Proposal for a New Diagram to Evaluate the Form of the Attractor Reconstructed from Electrogastrography

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Electrogastrography (EGG) measures the electrical activity of the stomach through electrodes placed on the abdomen, which is primarily rhythmical. We analyzed the attractor reconstructed from EGG data and the factors characterising diseases resulting from constipation and erosive gastritis. The degree of determinism and complexity in the attractor are measured using the translation error and the maximum Lyapunov exponent, respectively. A new diagram is proposed to evaluate differences in the waveform of time-series data and to classify EGG data for the sitting and supine positions. Postural change enhanced the complexity in the attractor. Changes were also observed in the waveform characteristics.

Key words: Wayland Algorithm, Translation Error, Maximum Lyapunov Exponent (MLE), Electrogastrography (EGG)

1. Introduction

Attractors can be reconstructed using dynamical equation systems such as the Duffing equation, Henon map, and Lorenz differential equation. It is very interesting to note that the structure of an attractor derived from time series data obtained by electrogastrography (EGG) can also be represented in a phase space (an embedding space). The form of the attractor is regarded as a subject of mathematical interest and can be measured by using Wayland (Wayland *et al*., 1993) and Rosenstein's algorithm (Sato *et al*., 1987; Rosenstein *et al*., 1993). In this study, a novel projection of the attractor is proposed for the evaluation of the form of the attractor. The time series data obtained by EGG are analysed using these algorithms.

Contraction of the smooth muscles in the stomach and intestine is controlled by electrical activity. This electrical activity can be recorded using an EGG, which also detects other biological signals. EGG is a non-invasive procedure used to evaluate gastrointestinal motility and autonomic nervous system activity, for the diagnosis of the diseases of the alimentary canal and autonomic nervous system and for confirming the effectiveness of the therapy administered.

In 1921, Walter C. Alvarez reported performing EGG for the first time in humans (Alvarez, 1922). In EGG the electrical activity of the stomach is recorded by placing the electrodes on the surface of the abdominal wall (Hongo and Okuno, 1992).

Many previous studies on EGG have been reported, and most of them pertained to the clinical field (Chen and McCallum, 1993), e.g., evaluation of the effects of hormones and drugs on EGG and the relationship between EGG and the motion sickness. EGG has been used to study the effects of warm compresses (for the improvement of constipation) on gastrointestinal activity (Nagai *et al*., 1993), the usefulness of warm compresses in the epigastric region for the improvement of constipation (Kawachi *et al*., 2002), and characterization of intestinal activity in patients with chronic constipation (Matsuura *et al*., 2003).

In stomach, a pacemaker on the side of the greater curvature generates electrical activity at a rate of 3.0 cycles per minute (3 *cpm*); the electrical signal is then transferred to the pyloric side (Fig. 1) (Kwong *et al*., 1970; Counturier *et al*., 1972; Hinder and Kelly, 1977). Previously, it was difficult to measure this electrical activity because the EGG signal was composed of low-frequency components and high-frequency noise caused by the electrical activity of the diaphragm and heart. However, the accuracy of EGG measurements has improved recently, and gastroenteric motility can be evaluated by spectrum analysis of the EGG signals (Van Der Schee *et al*., 1982; Van Der Schee and Grashuis, 1987). Gastric electrical potential is generated by interstitial cells of Cajal (ICCs) (Fig. 1). The ICCs are the pacemaker cells that spontaneously depolarize and repolarize at a rate of 3 *cpm*. They demonstrate low-amplitude, rhythmic, and circular contractions only if the electrical potential is over a threshold.

Human gastric pacemaker potential migrate around the stomach very quickly and moving distally through the antrum in approximately 20 seconds resulting in the normal gastric electrical frequency of 3 *cpm*. It is the moving electrical wavefront that is recorded in the electrogastrography (EGG), the gastric myoelectrical activity is recorded using electrodes placed on the surface of the epigastrium (the pit

