Smartphone-based Device for Checking Mental Status in Real Time

Mayumi Oyama-Higa[1, 2], Wenbiao Wang[3], Shigeo Kaizu[1, 2], Terufumi Futaba[4] and Taira Suzuki[5]
[1]*Chaos Technology Research Laboratory, Otsu, Japan*
[2]*Kwansei Gakuin University, Nishinomiya, Japan*
[3]*PricewaterhouseCoopers Aarata, Tokyo, Japan*
[4]*Ryukoku University, Kyoto, Japan*
[5]*J. F. Obern University, Tokyo, Japan*

Keywords: Smartphone-based Device, Largest Lyapunov Exponent, Real-Time Mental Health Check-up for Highway Drivers, Application to the Caring for Amyotrophic Lateral Sclerosis Sufferers.

Abstract: In this article, we present a smartphone-based device for checking mental status in real time, which for the first time enables real-time check-up of mental status with a smartphone. With this device, by measuring pulse waves, two important mental health indicators can be visualized at the same time: the largest Lyapunov exponent obtained from non-linear analysis of pulse waves, and the autonomic nerve balance. Before the development of this device, the measurement of these indicators had already been conducted in thousands of experiments, and their relationship with individual's mental status had been intensively studied in recent years. This device enables users to conduct the measurement and capture the mental status dynamically, without the limitation of place and time. It has the potential application in preventing accidents due to failure of emotional management. The device is convenient to use and cost-effective.

1 INTRODUCTION

Problems related to mental disorder, or simply mental changes, can lead to serious consequences. In order to measure and analyse individual's mental status for early detection of potential mentally related problems, we have performed a number of studies in recent years, whose general description can be found in Oyama's 2012 book. It has been discovered that chaotic fluctuations obtained from the fingertip pulse waves contain information of the central nervous system. In particular, the largest Lyapunov exponent (LLE), which quantifies the variation of the attractor trajectory, can serve as an indicator of mental immunity. Besides, we have developed the measuring device in order that a measurement of fingertip pulse waves can be conducted anywhere at any time.

For the results of our recent studies, specifically, the method of measuring and analysing fingertip pulse waves have been applied to various research subjects concerning detection of mental changes (Oyama-Higa et al., 2008; Wang et al., 2012) and check-up for mental and cognitive disorders, such as dementia (Oyama-Higa and Miao, 2006; Oyama-Higa et al., 2008; Pham et al., 2015) and depression (Oyama-Higa et al., 2008; Hu et al., 2011; Pham et al., 2013).

This paper presents our improvement in the measuring device: We have made the device more convenient by connecting the pulse wave sensor to a smartphone. Moreover, we calculate and display values of autonomic nerve balance (ANB) at the same time, which indicates whether sympathetic nerve or parasympathetic nerve predominates. Thus, we have made it possible to examine minute changes in mental condition by graphic display of LLE and ANB. Although this device still needs improving in some aspects, it is so far the only existing device that makes such mental check-up possible and convenient with a smartphone.

2 CALCULATION METHOD

We introduce the two key indexes calculated and displayed by our measuring device: LLE and ANB. In addition, an index of vascular age will also be shown.

Oyama-Higa, M., Wang, W., Kaizu, S., Futaba, T. and Suzuki, T.
Smartphone-based Device for Checking Mental Status in Real Time.
DOI: 10.5220/0005655401370142
In *Proceedings of the 9th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2016) - Volume 4: BIOSIGNALS*, pages 137-142
ISBN: 978-989-758-170-0

2.1 Largest Lyapunov Exponent (LLE)

Time series data with deterministic chaos can be constituted by fingertip plethysmograms (Tsuda, Tahara and Iwanaga, 1992). Let

$$x(i),\ i = 1, 2, \ldots \tag{1}$$

denote the time series data. Using the method of delays, the phase space is reconstructed with vectors represented as

$$\begin{aligned} X(i) &= (\, x(i), x(i-\tau), \ldots, x(i-(d-1)\tau)\,) \\ &= \{\, x_k(i)\,\}_{k=1,\ldots,d} \end{aligned} \tag{2}$$

where τ is a constant delay, d is the embedding dimension and $x_k(i)$ is defined as

$$x_k(i) = x(i-(k-1)\tau),\ k = 1,\ \ldots,\ d. \tag{3}$$

In our study where the time series are recorded from fingertip pulse waves, studies (Sano and Sawada, 1985; Sumida et al., 2000) have shown that the optimal choices for the constant delay and the embedding dimension are

