Abstract—The fingertip pulse waves (plethysmograms) of 179 elderly people were measured and chaos analysis were performed on these waves to calculate the largest Lyapunov exponent, we acquired dementia data and ADL index recorded by healthcare professionals for the same subjects. We discovered a significant relationship between the value of the largest Lyapunov exponent and the degree of dementia and also communication skill. The relationship is displayed as a constellation graph of the time series.

I. INTRODUCTION

Almost biological systems that exist in the natural world are believed to be complex systems with chaotic fluctuations. Chaotic systems appear to be very complex and to behave in a random and unstable manner. But in fact they are systems that change according to deterministic rules. Biological signals collected from fingertip pulsations constitute time series data with chaotic characteristics [1]. In the present study, we recorded fingertip pulse waves of aged subjects, carried out chaos analysis on the plethysmogram data thus obtained, and examined their relationship with dementia. We found a clear relationship between the Lyapunov exponents of the time series, obtained by chaos analysis of the plethysmogram data, and dementia and communication skill. Further, it became clear that among the activities of daily living of aged persons observed by persons providing them care, communication skill had a high correlation with the severity of dementia diagnosed clinically. Measurement of fingertip pulse waves, which are biomedical signals, is easier than electroencephalography because it is less restrictive and more convenient. In the present study, we conducted experiments to examine whether senile and other types of dementia have any relationship with the fingertip pulse waves. The study subjects were aged persons living in an old people’s home and persons receiving day-care there. The fingertip pulse waves of each subject were measured and chaos analysis carried out with 3 minutes of time series data thus obtained. The chaos attractor, entropy and the Lyapunov exponent, which is a measure of divergence of the entropy trajectory, were calculated as time series data. We gathered data on the Activities of Daily Living (ADL) measured by persons who took care of the aged subjects and criteria for different severity of dementia as the criteria for estimating the condition of the life and severity of dementia of the subjects. The relationship of the ADL indices obtained by chaos analysis with the severity of dementia was analyzed. As a result, we discovered that the mean value and standard deviation of the Lyapunov exponent of the time series had a clear relationship with the severity of dementia and the communication skill of the aged subjects. We further examined the relationship between dementia and communication skill. We could also clearly demonstrate the relationship between dementia and the Lyapunov exponents through constellation graphs of the time series data, prepared by one of the authors.

II. METHOD

A. Study subjects, Study location and Study period.

For the informed consent of the selected subjects, consent was obtained both from the old people’s home of the subjects and their families.

Number of subjects
- Total 179, 139 females and 40 males

Age
- 65 to 100 years (Mean 83.4)

Period of measurement
- August to November 2003

The temperature, systolic blood pressure, diastolic blood pressure and pulse rate were measured before recording the photoplethysmograms.

B. Method of measurement

The pulse waves were measured using a CCI BC2000 (photoplethysmography sensor) following the procedure described below.

The subjects were allowed to get accustomed to the surroundings in a room maintained at 25°C for at least 10 minutes.

They were allowed to sit comfortably in a chair with both hands placed in a relaxed manner on a desk (at a height that was comfortable for writing). Subjects kept their eyes open while measurements were made on the left index finger for 180 sec. The signals were A/D converted. Digital data sampled at a frequency of 200Hz and a resolution of 12 bits was fed to a PC.
C. Method of chaos analysis and calculation of Lyapunov exponents

For the time series data $x(i)$, with $i=1,\ldots, N$ obtained from the fingertip pulse waves, the phase space was reconstructed by using the method of delays. Assuming that we create a $d$-dimensional phase space using a constant delay $\tau$, the vectors in the space are generated as $d$-tuples from the time series and are given by:

$$X(i) = (x(i), \ldots, x(i-(d-1)\tau)) = \{x_k(i)\}$$

(1)

where $x_k(i) = x(i-(k-1)\tau)$, with $k=1,\ldots,d$. In order to correctly reconstruct the phase space, the parameters of delay $\tau$ and embedding dimensions $d$ should be chosen optimally (4). In time series recorded from human finger photoplethysmograms, we chose parameters of $\tau=50$ms and $d=4$, as in references[2] and[3].