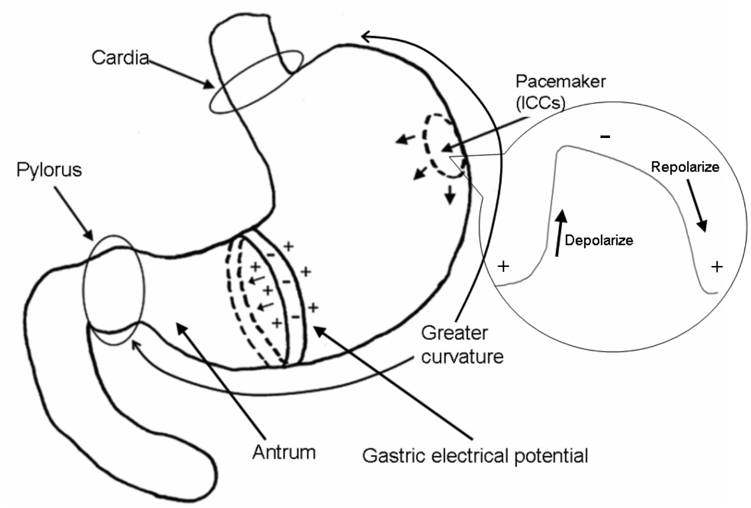


Fig. 1. Travelling wave in the gastric electrical potential.

of the stomach). However, EGG also contains other biological signals, for instance, electrical activity of the heart, intestinal movements, and myenteric potential oscillations in general.

Some studies have discussed solutions to the forward and inverse problems associated with the dynamics generating the gastric electrical potential (Kothapalli, 1993; Liang and Chen, 1997; Irimia and Bradshaw, 2005). These studies suggest that it is convenient to use current dipoles in an ellipsoid and use the computer simulations to generate a mathematical model for the stomach. However, there are no studies on the form of attractors reconstructed from EGG data. We have applied a complex dynamical analysis method (Wayland and Rosenstein algorithms) for EGG analysis.

The Wayland algorithm has been developed in order to evaluate the degree of determinism for dynamics that generate a time series (Wayland *et al.*, 1993). This algorithm can estimate a parameter called translation error (E_{trans}) to measure smoothness of flow in an attractor, which is assumed to generate the time-series data. In general, the threshold of the translation error for classifying the time-series data as deterministic or stochastic is 0.5, which is half of the translation error resulting from a random walk.

The chaos processes generate complexity in the attractor. For instance, the processes have sensitive dependence on initial conditions and can be quantified using the Lyapunov exponent (Lyapunov, 1892). If the Lyapunov exponent has a positive value, the dynamics is regarded as a chaotic process. In this study, Rosenstein's algorithm (Rosenstein *et al.*, 1993; Sato *et al.*, 1987) was used to calculate the maximum Lyapunov exponent (MLE, λ).

The purpose of this study is to propose a new diagram (E_{trans}-λ) to evaluate difference in the waveform of the time-series data. This diagram is two-dimensional; it shows the translation error (E_{trans}) and the MLE (λ). The EGG data obtained during sitting posture and supine posture (lying with the belly upwards) were classified on the basis of this diagram.

2. Method

2.1 Calculation of E_{trans}-λ diagram

In E_{trans}-λ diagram, one time series is represented as a single point in two-dimensional space. Thus, one EGG data item is projected as a single point on this plane. The diagram is constructed with the abscissa representing E_{trans} and the ordinate representing λ.

To remove the noise from the time series of EGG $\{y_j \mid j = 0, 1, 2 \dots, N-1\}$ data obtained at 1 kHz, resampling was performed at 0.5 Hz. For analysis we then obtained a resampled time series $\{x_i \mid i = 0, 1, 2 \dots, (N/20000) - 1\}$ as follows;

$$x_0 = \frac{1}{2000}\sum_{j=0}^{1999} y_j,\ x_1 = \frac{1}{2000}\sum_{j=1\times 2000}^{3999} y_j, \dots,$$
$$x_i = \frac{1}{2000}\sum_{j=i\times 2000}^{i\times 2000+1999} y_j.$$

The delay coordinates used were as follows:

$$\{\vec{x}_t = (x_t \quad x_{t+\tau} \quad \cdots \quad x_{t+\tau(m-1)})\}.$$

Here, m represents the embedding dimension. These delay coordinates can be used to reconstruct a continuous trajectory without intersections in an embedding space having a large m. Embedding delay τ is defined as a minimum delay time ($\tau \geq 0$) when the auto-correlation coefficient is regarded as zero. Linear correlations must be left between vicinal components of the delay coordinates unless the time series data is resampled every embedding delay τ. The auto-correlation function $\hat{\rho}(t)$ was estimated from the time series data (Matsumoto *et al.*, 2002). We assumed that there is no correlation when $\hat{\rho}(t)$ decreased below $1/e$ for the first time ($t \geq 0$) in this study.