$$\tau = 50\ ms \tag{4}$$

and

$$d = 4. \tag{5}$$

The largest Lyapunov exponent (LLE) is a measure of complexity that reflects the divergence and instability of the attractor trajectory. Let $X(t)$ evolve with time starting with an initial trajectory $X(0)$. Then, LLE can be calculated as

$$LLE = \lim_{t\to\infty}\lim_{\epsilon\to 0}\frac{1}{t}\log\frac{|\delta X_\epsilon(t)|}{|\epsilon|}, \tag{6}$$

where the separation of the trajectories is represented by

$$\delta X_\epsilon(t) = X(t) - X_\epsilon(t) \tag{7}$$

and the initial separation is represented by

$$\epsilon = X(0) - X_\epsilon(0) \tag{8}$$

in the phase space. In the measuring device in our previous studies as mentioned above, the method proposed by Rosenstein et al. in 1993 is applied for estimating the LLE. For convenience, the value of LLE is normalized to a range of 0-10 in the display of our device.

Figure 1 shows the plethysmogram and attractor obtained from the measurements, and LLE obtained. Our previous studies have shown that the values of LLE of a mentally healthy individual fluctuate within a reasonable scope (from 2-7, centred at 5).

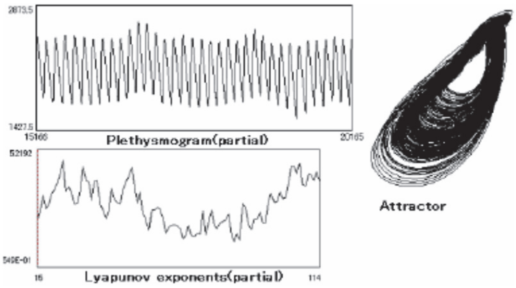

Figure 1: Plethysmogram (top), attractor (right) and LLE (bottom).

When LLE is abnormally high, the mental immunity of the individual is so strong that he or she is likely to go to extremes: such individual can be easily irritated and take unexpected actions. On the other hand, when it is abnormally low, the mental immunity is so weak that the individual is prone to mental illnesses. In other words, a high LLE indicates a mental status of adapting to the external environment (we simply called it "external adaptation" in some of our previous articles), while a low LLE indicates a status of "internal focusing".

2.2 Autonomic Nerve Balance (ANB)

Spectral analysis of heart rate variability can evaluate the activity of the autonomic nervous system. We consider the high frequency (HF, 0.15-0.40 Hz) component which represents parasympathetic nerve activity, and the low frequency (LF, 0.04-0.15 Hz) component which is an index of sympathetic nerve activity. In our study, autonomic nerve balance (ANB) is defined as a normalized index ranging from 0 to 10 as follows.

$$ANB = 10\, B\, /\, 3.5, \tag{9}$$

where

$$B = \ln(LF)\, /\, \ln(HF). \tag{10}$$

From the ranges of LF and HF, we can clearly observe that B ranges from 1, when both LF and HF take the value 0.15, to approximately 3.5, when LF is at the minimum while HF is at the maximum. Therefore, ANB goes from approximately 2.86 to 10. For convenience, in our current study, we still apply a 0-10 valued graph to display the result of ANB. $ANB < 5$ indicates predominance of parasympathetic nerve while $ANB > 5$ indicates sympathetic predominance.

The computation method has also been embedded in the measuring device that has been used so far in our studies, and it has been registered as a U.S. patent (Higa, 2011).

2.3 Vascular Age

In addition to LLE and ANB, a normalized index of vascular age will also be calculated and displayed. This index is defined as

$$\sigma = \frac{10}{1 + \exp\{-\frac{2.8571N - 100}{30}\}} \quad (11)$$

where N is the physical balance of the blood vessel, computed using second derivative of photoplethysmogram (SDPTG) (Sano et al., 1985). N is comparable to the actual age: a high N indicates unbalanced function of the vessel and vulnerability to sclerosis, while a low N indicates plasticity of the vessel. Note that σ is monotonically increasing with respect to N, ranging approximately from 0 to 10 as N goes from 0 to 100.

In this article concerning only LLE and ANB will be discussed in details, so we omit further explanation of the vascular age.

