Analysis of the Electrogastrograms of Elderly Subjects by using Maximum Lyapunov Exponent

Matsuura Yasuyuki, Miyao Masaru, and Takada Hiroki

***Abstract*— Not much data are available regarding the electrical activity in the stomachs and intestines of elderly gastrectomized patients. The purpose of this study was to determine the feasibility of using a complex dynamic method to analyze the electrogastrograms (EGGs) of healthy young, healthy elderly, and gastrectomized elderly male individuals. We analyzed the EGGs by using the maximum Lyapunov exponent (MLE), which is one of the indices of the chaotic characteristics of time series. Significant differences were observed between the MLEs estimated from the EGGs of the young and elderly individuals for most of the temporal intervals. Our data indicate that the EGGs of elderly gastrectomized subjects might be distinguished from the EGGs of healthy elderly individuals on the basis of the MLE distribution.**

I. Introduction

MANY young women suffer from gastrointestinal diseases such as constipation and functional dyspepsia including gastroesophageal reflux disease (reflux esophagitis). Percutaneous electrogastrograms (EGGs) unrestrainedly and easily measure gastrointestinal activities.

The first electric activity record on the body surface was performed by Alvarez in 1921, and he named it an electrogastrogram (EGG) [1]. EGGs were easily affected by electrocardiograms (ECGs) and electromyograms (EMGs) of the diaphragm during breathing due to the law induced potential from the abdominal wall. There was also no clear association with gastric activity and data analysis methods, and, therefore, they did not achieve clinical application like ECGs and electroencephalograms.

There is regular electrical activity in the stomach and small intestine, like the heart, and electric depolarization and repolarization are repeated. A pacemaker for gastric electrical activity exists in 1/3 of the greater curve of the gastric body, and electrical activity travels to the pyloric part 3 times per minute (3 cpm, cycle per minute) in humans. The pacemaker triggers periodical electric activities controlled by the vagus nerve. This involves a cell group network called the interstitial cells of Cajal (ICCs) [2 – 4].

The advantages of EGGs were their utility to measure the above-mentioned periodical electric activity and evaluate the (gastrointestinal) autonomic nerve function. In the stomach of resting healthy individuals, peristalsis occurs 3 times per minute when a certain period of time has passed after meals [2 – 4]. The normal range of the EGG fluctuation cycle is between 2.4 – 3.6 cpm, but there is no clear standard except for a frequency close to 3 cpm [5, 6].

EGG studies have made progress with the recent improvement of measurement technology. However, the common EGG analysis method is a spectral analysis technique such as Fast Fourier Transform (FFT), and few reports are available on non-linear analysis. However, considering complex organic activity, non-linear analysis methods including chaos analysis and evaluation based on stochastic process analysis are considered inevitable for the modelization of dynamic movement, an accurate diagnostic index, and extraction of a body assessment index.

Maximum Lyapunov exponent (MLE) is a common index of non-linear analysis [7, 8], and has been widely used in various fields including economic model and sound analysis [9 – 11]. In biosignal analysis, biosignals are considered to be generated based on the non-linear dynamic systems with a few degrees of freedom in the pulse and brain waves, and R – R interval of ECG. Therefore, chaos analysis is used [12 – 13]. In contrast, few reports are available on the chaos analysis of EGGs using the Lyapunov exponent.

A previous study showed that there were groups with and without gastric electrical activities in subtotal gastrectomy cases, although no EGG was recorded in total gastrectomy cases [14]. Therefore, it is difficult to diagnose and judge gastrectomized EGGs of healthy individuals and gastrectomized patients whose intestinal electrical activities and digestive functions decline with age solely with spectral analysis.

The purpose of the present study was to perform a basic examination of non-linear analysis application in EGG. The EGGs of healthy young males, healthy elderly males, and elderly gastrectomized males were analyzed using MLE, which analyzes the chaos of time series signals, and compared.

This work was supported in part by scientific research fund grants (Grant-in-Aid for Scientific Research) and the Young Project "The influence of hot fomentation in the stomach on chronic constipation in the middle-aged and elderly" (2007) by the Japanese Society of Public Health Active Research Fund, and the Hori Art and Science Promotion Foundation.

Matsuura Yasuyuki is with University of Fukui Headquarters for Innovative Society-Academia Cooperation, 3-9-1 Bunkyo, Fukui City, Fukui JAPAN (e-mail: matsuura@ nagoya-u.jp).

