Bulletin of Toyohashi Sozo College
2003, No. 7, 63–78

Non-linear dynamics in heart rate variability in different generations

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ABSTRACT

It has been well known that R-R intervals in the electrocardiogram fluctuate at all times in healthy humans that called as heart rate variability (HRV). Spectral analysis had been widely applied to separate the constituents of the HRV and could clarify that several components which would be relating to respiration, blood pressure oscillation and temperature regulation, were existing. Spectral analysis can provide an analytical features of the fluctuations but can not show the dynamic properties of the fluctuations. From this reason, a chaotic analysis became to use for the analysis of the complex phenomena such as biological signals like electroencephalogram (EEG) and the HRV. However the chaotic property of the HRV with respect to advancing age has not been investigated. In the present study we aimed to examine the effect of aging on the HRV by using the chaotic and a spectral analysis.

Electrocardiogram were obtained from 86 subjects ranging to the different generations: the little children from 5 to 6 years, children from 11 to 12 years old, the young adults from 18 to 21 years and the elderly people from 61 to 83 years old in both sexes at sitting rest. R-R intervals were measured by using double threshold algorithm and converted into the heart rate unit of beats/min. Following the calculation of an individual mean value, a standard deviation of the HRV, a power spectrogram and the chaotic dimensions such as the maximal lyapunov exponent, the lyapunov dimension and the KS entropy, were also calculated from the attractor embedded into the 4-dimensional phase space.

Group mean values of HR decreased from little children to young adults, but slightly increased from young adults to elderly people. The magnitude of fluctuation expressed as the standard deviation of heart rate (SDHR) gradually decreased with age. The values of the maximal lyapunov exponent, the lyapunov dimension and the KS entropy gradually decreased with age, and were positively correlated with SDHR. The HRVs in all subjects were identified as chaos, because it satisfied the criteria.

It may suggest from the above results that the HRV shows a low dimensional chaotic characteristic and the complexity of the chaos was reduced with advancing age.

Keywords : chaos, aging, heart rate

1. Introduction

Apparent irregular oscillation in the biological signals, such as electroencephalogram (EEG), heart rate, breathing pattern, blood pressure, and peripheral blood flow, has recently come to attract attention from the non-linear dynamics of the system. So far, the spectral analysis was mainly used for such a nonlinear oscillating phenomenon and for the separation of the oscillatory components of the wave. Sayers (1973) first applied the spectral analysis for heart rate variability (HRV), and found that several oscillatory components; a high-frequency components that is synchronous with respiration, a low-frequency components belonging to the frequency band around 0.1Hz, and a very low-frequency components that belongs below 0.05Hz. The physiological mechanism of each oscillatory component has been examined by means of the spectral analysis and the pharmacological technique. Since the fluctuation synchronous with respiration almost disappeared when atropin, which is one of the blocker of the vagus nerve activity to the heart, was treated, this oscillatory component was specified with the reflection of the heart vagus nerve activity. It was also clarified that the low oscillatory component located around 0.1Hz decreased by propranolol ingestion which is a blocker of the sympathetic nerve to the heart and disappeared mostly by combined treatment with atropin and propranolol. Therefore, this low-frequency component is considered to be controlled by both sympathetic and vagal nerve activity (Pomerantz et al., 1985; Akselrod et al., 1985). However, there are still more controversies about the very low-frequency component below 0.025Hz. According to this reason, the relative contribution of the two oscillatory components; the respiratory synchronous fluctuation and the low frequency fluctuation has been used as an indirect assessment of the autonomic nerve activity to the heart.

Since the first introduction for the deterministic chaos by May (1976), the chaotic theory and analytical procedure have been used for biological signals such as the electroencephalogram (EEG) (Ikeguchi et al., 1990), the bursting pattern of the neuron cell (Mpitoses et al., 1988) and a respiratory pattern. Moreover the HRV showed a chaos-like property (Goldberger et al., 1990). However, they only determined a chaotic property from the attractor embedded in the 3-dimensional space. Recently it is also demonstrated that the chaos has many faces and therefore, should be determined by these view points. Ikeguchi and Aihara (1993) had introduced a theory in which the chaotic property could be identified as the orbital instability, the long-term unpredictability and the self-similarity, and those would be evaluated from the lyapunov spectrum, the KS entropy, and a fractal dimension, respectively.

In the present study, we aimed to examine the chaotic property of the HRV with respect to the advancing age.

2. Methods

2-1. Subjects

Eighty-seven subjects voluntarily participated to the study. The subjects were divided into four groups: (1) little children group from 5 to 6 years old with 10 boys and 10 girls; (2) children group from 11 to 12 years old with 9 boys and 18 girls; (3) young adults group from 18 to 21 years old with 6 men and 8 women; and (4) elderly people group from 61 to 83 years old with 8 men and 17 women. The physical conditions of the subjects in the former 3-groups are well and have no cardiovascular diseases. However in the elderly group some of the subjects have chronic metabolic or cardiovascular disorders.