3 SYSTEM DESCRIPTION

3.1 General Description

The software that runs on Android phones is named "Lady Alys". It has two main parts: the engine part, in charge of the computation process, and the driver portion, for connecting the sensor. It can also be connected to the Internet to save and deliver the measured data. The main feature, as stated above, is the real-time display of LLE and ANB during the pulse wave measurement, which enables the users (subjects) to check their mental status easily.

The sensor determines the haemoglobin levels in the finger capillary vessels using infrared spectroscopy (an 840 nm light-emitting diode is equipped), and performs digital transformation that converts 200 Hz to 12 bits.

Values of LLE calculated from the pulse wave, for clarity, are displayed in 10 colours according to the values, from red to blue in colour depth. The closer the colour is to red, the higher the chaotic fluctuation, and thus the external adaptability, is reflected. On the contrary, a colour close to blue represents a low fluctuation and in this case the user is internally focused

Besides fingertips, pulse waves from earlobes can also be used as inputs. Since the sensor is portable, even long-time measurement will not cause much inconvenience. Furthermore, equipped with devices such as Bluetooth, it is also possible to take the data wirelessly.

Figure 2: Smartphone and sensor.

The acquired data can be saved in the database on the Internet. These data can be further analysed with advanced analytical software "Dr. Lyspect" (computer-based). "Dr. Lyspect" is an updated version of "Lyspect" that we developed (described in details in Oyama-Higa et al., 2012), which has been used as a measuring device in our recent studies cited in the Introduction section.

3.2 Main Screens

In this section, we introduce the main screens of the smartphone-based device. Figures 3 and 4 show the starting screen and the pulse wave display respectively.

Figure 3: Starting screen.

Fluctuations in LLE due to emotional changes are displayed in colour: the higher LLE, the closer to red, while the lower the LLE, the closer to blue. During the measurement, after the trial time period of the first 17 seconds, values of LLE are recorded and displayed in colour every second. It turns red when the LLE is greater than 5, and darkens as the value increases. On the other hand, when the LLE is less than 5, the screen turns blue and grows lighter as the value decreases.

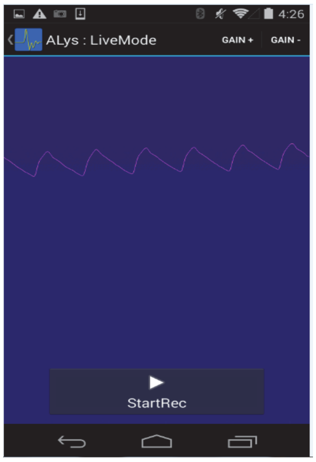

Figure 4: Pulse wave screen.

Figure 5: Coloured display of LLE.

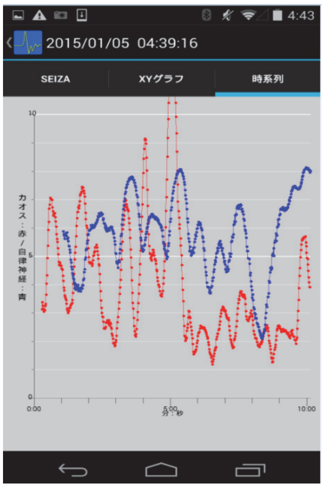

Figure 6: Time-series display of LLE (in red) and ANB (in blue).

Values of LLE and ANB are also displayed in time series. However, for ANB, the trial time period at the beginning of the measurement requires 60 seconds.

Moreover, LLE and ANB are displayed in Cartesian coordinates in real time, which visualizes the correlation of the two indexes.

At the end of the measurement, three semi-circular graphs are displayed, showing the results of the average values of LLE, ANB and vascular age respectively. As to Dr. Lyspect, these three graphs will also be displayed, among other detailed results, on the results window.

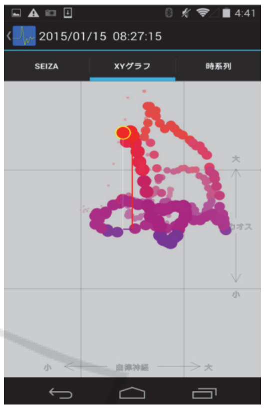

Figure 7: Display of the Cartesian coordinate plane (ANB: X-axis, LLE: Y-axis).

Figure 8: Semi-circular graphs of Lady Alys (top; from top to bottom: LLE, ANB and vascular age) and Dr. Lyspect (bottom; from left to right: LLE, vascular age and ANB).