In this study, the EGG data obtained at 10-min intervals, were analyzed using the Wayland algorithm and Rosenstein's algorithm. The procedure for plotting the E_{trans}-λ diagram is as follows.

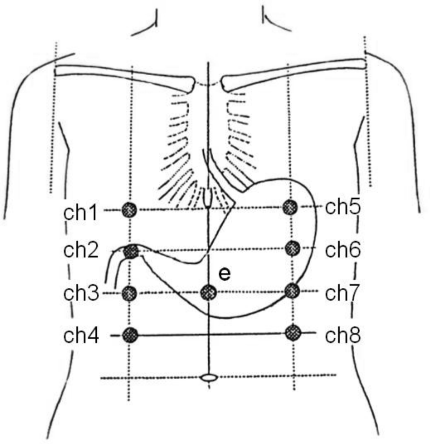


Fig. 2. Positions of electrode. In this study, we analyze the EGG data recorded on the ch5.

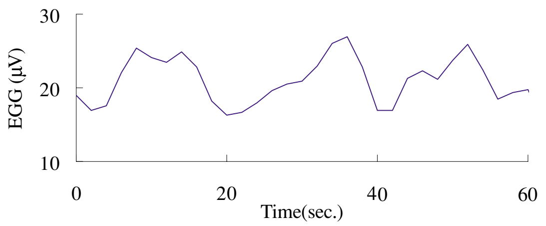


Fig. 3. A typical EGG with sampling frequency set to 0.5 Hz. The EGG has been recorded for 1 min after the onset of our measurement.

1) Analyze EGG data using the Wayland algorithm and estimate the translation errors (E_{trans}) in the attractors generating from the EGG data.

2) Analyze EGG data using the Rosenstein's algorithm, and calculate MLEs (λ) in the attractors generating from the EGG data using embedding delays and the embedding dimensions m (derived from 1).

3) Plot points on the E_{trans}-λ diagram. The abscissa represents the translation error (E_{trans}), and the ordinate represents the MLE (λ).

2.2 Physiological procedure

The subjects were 14 healthy people (7 M & 7 F) aged 21–25 years. Sufficient explanation of the experiment was provided to all subjects, and a written consent was obtained from them.

EGGs were obtained for 30 min in the sitting position and 150 min in the supine position at 1 kHz using an A/D converter (AD16-16U (PCI) EH; CONTEC, Japan). They were amplified using a bio-amplifier (MT11; NEC Medical, Japan) and recorded using a tape recorder (PC216Ax; Sony Precision Technology, Japan). In this experiment, 9 disposable electrodes (Blue Sensor; Medicotest Co. Ltd., Ølstykke, Denmark) were affixed on ch1-ch8 and e, as shown in Fig. 2. The electrode affixed on e was a reference electrode. Prior to the application of electrodes, the skin resistance was sufficiently reduced using SkinPure (Nihon Kohden Inc., Tokyo, Japan). EGG data obtained at ch5, which is the position closest to the pacemaker of gastrointestinal motility, were analyzed in this study.

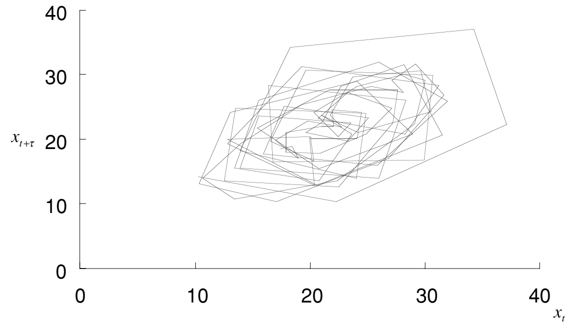


Fig. 4. An example of the attractor reconstructed from the EGG time-series data (100 sec.).

3. Results

We analyzed the EGG data obtained at ch5. Regular 3-*cpm* slow waves could be observed, but the amplitude of the wave fluctuated irregularly (Fig. 3). The Wayland algorithm was applied to attractors in the case of all the 252 (14 subjects $\times$ 18 $\times$ 10 min – EGGs = 252 EGGs) EGG data items (Fig. 4).