2-2. Data Recordings

The subjects entered the measurement room, and equipped the electrodes for electrocardiogram (ECG), after a sufficient rest on the sitting posture. An ECG was measured with a standard bipolar lead from the chest by using a bioamplifier (MEG-2100, Nihon Kohden) and stored simultaneously on a data recorder (RD-129TE, TEAC) for the subsequent analysis. During the measurements, the subjects kept a spontaneous breathing and relaxation.

2-3. Data Processing

After the experiments an ECG data was replayed and transferred to the computer with a sampling frequency of 200Hz through the A/D converter (98-AB05, ADTEC), and then created the primary data file. On the determination of the R-spike in ECG, two kinds of threshold for voltage and time were applied. In order to recognize the R-spike, an ECG waveform should be exceeds the threshold voltage and the threshold time from the prior R-spike to the present R-spike. In the present study we set the threshold time at 0.4 seconds. A time series data of the R-R intervals were transferred into the heart rate (beats/min) time series. Following the calculation of the average value and the standard deviation of the HR time series data for 512 seconds, the HR time series data was reconstructed into the same-time domain data for 4Hz by using a linear interpolation technique.

2-4. Chaos Analysis

2-4-1. Reconstruction of attractors

When the actual time series data which was sampled from the raw waveform by a sampling interval of Δt are obtained, the state variable x(t) in the n-dimensional space cannot be observed completely. In general, the time series data of one variable relevant to the state variable x(t) will be observed, the data length presupposes that it is given a formula (1) in the discrete series of N.

$$\xi(1),\ \xi(2),\ \ldots,\ \xi(t),\ \ldots,\ \xi(N) \qquad (1)$$

In such a case, it is necessary to reconstruct an orbit equivalent to the orbit on the attractor of the dynamics system in the original n-dimensional space from the time series data from the measured variable. The technique proposed by Takens which reconstructs the orbit on the attractor with using the difference for every fixed time delay from the time series data, is used well. Specifically in m-dimensional reconstruction state space, the following m-dimensional vectors consist of time series data using the size of time delay as τ.

$$X_1=(\xi(1),\ \xi(1+\tau),\ \ldots,\ \xi(1+(m-1)\tau))$$
$$\vdots$$
$$X_t=(\xi(t),\ \xi(t+\tau),\ \ldots,\ \xi(t+(m-1)\tau)) \qquad (2)$$

2-4-2. Presumption of lyapunov spectrum

One point of the attractor in the n-dimensional space reconstructed from the time series data is set to X_t. Other M points X_{ki} (i=1,2, . . . , M) on the attractor around it are selected.

At this time, the displacement vector y_i from X_t to X_{ki} and the displacement vector z_i after only time s passes is expressed in the formula (3).

$$y_i=X_{ki}-X_t,\ y_i\in R^n$$
$$z_i=X_{ki}+s-X_{t+s},\ z_i\in R^n \qquad (3)$$

Supposing time s is fully small, the following linear approximation of y_i and z_i which used matrix G_t will be attained.

$$z_i=G_t\cdot y_i \qquad (4)$$

Next, the unit vector group $U_1(t)$, . . . , $U_n(t)$ in the n-dimensional space are changed using this G_t.

$$e_i(t+1) = G_t \cdot U_i(t), \quad i = 1,2,\cdots,n \qquad (5)$$

Consequently, since there is no $e_i(t+1)$ in a orthogonal relation mutually, $e_i'(t+1)$ which orthogonalized $e_i(t+1)$ is calculated using orthogonalization of Gram-Schmidt.

Moreover, new $U_i(t+1)$ which normalized $e_i'(t+1)$ is calculated, and the process again changed by the formula (5) is repeated.

In this way, when the series of obtained $e_i'(t)$ is used, the lyapunov spectrum λ_i is expressed with a formula (6).

$$\lambda_i = \lim_{N\to\infty} \frac{1}{N} \bullet \sum_{t=1}^{N} \log\left|e_i'(t)\right|, \quad i=1,2,\cdots,n \qquad (6)$$

With respect to the estimated lyapunov spectrum, if the maximum lyapunov exponents is positive value, it will have an orbital instability and then it is identified as chaos.

2-4-3. Fractal Dimension

In the theory of dimension it is identified that a point is zero dimension, a straight line is one dimension, a plane is two dimensions and a space is three dimensions. Such dimensions are integers. However, when the figure became complicated such as the Koch curve or the Peano curve, such dimension takes a noninteger value dimension and is called as fractal dimension. Although some approaches for the determination of this dimension were introduced, in the present study, the lyapunov dimension was used as the fractal dimensions.

If a lyapunov dimension is set to D_L,

$$D_L = j + \frac{\sum_{i=1}^{j} \lambda_i}{\left|\lambda_{j+1}\right|} \qquad (7)$$

definition will be done.