In the reconstructed phase space, one of the important measures of complexity is the largest Lyapunov exponent $\lambda_1$. Considering $X(t)$ is the evolution with time of some initial trajectory $X(0)$ in the phase space, it is given by

$$\lambda_1 = \lim_{t \to \infty} \lim_{\epsilon \to 0} \frac{\ln |\delta X_\epsilon(t)|}{\epsilon}$$

(2)

where

$$\delta X_\epsilon(t) = X(t) - X_\epsilon(t)$$

$$\epsilon = X(0) - X_\epsilon(0)$$

for almost all initial difference vectors $\epsilon = X(0) - X_\epsilon(0)$.

We estimated $\lambda_1$ using the algorithm of Sano and Sawada [3]. $\lambda_1$ describes the divergence and instability of the orbits in the phase space.

The maximum Lyapunov exponents $\lambda_1$ were calculated for a basic window of 8000 points (40 sec). The 180 sec (36000 points) were covered by sequentially sliding, 200 points (1 sec) at a time and $\lambda_1$ was determined for each window. Figure 1 shows the plethysmogram and attractor obtained from a 3 minute measurement and the Lyapunov exponents determined by the sliding. The mean of the Lyapunov exponent values was used to evaluate the severity of dementia.

We prepared attractors for four embedding dimensions from pulse wave data with chaotic characteristics and calculated the largest Lyapunov exponents, which reflect the divergence of the attractor trajectory. In the analysis described below, we calculated the largest Lyapunov exponent from the plethysmograms for 179 subjects.

III. RESULTS

A. Activities of daily living (ADL) and dementia level data of the aged subjects

Data recorded by the persons who actually provided care to the subjects in the old people’s home was used as the ADL data. The dementia data used were those recorded by healthcare professionals.

For the ADL, each activity of daily living such as walking, eating, toileting, bathing, dressing, and grooming was assigned to one of the three care dependence categories: a. Can do independently although it takes a long time; b. Needs some assistance; and c. Totally dependent on assistance. The communication skill was also assigned to one of the three levels: a. Can communicate normally; b. Can communicate to some extent; and c. Can hardly communicate.

Data on dementia obtained from healthcare professionals was categorized into the five grades of dementia, 0: None, 1: Mild, 2: Moderate, 3: Severe and 4: Very severe. Figs 2 and 3 show the results of grouping of the subjects.

Fig 2. Distribution of subjects in the three care dependence categories of ADL (c>b>a)
Parameters obtained from the pulse wave data and analysis of ADL indices and severity of dementia

We examined whether the values of the Lyapunov exponent (group means and standard deviations) had any significant correlation with each of the factors, sex, age, body temperature, systolic blood pressure, diastolic blood pressure, pulse rate, walking, eating, toileting, bathing, dressing, grooming, communication skill and severity of dementia, in order to examine the relationship of the ADL indices and dementia with the pulse wave data.

We found that only the communication skill and the severity of dementia were significantly correlated with the mean and standard deviation of the Lyapunov exponent. Figs 4 and 5 show the relationship of these factors with mean and standard deviation respectively of the Lyapunov exponent.

The results of analysis of variance (JMP5.1.1J) were as follows. (TABLE 1 and 2)
The Lyapunov exponent is a measure of divergence of the attractor trajectory. It became clear from the above results that communication skill and dementia were related to the deviations of the Lyapunov exponent and that aged persons who could not communicate well had less deviations of the exponent compared to those who could communicate well. Similar relationships were observed with dementia also.

C. Verification of relationship between dementia and communication skill

Next, to study the relationship of communication skill with ADL and age, data was partitioned using the data mining technique, which proved that communication skill was the ADL index most closely related to dementia. The results are shown in Fig 6.

![Fig 6 Relationship of the severity of dementia with communication skill and other ADL indices](image)

We can say from Fig 7 that the factors that determine dementia can be arranged in the order of decreasing effect, as lack of communication skill, inability to feed oneself and age.

D. Representation of dementia in a constellation graph

If we could visually represent the changes in the Lyapunov exponent obtained by sliding within the 180 sec time interval, it would be possible to easily measure changes in the severity of dementia.