1) The translation errors were distributed from 0.21 to 0.67. The average $\pm$ standard deviation in the E_{trans} derived from the EGG data obtained in the sitting position and the supine position were 0.48 ± 0.089 and 0.50 ± 0.068, respectively. Of the 42 E_{trans} for the sitting position and the 210 E_{trans} for the supine position, 23 and 97 E_{trans}, respectively, were less than 0.5.

2) The embedding delays and embedding dimensions were distributed from 2 to 4 and from 2 to 7, respectively. Large MLEs were obtained from some EGG data obtained in the supine position. The average $\pm$ standard deviation in the MLEs was 0.80 ± 0.45.

3) All 252 EGGs were projected onto an E_{trans}-λ diagram (Fig. 5). Those obtained in the sitting and the supine positions were projected onto E_{trans}-λ diagrams (Figs. 6a and 6b, respectively). The distribution of the MLEs was obtained as 0.64 ± 0.13 (sitting position) and 0.84 ± 0.48 (supine position). The EGGs obtained for the supine position was projected onto E_{trans}-λ diagrams every 30 min (Fig. 7). Large MLEs were derived from EGG data measured for 30 minutes after the first interval during supine position, as shown in Fig. 7a. One-way analysis of variance (ANOVA) was employed to analyze the temporal variations in the MLEs and E_{trans} derived from the measurement for the supine position. The results indicated no significant variance in E_{trans}, although there were significant variance in MLEs ($p < 0.05$). The post-hoc test was applied to the MLEs. The MLE at the supine position in the initial 30 minutes (Fig. 7a) was significantly larger than the MLE at any other intervals (Figs. 7b–e).

4. Discussion

In this study, we analyzed EGG time-series data using complex dynamical methods. Translation errors (E_{trans}) and MLEs (λ) were calculated from the EGG data. E_{trans} was distributed from 0.2 to 0.7. In some cases, $E_{trans} \geq 0.5$ was obtained by the Wayland algorithm, which implies that the time series could be generated by stochastic processes in

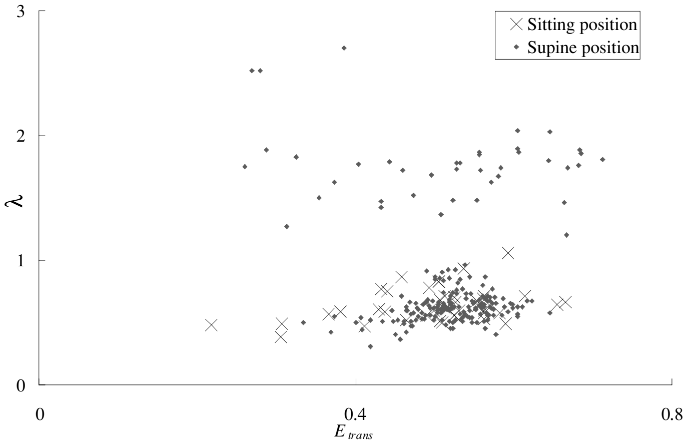
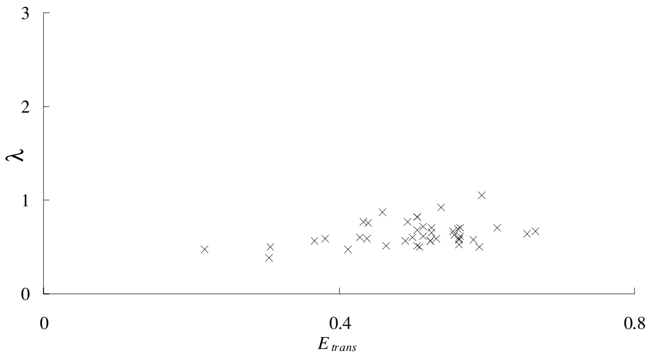
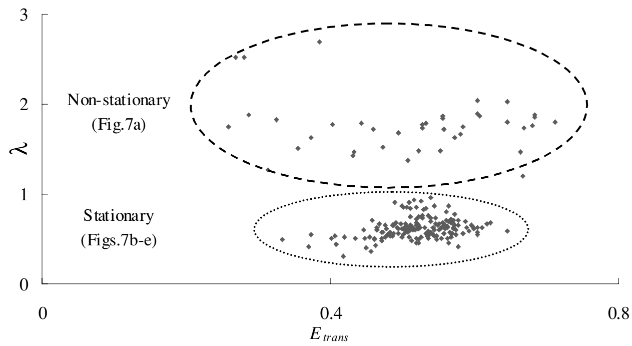


Fig. 5. An E_{trans}-λ diagram. × represent EGG data obtained with the subjects in the sitting position and ♦ represent data for the supine position.