2-4-4. KS Entropy

Moreover, the long-term unpredictability which is one of the features of chaos can be evaluated as the sum of the positive lyapunov exponents λ_1, λ_2, . . . , λ_k (KS entropy).

$$K = \sum_{i=1}^{k} \lambda_i \quad \text{for } 1 \leqq i \leqq k, \ \lambda_i > 0 \qquad (8)$$

3. Results

The average value, the standard deviation, the maximum lyapunov exponent, the lyapunov dimension and the KS entropy of the HRV in each subject and the group mean value are shown in Tables 1, 2, 3 and 4. The group mean values of the mean heart rate (MHR) and the standard deviations of the heart rate (SDHR) were 98.1±7.6 beats/min, 86.7±5.8 beats/min, 70.6±4.1 beats/min and 75.3±1.7 beats/min in the little children group, the children group, the young adult group and the elderly group, respectively. Significant differences were observed on the MHR among groups (Fig.1). The relationship between the MHR and the size of fluctuation indicated as the standard deviation (SDHR) in all subjects is shown in Fig.2. A significant positive correlation (r=0.585, p<0.0001) was observed between the MHR, and the SDHR. Typical examples of the time series of HR and its power spectrum of each subject in different generations are shown in Fig.3. The HRV in the little children is larger than the other three groups. Moreover, a large power spectrum appeared in a wide frequency band in the little children, but the height and number of the power spectrum decreased gradually with advancing age. For example a very low frequency component could be only observed in the elderly. The 3-dimensional attractors (upper), and convergence properties of the lyapunov spectrum (middle), and the self-correlation function (lower) on the same subjects as in the Fig.3 are shown in Fig.4. Most attractive finding is that the area in which attractors are drawn, narrowed in connection with advancing age. The time interval at which the self-correlation function firstly reach a zero was getting longer with respect to the advancing age.

Fig.5 shows the group average values and the SDs of the maximum lyapunov exponent, the lyapunov dimension and the KS entropy in four groups. The group mean values and (SDs) of the maximum lyapunov exponent were 0.531(0.096) in the little children group, 0.472(0.202) in the children group, 0.344(0.122) in the young adult group, and 0.141(0.092) in the elderly group, respectively, and the those difference among groups are statistically significant. The average values and (SDs) of the lyapunov dimension of each group are 3.639 (0.280) in the little children, 3.347(0.294) in the children, 3.116(0.313) in the young adults, and 1.830(0.545) in the elderly, respectively, and those difference among groups are also statistically significant. The average values and (SDs) of the KS entropy of each group are 0.757(0.171) in the little children, 0.631(0.331) in the children, 0.426(0.211) in the young adults, and 0.144(0.099) in the elderly, respectively, and those difference among groups are also significant. The relationships between SDHR and the chaotic indices are shown in Fig.6. Significant linear relationship were observed between them.

Table 1. Average value of heart rate fluctuation, its standard deviation, and the chaos analysis result. (little children)

			Heart rate		Lyapunov Exponents		Lyapunov dimension	KS entropy
Subjects	Age	Sex	Average	SD	Average	SD		
L1	5	M	95.3	6.5	0.508	0.0020	3.733	0.747
L2	5	M	105.5	10.0	0.533	0.0016	3.604	0.750
L3	5	M	107.0	4.8	0.448	0.0029	3.481	0.615
L4	5	M	109.2	8.3	0.513	0.0012	3.458	0.728
L5	5	M	100.8	8.0	0.433	0.0010	3.378	0.581
L6	5	M	100.7	6.4	0.409	0.0015	3.275	0.506
L7	5	M	107.2	6.5	0.597	0.0013	3.819	0.883
L8	5	M	94.6	8.2	0.677	0.0014	4.199	1.051
L9	6	M	96.5	7.6	0.536	0.0017	3.625	0.775
L10	5	M	82.8	5.6	0.349	0.0062	3.233	0.494
L11	6	F	97.5	11.8	0.533	0.0012	3.639	0.745
L12	5	F	91.7	8.1	0.700	0.0014	4.076	1.031
L13	5	F	113.2	8.3	0.603	0.0014	3.796	0.900
L14	5	F	131.5	8.1	0.485	0.0014	3.393	0.653
L15	5	F	89.8	7.6	0.621	0.0008	3.841	0.901
L16	6	F	83.5	7.7	0.540	0.0015	3.650	0.769
L17	6	F	79.6	7.6	0.670	0.0019	4.066	1.003
L18	5	F	78.6	7.8	0.590	0.0008	3.802	0.854
L19	5	F	95.2	6.5	0.428	0.0014	3.262	0.533
L20	5	F	102.4	7.2	0.443	0.0018	3.443	0.612
Average	5.2		98.1	7.6	0.531	0.0017	3.639	0.757
SD	0.4		12.6	1.5	0.096	0.0012	0.280	0.171

Table 2. Average value of heart rate fluctuation, its standard deviation, and the chaos analysis result. (children)