4 APPLICATION EXAMPLES

There are various applications of the device. We illustrate two typical ones.

4.1 Real-time Check-up of Mental Status for Highway Drivers

One is the possible application for the enhancement of driver safety.

We collected the real-time LLE data of a driver who was driving on a highway (Figure 9).

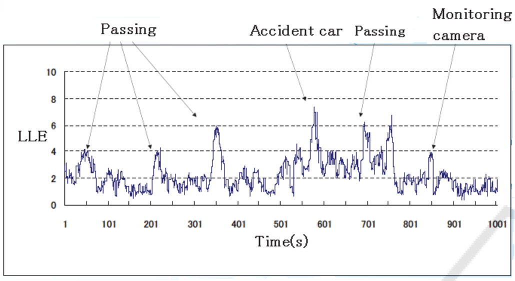

Figure 9: Driving experiment on a highway.

We observe that his LLE suddenly increased at several time points. These time points are actually when the driver was driving past another car, when he was passing a car that was stuck in the way due to accident, and when he was checking a monitoring camera. All these behaviours require carefulness and concentration that make the driver tense up. In Section 2.1, we have explained that a high value of LLE indicates strong mental immunity, which is inevitable in adapting oneself to the external environment.

A too high LLE represents the status of excessive stress that may give burden to the driver. On the other hand, however, if his LLE keeps low under such circumstances, the driver will be prone to operation error.

Therefore, self-adjustment is necessary in both extreme cases. "Lady Alys" can facilitate such self-adjustment in that it makes the real-time mental index visible to the driver who is driving. From this viewpoint, this device can help enhance traffic safety.

4.2 Caring for Amyotrophic Lateral Sclerosis Sufferers

The other is the potential application in the caring for the sick.

We conducted an experiment on the communication between a male end-stage Amyotrophic Lateral Sclerosis (ALS) sufferer and his wife. The patient's pulse waves were measured when his wife was talking to him for 16 minutes. The comprehensive result is obtained with "Dr. Lyspect" (Figure 10) (Undoubtedly, "Lady Alys" would be enough for the observation of time series of LLE).

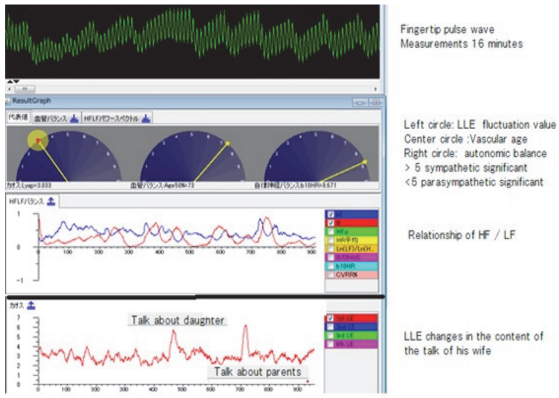

Figure 10: Conversation to end-stage ALS patients.

With end-age ALS, the patient was bedridden without any ability to initiate and control any voluntary movement, so he was not able to make any physical reaction to wife's talk.

However, from the graph of time series of LLE (bottom of Figure 10), we observe significant mental reaction of the patient. The LLE rose to the first peak when the wife was talking about their daughter, and then the second peak appeared when her topic moved to their parents. Since a high value of LLE indicates the mental status of external adaptation, this result reveals that the patient was actually listening to his wife attentively when she was talking about his concern.

The device can not only enable us to observe the emotional reaction of the patient, but also gratify the carer, namely, the wife in this experiment who realized that her husband did make response to her efforts.

In addition to ALS, we also conducted similar experiments with encephalopathy sufferers, and obtained the same conclusion.

In such a way, when physical communication is not possible, the simple measurement with "Lady Alys" can be of help for both carers and carees.

5 CONCLUSIONS

With this device, measurement with Android tablet or mobile phone can be easily conducted, irrespective of the limitation of place and time. The "Lady Alys" can help the users observe their real-time changes in mental status. The display with intuitive colours makes the values of LLE more visible. By conducting the measurement during various daily activities, the users are able to perform real-time mental check-up and then self-control according to his or her mental status.

The measurement is also possible to involve two or more subjects, in order to observe the reactions in their relationships, especially the carer-caree interaction.