Miyao Masaru is with Graduate School of Information Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya JAPAN (e-mail: mmiyao@ is.nagoya-u.ac.jp).

Takada Hiroki is with Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui City, Fukui JAPAN (corresponding author to provide phone: +81-776-27-8795; fax: +81-776-27-8955; e-mail: takada@u-fukui.ac.jp).

II. MATERIALS AND METHODS

A. Method

Subjects were 7 healthy young males aged between 21 and 25, 7 healthy elderly males aged between 65 and 76, and 3 elderly gastrectomized males aged between 67 and 76 whose stomach had been resected by more than 2/3. A full explanation was given to the subjects prior to the experiment, and signed consent forms were obtained. The research on young individuals was approved by the Ethics Committee, Nagoya City University Graduate School of Natural Sciences, and the research on healthy elderly and elderly gastrectomized males was approved by the Ethics Committee of Aichi Medical University.

EGG in a supine position was conducted for 90 minutes. Measurement was performed in a sound-insulated (40 dB) experimental room without windows. The room temperature was between 20 – 24℃, humidity was 40 – 55%, and the air current was below 0.1 m/s. Subjects were told to finish meals 2 hours before measurement so that it was not affected by the meals. Measurement was started between 14:00 and 15:00 for all subjects to avoid the influence of circadian rhythm (circadian change).

EGG measurement was performed using unipolar induction. The measurement was amplified by a biomedical amplifier (MT11: NEC Medical), and recorded in a data recorder (PC216 Ax, Sony Precision Technology).

Several methods have been proposed for EGG measurement methods [5], and the number of electrodes and pasting position vary. All the measurement and pasting methods include measurements involving the area closest to the stomach pacemaker. Therefore, measurement was performed in the area closest to the stomach pacemaker in the present study.

EGG electrodes were pasted as shown in Fig. 1, using 2 disposable ECG electrodes (Vitrode Bs, Nihon Kohden). Pasting was performed after confirming a sufficient reduction of skin resistance using Skin Pure (Nihon Kohden).

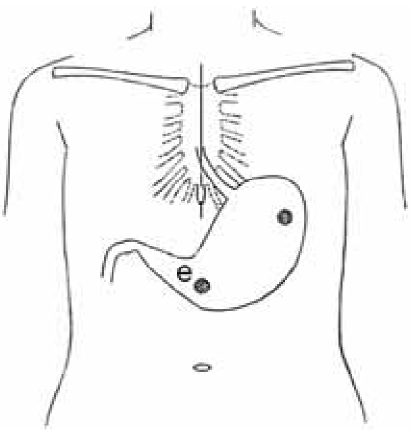

Fig. 1. Pasting position of EGG electrodes.

B. Time-series extraction

The recorded EGG was A/D converted at 1 kHz to obtain time-series data. A low-pass filter for a 0.15-Hz treble cutoff frequency was applied to the obtained data to remove electronic noise from the incorporated EMG and electronic devices, and resampling was performed at 1 Hz to remove noise.

The EGG time series with removed noise was moved at a 300-point (5-minute) interval in a 1,200-second (20 minutes) time window to divide data. EGG time series for a total of 255 subjects (supine position: 15 cases x 17 subjects (7 young healthy, 7 elderly healthy, and 3 gastrectomized individuals)) were developed for analysis.

C. Analysis method

The Lyapunov exponent is a quantity that characterizes the rate of separation of two trajectories on an attractor with time, and demonstrates the enlarged distance of the behavioral gap caused by a minute initial gap [7, 8]. The maximum exponent is called MLE. This exponent quantitatively evaluates the complexity of the attractor that formulates the time series $\{x_t\}_{t=0}^{1199}$.

The Rosenstein analysis method was used in the present study [15, 16]. The attractor was constructed using the obtained data. An infinitesimally close point $\mathbf{x_j}$ from the point $\mathbf{x_i}$ on the attractor was created, and the ratio of the distance with d intervals was assessed by the changes with time as shown in the following Eq.(1).

$$\Delta_i(t,d) = \frac{|\mathbf{x_i(t+d)} - \mathbf{x_j(t+d)}|}{|\mathbf{x_i(t)} - \mathbf{x_j(t)}|} \quad (1)$$,

where the interval d expresses an embedded dimension. The calculations are made for multiple pairs, and uniform operation is performed using the following formula:

$$\langle \log \Delta(t,d) \rangle = \frac{1}{N} \sum_{i=1}^{N} \log \Delta_i(t,d) \quad (2)$$

The Lyapunov exponent λ is estimated using the following formula in which τ means the embedding delay:

$$\lambda(d) = \frac{1}{\tau} \langle \log \Delta(t,d) \rangle \quad (3)$$.