			Heart rate		Lyapunov exponentss		Lyapunov dimension	KS entropy
Subjects	Age	Sex	Average	SD	Average	SD		
C1	11	M	83.9	5.1	0.503	0.0020	3.740	0.740
C2	11	M	83.1	3.6	0.345	0.0019	3.139	0.402
C3	11	M	78.2	5.7	0.387	0.0032	3.500	0.504
C4	11	M	100.1	4.9	0.405	0.0012	3.204	0.559
C5	11	M	94.3	7.4	0.396	0.0015	3.323	0.509
C6	11	M	90.6	5.3	0.297	0.0007	3.098	0.330
C7	11	M	73.8	5.2	0.372	0.0011	3.224	0.442
C8	11	M	101.2	4.4	0.438	0.0015	3.414	0.588
C9	12	M	96.1	3.4	0.304	0.0018	2.826	0.323
C11	11	F	82.0	7.4	0.439	0.0014	3.422	0.582
C12	11	F	73.8	5.3	0.233	0.0012	3.147	0.292
C13	11	F	96.2	6.9	0.425	0.0007	3.383	0.561
C14	11	F	96.2	6.5	0.389	0.0014	3.282	0.514

C15	12	F	83.4	3.9	1.001	0.0145	3.919	1.464
C16	12	F	88.2	5.5	0.600	0.0009	3.843	0.885
C17	11	F	82.7	5.7	0.449	0.0007	3.332	0.625
C18	11	F	101.4	5.0	0.357	0.0009	3.147	0.444
C19	11	F	85.6	3.3	0.352	0.0016	3.061	0.415
C20	11	F	78.9	4.8	0.402	0.0011	3.222	0.505
C21	11	F	81.2	7.7	0.687	0.0013	3.744	0.995
C22	12	F	82.2	7.6	1.054	0.0103	3.951	1.571
C23	12	F	86.6	4.5	0.513	0.0026	3.441	0.665
C24	11	F	100.1	8.3	0.340	0.0028	3.067	0.390
C25	11	F	87.3	8.8	0.832	0.0291	3.039	1.226
C26	11	F	79.8	6.3	0.360	0.0006	3.179	0.431
C27	11	F	85.0	10.1	0.507	0.0018	3.638	0.696
C28	11	F	73.1	5.0	0.367	0.0019	3.084	0.386
Average	11.2		86.9	5.8	0.472	0.0033	3.347	0.631
SD	0.4		8.7	1.7	0.202	0.0060	0.294	0.331

Table 3. Average value of heart rate fluctuation, its standard deviation, and the chaos analysis result. (young adults)

			Heart rate		Lyapunov Exponents		Lyapunov dimension	KS entropy
Subjects	Age	Sex	Average	SD	Average	SD		
Y1	19	M	59.9	3.1	0.291	0.0007	3.020	0.313
Y2	19	M	73.7	3.5	0.287	0.0006	2.876	0.325
Y3	19	M	77.4	4.3	0.297	0.0016	3.121	0.366
Y4	19	M	82.1	3.4	0.278	0.0009	2.758	0.309
Y5	21	M	52.6	4.0	0.270	0.0018	2.842	0.280
Y6	19	M	72.9	5.9	0.279	0.0012	3.027	0.328
Y7	18	F	82.4	6.3	0.690	0.0017	3.898	1.011
Y8	19	F	66.0	2.4	0.358	0.0013	3.205	0.452
Y9	19	F	92.0	4.8	0.473	0.0010	3.493	0.671
Y10	20	F	62.5	5.6	0.428	0.0007	3.438	0.603
Y11	19	F	63.1	3.2	0.230	0.0007	3.021	0.261
Y12	20	F	76.5	3.1	0.244	0.0006	2.783	0.244
Y13	21	F	66.8	5.5	0.386	0.0018	3.121	0.472
Y14	20	F	61.0	2.3	0.307	0.0017	3.019	0.335
Average	19.4		70.6	4.1	0.344	0.0012	3.116	0.426
SD	0.9		10.8	1.3	0.122	0.0005	0.313	0.211

Table 4. Average value of heart rate fluctuation, its standard deviation, and the chaos analysis result. (elderly)

			Heart rate		Lyapunov Exponents		Lyapunov dimension	KS entropy
Subjects	Age	Sex	Average	SD	Average	SD		
A1	83	M	90.5	2.5	0.088	0.0005	1.334	0.088
A2	78	M	76.7	2.6	0.173	0.0005	2.164	0.173
A3	62	M	81.3	1.9	0.107	0.0009	1.662	0.107
A4	79	M	57.6	1.8	0.123	0.0011	1.606	0.123
A5	88	M	71.3	1.3	0.040	0.0013	1.057	0.040