(a) Sitting



(b) Supine

Fig. 6. E_{trans}-λ diagrams for the data for the sitting position in (a) and for the supine position shown in (b). The obtained data (b) were classified into two cases, in stationary and non-stationary state. EGG data measured for 30 minutes after the first interval during supine position were projected onto the region upper the cluster of points for this E_{trans}-λ diagram, which would be reproduced in Fig. 7a.

accordance with the previous standard. It is considered that the EGG data are generated from the intermediate dynamics of deterministic and stochastic processes. On the other hand, there was no exception that Lyapunov exponents were positive without exception. Hence, sensitive dependence on initial conditions was observed in the attractors that were recomposed from the EGG data.

There were 2 clusters in the E_{trans}-λ diagram for the supine position (Fig. 6b). All points in the E_{trans}-λ diagram for the sitting position were distributed around the lower cluster.

According to the analysis of the degree of determinism for the time series dynamics, EGG data obtained for 30 min after postural change were significantly different from the other EGG. Autonomic nervous system controls the gastric electrical activity, which can be measured by EGG. The

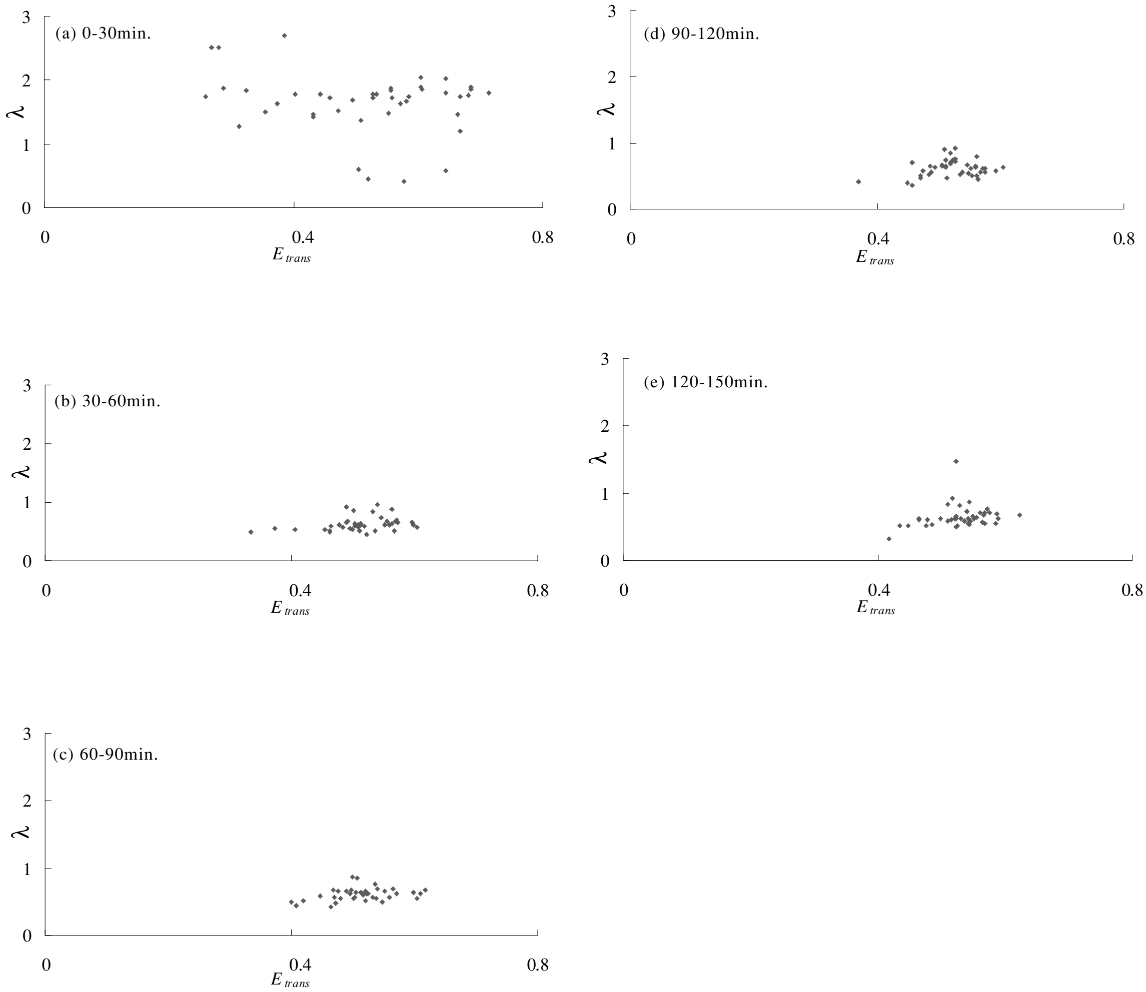


Fig. 7. E_{trans}-λ diagrams derived from EGG data for the supine position (a) 0–30 min., (b) 30–60 min., (c) 60–90 min., (d) 90–120 min., (e) 120–150 min.

autonomic nervous system might not be represented by a stationary process.

In this study, we proposed a new diagram (E_{trans}-λ) and could qualitatively measure characteristics of the waveform in the EGG data obtained in the sitting and supine positions. The change in posture accounted for the difference in the EGG characteristics. Our novel diagram demonstrated these changes. We considered that blood pressure in the entire body was constant because of the gravity-related fluid shift, which occurred due to the change in position from sitting to supine. The autonomic nervous system was stimulated by the baroreflex (one of the body's homeostatic mechanisms for maintaining blood pressure.) and parasympathetic nerve activity is dominant. Thus, it can be represented by a non-stationary process (Fig. 6b).

