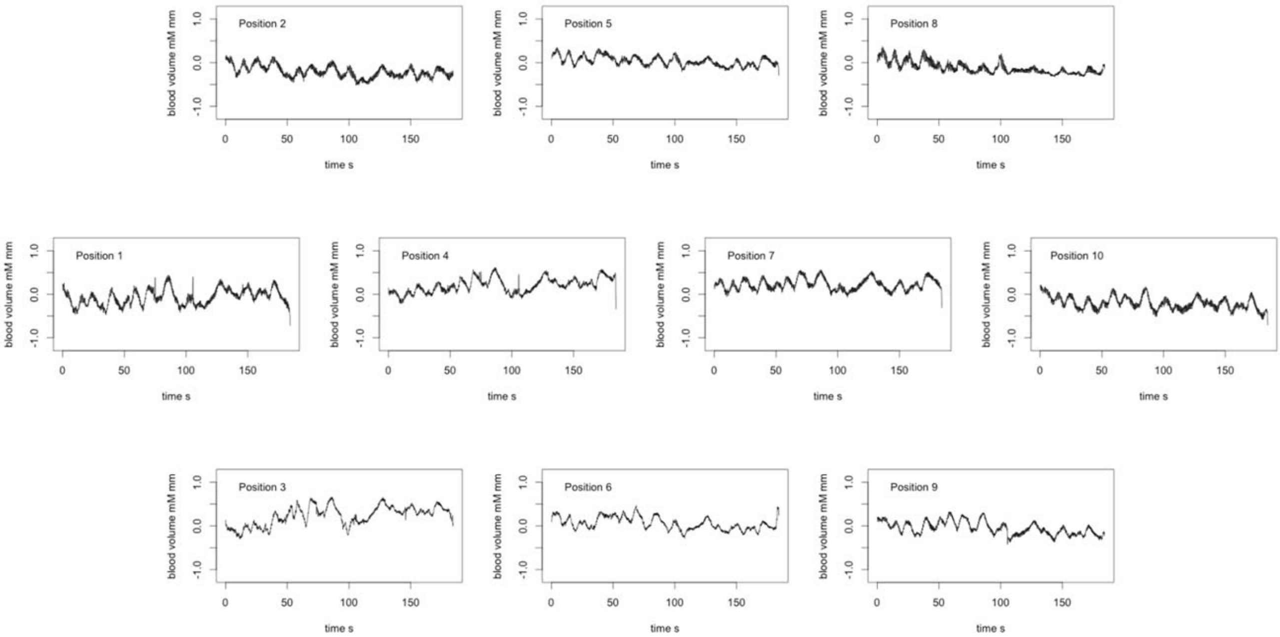
Table I shows the correlation coefficient ρ between the proposed index and the actual STAI score Z with respect to the number of selected positions N. Although all possible combinations of $\boldsymbol{X}_L(t)$ and $\boldsymbol{X}_R(t)$ were calculated, only the combinations that showed the highest correlation coefficients are presented. As noted earlier, N=1 corresponds to the previous study [2]. The results show that the proposed index was correlated better than when more than one position was used. Furthermore, the proposed index correlated best when N = 3. On the other hand, when all positions were used (N=6), the correlation coefficient was lower than when only one position was used (N=1).

TABLE I
CORRELATION COEFFICIENT OF THE PROPOSED INDEX (MC-LIR) BASED ON THE SELECTED POSITIONS AND STAI SCORE

Number of positions N	Selected right positions $X_R(t)$	Selected left positions $X_L(t)$	Correlation efficient ρ
1	4	9	0.3384
2	4,6	6,9	0.4038
3	2,4,6	6,8,9	0.4635
4	1,4,5,6	5,6,8,9	0.4530
5	1,2,4,5,6	5,6,8,9,10	0.3430
6	1,2,3,4,5,6	5,6,7,8,9,10	0.2396



(a) A time series data with high STAI score (ID:24 STAI Score 61)



(b) A time series data with low STAI score (ID:16 STAI Score 28)

Fig. 2 Time series blood volume data. The vertical axis presents the blood volume in millimolar · mm, and the horizontal axis represents time in seconds. (a) A time series data with high STAI score, shows an example of a subject with high STAI score whereas (b) A time series data with low STAI score, shows an example of low STAI score

TABLE II
MEAN ABSOLUTE ERROR OF THE ESTIMATED STAI SCORE

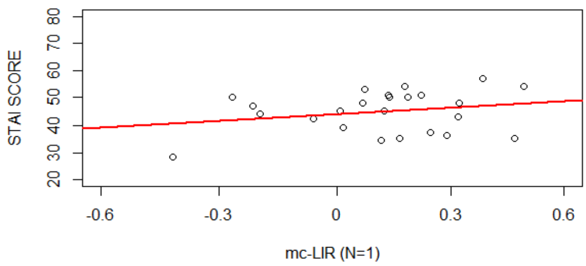
Number of positions N	Mean Absolute Error
1	5.0822
2	4.9036
3	4.7743
4	4.9563
5	5.1962
6	5.2654

Fig. 3 shows the scatter plots of the proposed index (mc-LIR) and STAI score with N = 1 to 6. The red line shows linear regression. As shown, when N = 3, the red line best fits the plots.