A6	85	M	64.6	1.0	0.141	0.0025	1.430	0.141
A7	71	M	70.4	2.0	0.050	0.0013	1.273	0.050
A8	61	M	80.3	1.6	0.056	0.0007	1.466	0.056
A9	74	F	74.7	1.6	0.157	0.0009	2.142	0.157
A10	69	F	83.3	2.1	0.321	0.0012	2.953	0.366
A11	74	F	88.2	1.2	0.012	0.0011	1.047	0.012
A12	77	F	80.5	1.9	0.254	0.0013	2.425	0.254
A13	75	F	74.3	1.6	0.273	0.0011	2.331	0.273
A14	81	F	79.5	2.4	0.107	0.0005	1.732	0.107
A15	76	F	83.1	2.4	0.341	0.0020	3.050	0.373
A16	71	F	88.9	2.8	0.090	0.0007	1.634	0.090
A17	82	F	61.0	1.5	0.065	0.0009	1.462	0.065
A18	75	F	72.6	1.1	0.308	0.0014	2.684	0.308
A19	82	F	64.9	1.5	0.081	0.0006	1.503	0.081
A20	61	F	71.8	1.7	0.070	0.0013	1.637	0.070
A21	77	F	71.1	1.7	0.089	0.0009	1.538	0.089
A22	66	F	74.8	1.4	0.203	0.0022	2.308	0.203
A23	74	F	62.1	1.3	0.140	0.0010	1.889	0.140
A24	71	F	77.2	1.4	0.107	0.0019	1.811	0.107
A25	81	F	83.0	1.2	0.138	0.0012	1.624	0.138
Average	74.9		75.3	1.7	0.141	0.0012	1.830	0.144
SD	7.3		8.8	0.5	0.092	0.0005	0.545	0.099

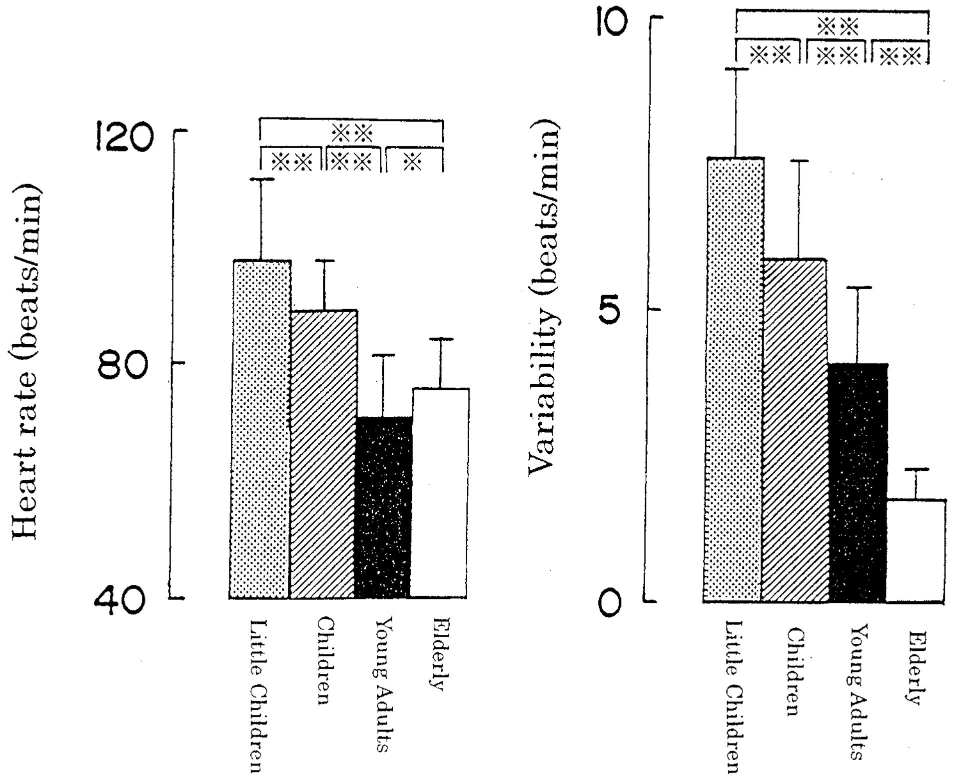


Fig. 1 little child, child, adult, elderly comparison of number of average heart rate and its fluctuation (SD). (※ PC0.05, ※※ PC0.001)