There is a potential for the time series to show chaos when MLE is positive [7, 8]. The bigger the value, the more irregular the wave becomes, suggesting a complex orbit [7, 8]. In the present study, numbers were fixed including the data length for 1,200 points, d for 3 (dimension), and τ for 3 to estimate the MLE.

III. RESULTS

Fig. 2 shows EGGs of healthy young (a), healthy elderly (b), and gastrectomized individuals (c) 10 minutes after measurement initiation for 5 minutes. Normal fluctuation cycles are observed in EGGs of Figs.2 (a), (b), and (c). However, EGGs of the healthy young individuals (Fig. 2 (a)) showed a large amplitude and unstable fluctuation cycle. In contrast, EGGs of the healthy elderly (Fig. 2 (b)) showed a regular pattern, and that of gastrectomized individuals showed wavelengths with a shorter cycle compared to the two other groups, suggesting a different fluctuation pattern.

Figs. 3 (a), (b), and (c) show the two-dimensional attractors (τ=3) formed based on EGGs of the healthy young (Fig.2 (a)), the healthy elderly (Fig.2 (b)), and gastrectomized individual (Fig.2 (c)), respectively.

Fig. 4 shows fluctuation of the average and the standard deviation of the MLE estimated from EGGs of the healthy young, healthy elderly, and gastrectomized individuals. Fig. 5 shows the frequency distribution of the MLE estimated from EGGs of the healthy young, healthy elderly, and gastrectomized individuals.

MLEs of EGGs in the healthy young ranged from 0.69 – 0.79, with an average of 0.75, standard deviation of 0.018, and standard error of 0.069. MLEs of EGGs in the healthy elderly ranged from 0.59 – 0.76, with an average of 0.72, standard deviation of 0.031, and standard error of 0.012. MLEs of EGGs in the gastrectomized individuals ranged from 0.68 – 0.78 with an average of 0.73, standard deviation of 0.028, and standard error of 0.016. The MLE was positive in all subjects and all analysis intervals. The results suggested that sensitivity to initial conditions was seen in EGGs of the healthy young, healthy elderly, and gastrectomized individuals. There was a significant difference in MLEs estimated from EGGs of the healthy young and healthy elderly according to the time.

IV. DISCUSSION

MLEs were estimated based on EGGs of healthy young, healthy elderly, and gastrectomized individuals. The results showed that MLEs of healthy young individuals were around 0.74. In contrast, MLEs of healthy elderly individuals were around 0.72. The results suggested that EGGs of healthy young individuals are more irregular in wavelength and