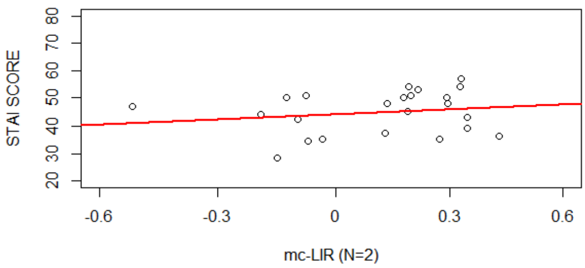
Table II shows the mean absolute error of the estimated score. Compared to the case where N = 1, the error is smaller when N = 2, 3, and 4 respectively. The error is the smallest when N = 3.

V. DISCUSSION

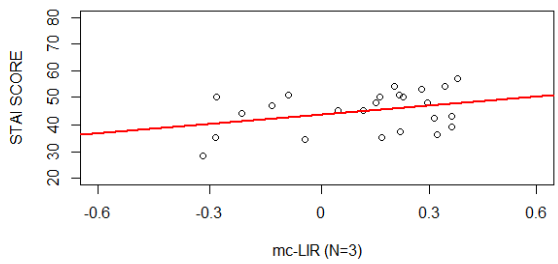
By using a wider area of the frontal lobe, the experimental results showed better accuracies. Positions around F_{pz} (positions 5 and 6) tend to be selected, which may imply the blood volume in the central area may affect the accuracy of the index. However, using too many positions increased the absolute error. A method to select the best number of positions may be required. Furthermore, defining a weighted mean of the positions may yield better results. These results will be reported elsewhere.



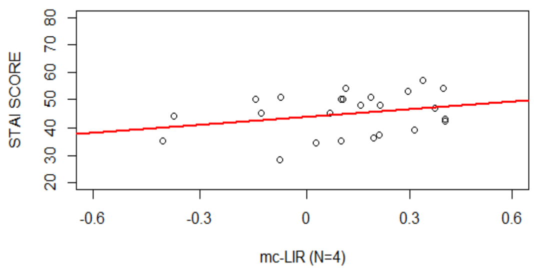
(a) Proposed index (mc-LIR) vs. STAI score where N=1. Position 4 for $X_R(t)$ and position 9 for $X_L(t)$ were selected



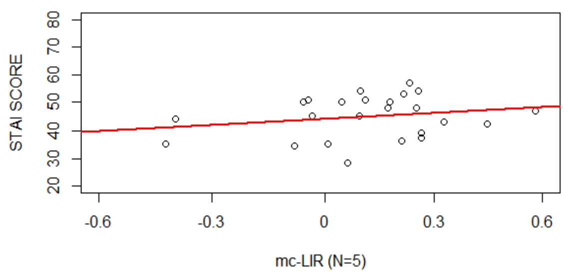
(b) Proposed index (mc-LIR) vs STAI score where N=2. Positions 4 and 6 for $X_R(t)$ and positions 6 and 9 for $X_L(t)$ were selected



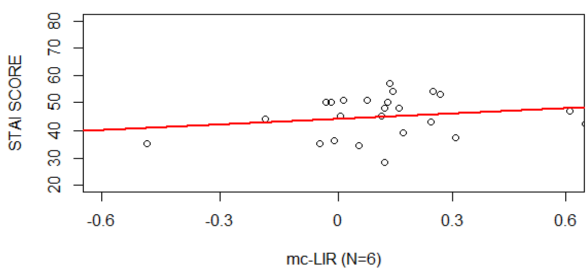
(c) Proposed index (mc-LIR) vs STAI score where $N = 3$. Position 2, 4, and 6 for $X_R(t)$ and positions 6, 8, and 9 for $X_L(t)$ were selected



(d) Proposed index (mc-LIR) vs. STAI score where N=4. Positions 1, 4, 5, and 6 for $X_R(t)$ and positions 5, 6, 8, and 9 for $X_L(t)$ were selected



(e) Proposed index (mc-LIR) vs STAI score where N=5. Positions 1, 2, 4, 5, and 6 for $X_R(t)$ and positions 5, 6, 8, 9, and 10 for $X_L(t)$ were selected



(f) Proposed index (mc-LIR) vs STAI score where $N = 6$. Positions 1 to 6 for $X_R(t)$ and positions 5 to 10 for $X_L(t)$ were selected

Fig. 3 Scatter plots of the proposed index (mc-LIR) and STAI score. The red line shows the estimated regression. (a) to (f) show the number of positions used. XR(t), selected right positions; XL(t), selected left positions

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