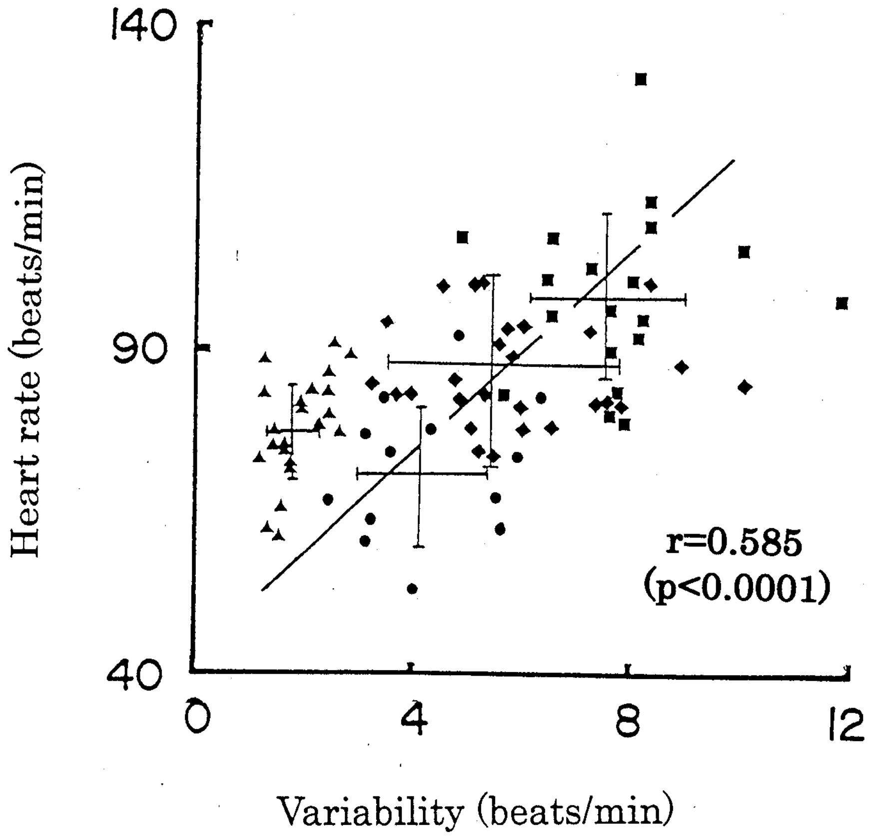


Fig. 2　Relation of number of average heart rate and fluctuation of each subject.

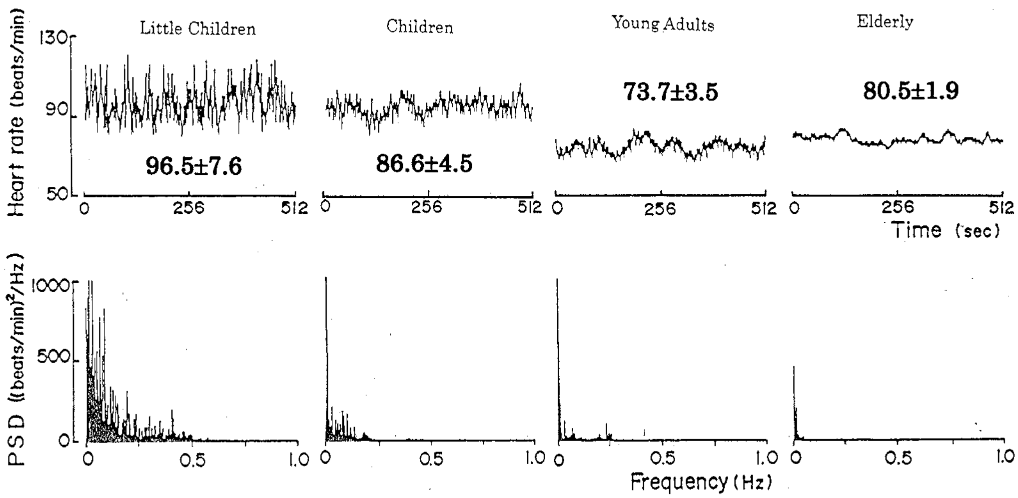
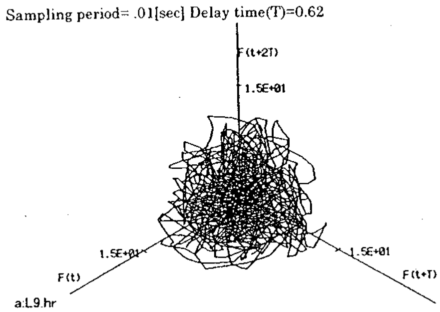