In addition, admittedly, there are several drawbacks with the system. For example, instead of showing changes in the screen colour, an acoustic alarm would be more applicable, as it can make the driver much easier to recognize the alarm without sporadic attention to the smartphone screen. Such improvement is under consideration and will serve as a subject of our future study. Further development of wireless devices and the improvement of sensors are also in progress.

ACKNOWLEDGEMENTS

We would like to express our sincere thanks to Mrs. Mitsuko Tanabiki, Director, and the nursing staff members of Himeji Himawari Nursery School, for her cooperation in our experiments.

REFERENCES

Higa, M. (2011) *Autonomic nervous balance computation apparatus and method therefor*, U.S. Patent US 2011/0313303 A1.

Hu, Y., Wang, W., Suzuki, T. and Oyama-Higa, M. (2011) 'Characteristic extraction of mental disease patients by nonlinear analysis of plethysmograms', *AIP Conf. Proc.,* vol. 1371, pp. 92-101.

Oyama-Higa, M. and Miao, T. (2006) 'Discovery and application of new index for cognitive psychology', *2006 IEEE Conf. on Systems, Man, and Cybernetics Proc.,* vol. 4, pp. 2040–2044.

Oyama-Higa, M., Miao, T., Kaizu, S. and Kojima, J. (2012) 'Mental health self-check system using "Lyspect" ', *Proc. of the Sixth International Symposium on e-Health Services and Technologies,* Sixth International Symposium on e-Health Services and Technologies (EHST 2012), Geneva, pp.9-18.

Oyama-Higa, M., Miao, T., Tsujino, J. and Imanishi, A. (2008) 'Possibility of mental health self-checks using divergence of pulse waves', *Proc. of the First International Conference on Biomedical Electronics and Devices*, BIOSIGNALS 2008, Funchal, pp. 361-370.

Oyama, M. (2012) *Psychology of mental flexibility (English edition, Kindle)*, Seattle: Amazon Services International, Inc.

Pham, T.D., Oyama-Higa, M., Truong, C.T., Okamoto, K., Futaba, T., Kanemoto, S., Sugiyama, M. and Lampe, L. (2015) 'Computerized assessment of communication for cognitive stimulation for people with cognitive decline using spectral-distortion measures and phylogenetic inference', *PLos One*, vol. 10(3), e0118739.

Pham, T.D., Thang, T.C., Oyama-Higa, M., Nguyen, H.X., Saji, H. and Sugiyama, M. (2013) 'Chaos and nonlinear time-series analysis of finger pulse waves for depression detection', *Proc. of the International Conference on Bio-inspired Systems and Signal Processing,* BIOSIGNALS 2013, Barcelona, pp. 298-301.

Rosenstein, M.T., Collinsa, J.J. and De Luca, C.J. (1993) 'A practical method for calculating largest Lyapunov exponents from small data sets', *Physica D: Nonlinear Phenomena*, vol. 65, pp. 117-134.

Sano, M. and Sawada, Y. (1985) 'Measurement of the Lyapunov spectrum from a chaotic time series', *Phys. Rev. Lett.,* vol. 55, pp. 1082.

Sano, Y., Kataoka, Y., Ikuyama, T., Wada, M., Imano, H., Kawamura, K., Watanabe, T., Nishida, A. and Osanai, H. (1985) 'Evaluation of peripheral blood circulation to predict the possible impairment of circulatory organs by quadratic differential plethysmography and its application (in Japanese)', *Science of Labour,* vol. 61, no. 3, pp. 129-143.

Sumida, T., Arimitu, Y., Tahara, T. and Iwanaga H. (2000) 'Mental conditions reflected by the chaos of pulsation in capillary vessels', *International Journal of Bifurcation and Chaos*, vol. 10, pp. 2245-2255.

Tsuda, I., Tahara T. and Iwanaga. I. (1992) 'Chaotic pulsation in capillary vessels and its dependence on mental and physical conditions', *International Journal of Bifurcation and Chaos*, vol. 2, pp. 313-324.

Wang, W., Hu, Y., Oyama-Higa, M., Suzuki, T., Miao, T. and Kojima, J. (2012) 'Analysis of electroencephalogram and pulse waves during music listening', *Proc. of the Sixth International Symposium on e-Health Services and Technologies,* Sixth International Symposium on e-Health Services and Technologies (EHST 2012), Geneva, pp. 31-35.