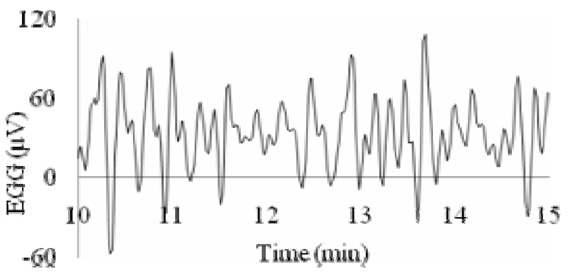

Fig. 2(a). Example of an EGG in a healthy young individual

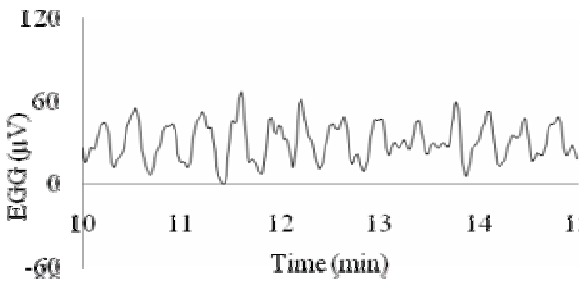

Fig. 2(b). Example of an EGG in a healthy elderly individual

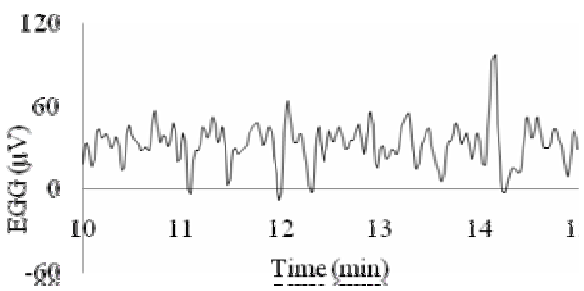

Fig. 2(c). Example of an EGG in a gastrectomized individual

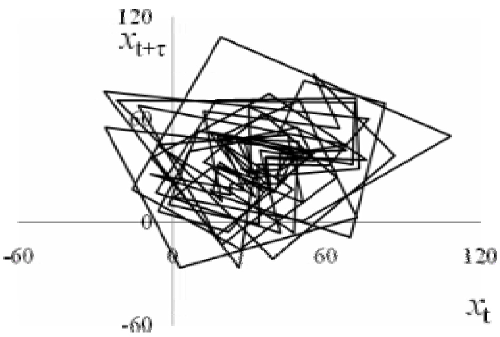

Fig. 3(a). Attractor of the healthy young EGG (Fig. 2(a))

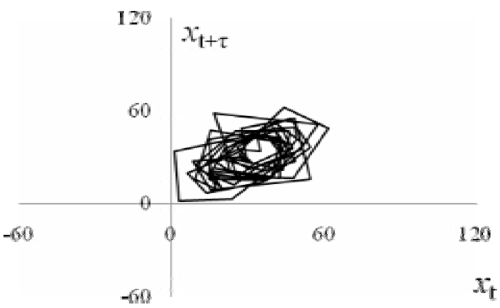

Fig.3(b). Attractor of the healthy elderly EGG (Fig. 2(b))

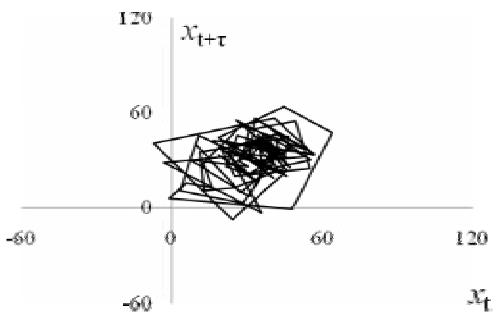

Fig. 3(c). Attractor of the gastrectomized EGG (Fig. 2(c)) complex in the orbit compared to those of the healthy elderly. Although MLEs of the healthy young and healthy elderly EGGs generally continued to be flat, MLEs of gastrectomized individuals' EGGs changed over time. This is considered to be due to the fact that part of the gastric pacemaker cell group was lost on subtotal gastrectomy, and the electrical activity-derived component of the intestine was dominant in the EGG wavelength.

The shape of the MLE frequency distribution showed a one-peak distribution in the healthy young, strained-floor distribution in the healthy elderly, and multiple-peak distribution in the gastrectomized individuals. The elderly show larger individual differences compare to the young. This causes a strained frequency distribution and greater variance in the healthy elderly. Multiple-peak distribution of MLEs in the gastrectomized individuals is considered to be caused by transmission fluctuation of gastric electrical activity due to gastrectomy.

In this study, EGGs of the healthy young, healthy elderly, and gastrectomized individuals were compared using an index in the non-linear analysis. The indices in the non-linear analysis are expected to apply to the evaluation of motion sickness induced by stereoscopic movies.

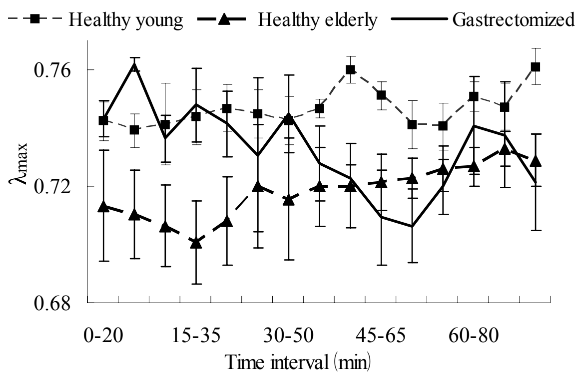

Fig. 4. Average and standard error of MLE (λ_{max})