Fig. 3　Representative examples of time series of heart rate and power spectrum of little child, child, adult, and elderly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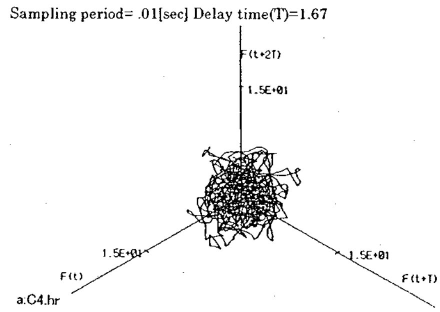
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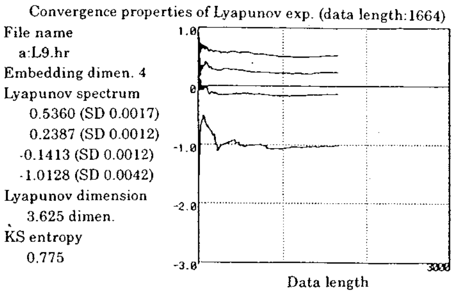
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-0.1413 (SD 0.0012)
-1.0128 (SD 0.0042)
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KS entropy
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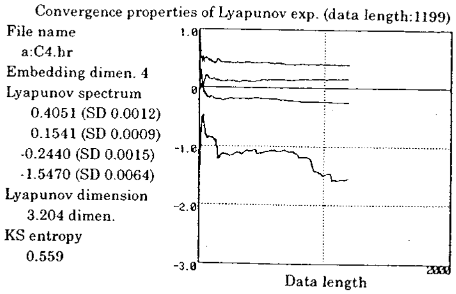
Data length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-1.5470 (SD 0.0064)
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KS entropy
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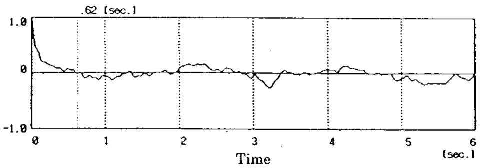
Data length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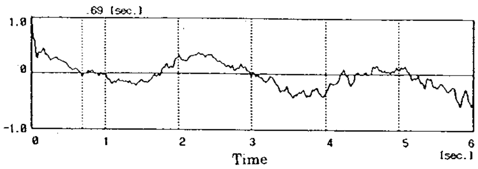
Time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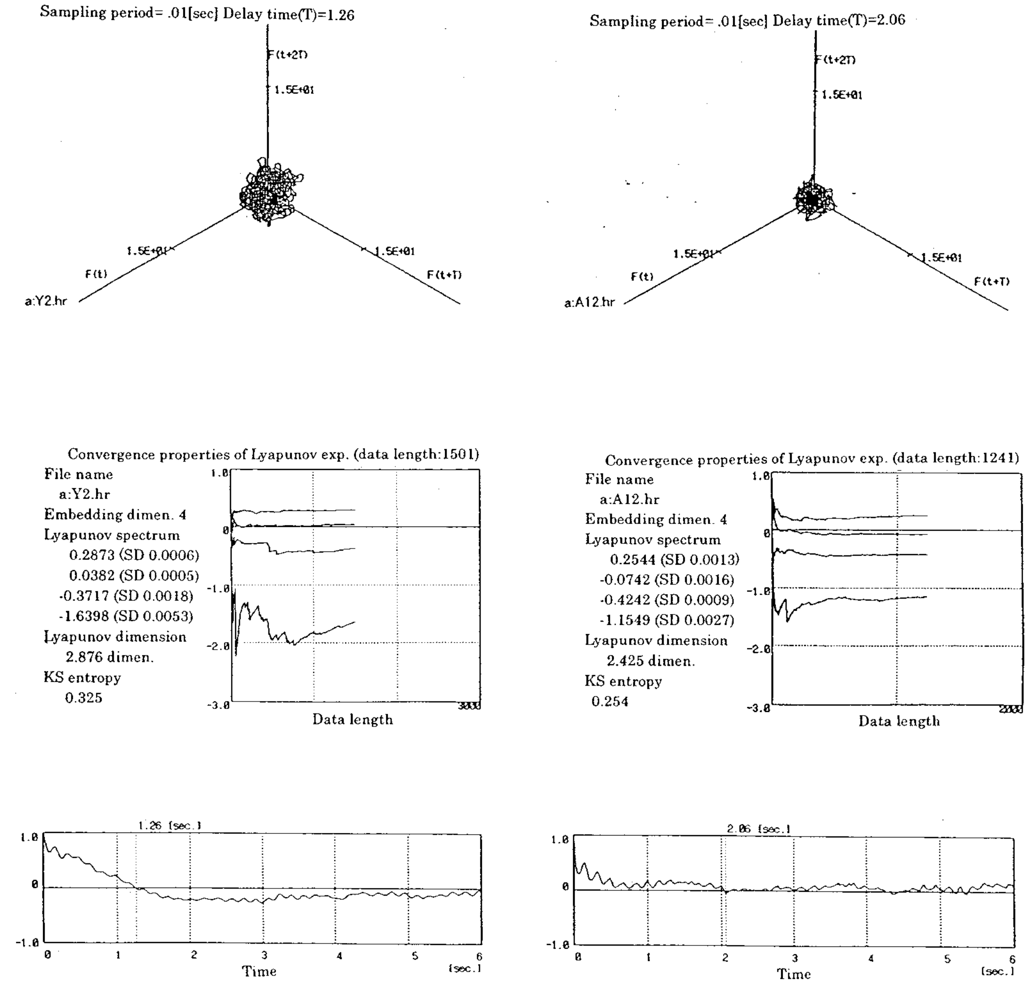

Fig. 4　3-dimension attractor, lyapunov spectrum, self-correlation function of four examples shown in fig. 3