The diseases resulting from constipation and erosive gastritis (an illness in which the inside of the stomach becomes swollen and painful) are accompanied with anomalous autonomic nervous activity. A decline in the electrical activity of the stomach should increase the degree of determinism (E_{trans}). Conversely, excessive electrical activity would enhance the complexity (λ) in the attractor reconstructed from the EGG data.

Most previous studies were aimed at clinical applications, and the subjects were patients. There are few studies on the EGG dynamics for healthy subjects (normal EGGs). However, Sarna *et al.* proposed the van der Pol equation (VPE) as a mathematical model of electrically controlled activity of dog's stomach (Sarna *et al.*, 1972). The VPE is a non-linear differential equation of the second order, which is well known as a mathematical description for the transition between 2 states. In terms of physiology, these states may be referred to as the depolarized and repolarized states in the local interstitial cells. By improving the precision of the mathematical model of normal EGG data, we can qualitatively evaluate abnormal EGG data, for instance, in the case of tachygastria (increased rate of electrical pacemaker activity in the stomach, defined as more than 4 *cpm*) (Hongo and Okuno, 1992) or a disorder of the alimentary canal.

The VPE is regarded as a deterministic process. However, EGG data are necessarily generated using a deterministic process, in accordance with our analysis using the Wayland algorithm (Wayland *et al.*, 1993; Matsuura *et al.*, 2007). As a mathematical model of EGG, we now propose the following stochastic differential equations in which the periodic function is included in Eq. (1).

$$\dot{x} = y - \lambda \, \mathrm{grad} f(x) + s(t) + \mu w_1(t) \qquad (1)$$

$$\dot{y} = -x + \mu w_2(t) \qquad (2)$$

$$s.t. \quad f(x) = \frac{1}{12}x^4 - \frac{1}{2}x^2. \qquad (3)$$

The function $s(t)$ and the white noise $w_i(t)$ represent intestinal movements and other biological signals, for instance, myenteric potential oscillations that are weak and random, respectively ($i = 1, 2$). The double-well potential $f(x)$ generates depolarizations and repolarization in interstitial cells. In the next step, we will employ numerical simulations of Eq. (2). By comparing E_{trans}-λ diagrams derived from EGG data and numerical simulations of Eq. (2), we will evaluate Eq. (2) as a mathematical model of EGG data.

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