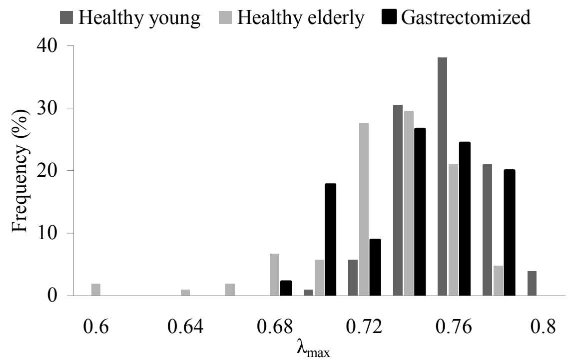

Fig.5. Frequency distribution of MLE (λ_{max})

V. Conclusion

EGGs of the healthy young, healthy elderly, and gastrectomized individuals were compared using the MLE, which is an evaluation method of time-series chaos as a basic examination of non-linear analysis method application to EGG.

There was a significant difference in MLEs estimated from EGGs of the healthy young, healthy elderly, and gastrectomized individuals according to the time. There is a potential for EGG classification of gastrectomized individuals based on the MLE distribution.

The MLE was used for analysis in the present study, and further basic examinations are planned employing other non-linear analysis methods.

EGGs of 3 gastrectomized individuals were used in the present study. Further studies are planned with an increasing number of cases.

References

[1] W. C. Alvarez, "The electrogastrogram and what it shows," *Journal of the American Medical Association*, vol.78, pp.1116-1119, 1922.

[2] S. Homma, "Isopower mapping of the electrogastrogram (EGG)," *Journal of the Autonomic Nervous System*, vol.62, pp.163-166, 1997.

[3] L. K. Kenneth, M. Robert, *Handbook of Electrogastrography*, Oxford University Press, Oxford, 2004.

[4] J Z. Chen, R. W. McCallum, *Electrogastrography Principles and Applications*, Raven Press, New York, 1994.

[5] J. Z. Chen, R. W. McCallum, "Clinical applications of electrogastrography", *American Journal of Gastroenterology*, vol.88, no. 9, pp.1324-1336, 1993.

[6] M. Nagai, M. Wada, Y. Kobayashi, S. Togawa, "Effects of lumbar skin warming on gastric motility and blood pressure in humans", J*apanese Journal of Physiology*, vol.53, no. 1, pp.45-51, 2003.

[7] A. M. Lyapunov, *The general problem of the stability of motion*, Comm. Soc. Math., Kharkow, 1892 (in Russian) (reprinted in English, A. M. Lyapunov, "The general problem of the stability of motion," *International Journal of Control*, vol.55, no.3, pp.531-534, 1992)

[8] C. Sato, *Theory of nonlinear oscillation*. Asakura Shoten, Tokyo, 1970.

[9] M. Tanaka-Yamawaki, M. Tabuse, "A Dynamical Model of the Economic System : Simulation and its Time Series Analysis," *Technical report of IEICE*, NLP98-4, pp.23-29, 1998.

[10] E. Hojin, Y. Shiraishi, N. Furuse, "A Comparison among Lyapunov Exponents Calculation Methods in Human Voice Analysis," *Technical report of IEICE*, CAS2003-3, pp.13-18, 2003.

[11] T. Suzuki, M. Nakagawa, "Fluctuation of the vocal sound and its chaotic and fractal analyses," *Technical report of IEICE*, NLP2004-55, pp.7-12, 2004.

[12] T. Sugiura, T. Iokibe, S. Murata, M. Koyama, "A Method for Discrimination of Arrhythmia by Chaotic Approach," *Journal of Japan Society for Fuzzy*, vol.8, no. 3, pp.541-546, 1996.

[13] Y. Fujiwara, H. Genno, K. Matsumoto, R. Suzuki, K. Fukushima, "Estimating Human Sensations Using Chaos Analysis of Nose Skin Temperature," *Journal of Japan Society for Fuzzy*, vol.8, no.1, pp.95-104, 1996.

[14] K. Imai, M. Sakita, "Pre- and postoperative electrogastrography in patients with gastric cancer," *Hepatogastroenterology*, vol.52, pp.639-644, 2005

[15] M. T. Rosenstein, J. J. Collius, C. J. De Luca, "A practical method for

calculating largest Lyapunov exponents from small data series," *Physica D*, vol.65, pp.117-134, 1993.

[16] S. Sato, M. Sano, Y. Sawada, "Practical methods of measuring the generalized dimension and the largest Lyapunov exponent in high dimensional chaotic systems," *Progress of theoretical physics*, vol.77, no.1, pp.1-5, 1987.