We realized such a visual representation by preparing constellation graphs. In these constellation graphs, the numerical data of a time series was converted into angles (minimum=0°, maximum=180°), and the vectors of the same length were joined together and depicted on a semicircular graph. The maximum and minimum values were set automatically from the values of the Lyapunov exponent. Each line represents the data of one subject. The smaller the value of the Lyapunov exponent, the closer is the vector to the bottom right of the constellation graph. As the value of the Lyapunov exponent increases, the line moves to the left in the graph. The line is straighter when the standard deviation is small and more kinky and bent when it is large. The vector calculation for this constellation graph is described below.

First, we shall describe a method of drawing a general constellation graph. Here, \( p \) is the number of Lyapunov exponents. For a 180sec measurement, \( p=163 \), \( n \) is the number of subjects.

\[
(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{ip}), \quad i = 1, 2, \ldots, n \tag{3}
\]

Next, \( f_1, f_2, \ldots, f_p \) we use the real number functions

\[
\theta_{ij} = f_j(x_{ij}), \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, p \tag{4}
\]

Each \( x_{ij} \) is changed into an angle under the condition of Eq. (5).

\[
0 \leq f_j(x_{ij}) \leq \pi \quad f_j, \quad j = 1, 2, \ldots, p \tag{5}
\]

Eq. (6) is used in case the value increases continuously.

\[
f_j(x_{ij}) = \frac{x_{ij} - x_j^{(1)}}{x_j^{(2)} - x_j^{(1)}} \pi \tag{6}
\]

Here, \( x_j^{(1)}, x_j^{(2)} \) are shown in Eq. (7).

\[
x_j^{(1)} = \min_{1 \leq i \leq n} x_{ij}, \quad x_j^{(2)} = \max_{1 \leq i \leq n} x_{ij}; \quad (j = 1, 2, \ldots, p) \tag{7}
\]

1) We draw a semicircle with radius 1 and mark it with degrees.

2) We make each vector \((\cos \theta_{ij}, \sin \theta_{ij})\) correspond to \( x_{ij} \).

Next we multiply by the weight \( w_j \) that is suitable for this vector. The vector is shown in Eq. (8).

\[
x_i = \sum_{j=1}^{p} (w_j \cos \theta_{ij}, w_j \sin \theta_{ij}) \quad j = 1, 2, \ldots, p \tag{8}
\]

Then we join these vectors. Here,

\[
\sum_{j=1}^{p} w_j = 1
\]

Figure 7 shows the relationship between dementia and the Lyapunov exponents obtained by the analysis. The 5 levels of dementia are shown in different colors. Subjects with more severe dementia have their lines more to the right side of the
Subjects of the 5 different dementia categories were sorted according to severity and 5 subjects around the median value were selected from each category to prepare this graph. Fig 8 is similar to Fig 7 but shows the relationship between communication skill and the Lyapunov exponent.

Fig 7 The relationship between severity of dementia and the Lyapunov exponents of the time series (each line represents one subject).

Fig 8 The relationship between communication skill and the Lyapunov exponents of the time series.

IV. DISCUSSION

The traditional view of homeostasis has been that when certain factors disturb the vital signs like pulse rate, respiration rate, blood pressure, body temperature, etc directly related to the maintenance of life, and push them outside the normal range, corrective feedback kicks in to stabilize them, and that stable values of these signs indicate the proper functioning of the control mechanisms of the living body.

However, it is known that even when a healthy subject is in bed rest, the heart beat intervals are not constant and show irregular fluctuations. The respiration rate, blood pressure, body temperature, etc are also no exceptions to this. In fact the fluctuations of the heart rate are less prominent in aged persons and sick persons.

In the present study, changes in vital signs caused by aging were measured through fingertip pulse waves, represented as constellation graphs and verified. We also demonstrated that the Lyapunov exponent was related to dementia in aged persons. Research carried out so far has shown that the decrease in divergence of the Lyapunov exponent in subjects with advanced senile dementia was similar to that observed in persons with depressive psychosis. We plan to advance this study further by obtaining detailed data on the changes in divergence during the time when a newborn infant becomes a young child and in patients of mental diseases like depressive psychosis.

ACKNOWLEDGMENT

We are grateful to the staff of the old people’s home, and also to Associate Professor Hirohashi of the Seisen University and Dr Junko Tsujino and students of the Oyama Laboratory, of the Kwansai Gakuin University, for their help and cooperation in collecting data and making measurements on aged persons.

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