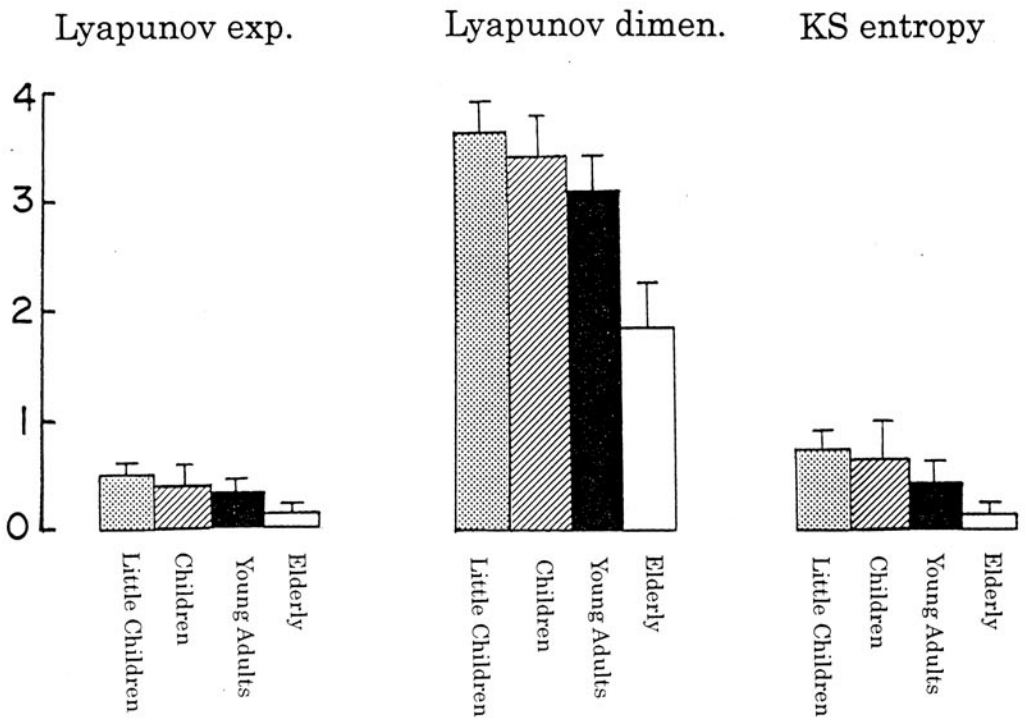

Fig. 5 Comparison of average value of lyapunov exp., lyapunov dime., and KS entropy of each subject.

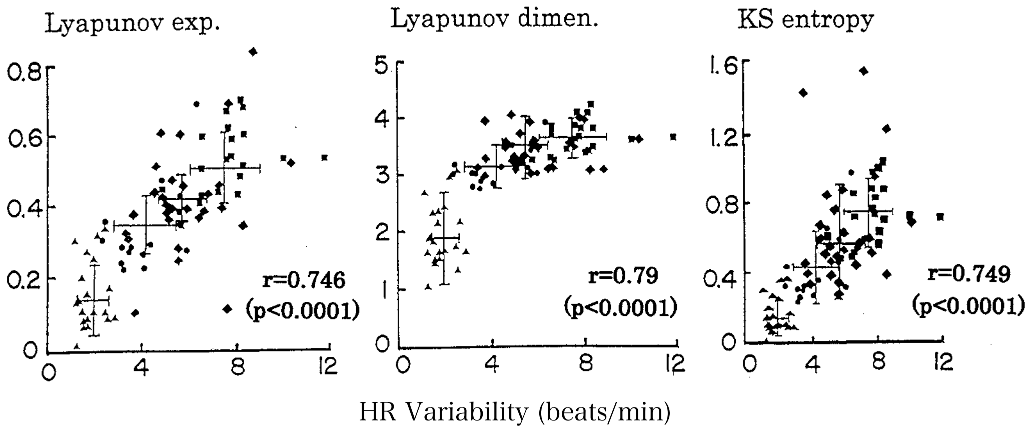

Fig. 6 Relation between heart rate fluctuation, lyapunov exp., lyapunov dime., and KS entropy of each subject.

4. Discussion

The major findings of the present study are as follows:

① the MHR and SDHR were reduced with advancing age except from young adults to the elderly in MHR,

② the HRV showed a chaotic property in all subjects,

③ the complexity of the HRV evaluated by the chaotic indices reduced with advancing age,

④ there are linear relationships between SDHR and the chaotic indices.

Concerning the MHR, Yamaji (1981) had reported that the MHR decreased with growth from 3 to 20 years old, but unchanged from 20 to 60 years old. The significant decrease with maturation in MHR was reported by Pikkujämsä et al., (1999). Eriksson and Rodal (1979) also reported a slight reduction in the MHR from 40 to 59 years old. Byrne et al., (1996) had reported that the MHR decreased significantly from 20 to 87 years old. Present results could confirm the previous results that the MHR decreased with maturation but unchanged with advancing age.

Concerning the magnitude of the SDHR in relation to advancing age, Pagani et al., (1986) had reported that the SDHR decreased with advancing age from 20 to 60 years old. Byrne et al., (1996) also reported similar results that the magnitude of the respiratory synchronous fluctuation and the 10-second fluctuation decreased linearly against advancing age determined by the spectral analysis onto the 164 subjects from 20 to 87 years old in both sexes. These results are essentially in agreement with the present study because the SDHR decreased gradually from 7.6 beats/min in little children, 5.8 beats/min in children, 4.1 beats/min in young adult to 1.7 beats/min in the elderly. From the results in the MHR and SDHR with respect to advancing age, it was suggested that the relationship between MHR and SDHR showed a linear fashion until maturation.

On the other hand, the chaotic analysis had first introduced on the HRV by Goldberger and co-workers in late 1980s by means of the phase-space trajectory. It was also claimed that the chaos has many facets and, therefore, should be evaluated from such points of view, however, the objective method(s) for chaos has not been established. Ikeguchi and Aihara (1993) had proposed that the chaotic characteristic could be defined as the orbital instability, the long-term unpredictability and the self-similarity, and those characteristics could be calculated from the maximal lyapunov exponent, the KS entropy and a fractal dimension, respectively. Then we used this methodology to the chaotic analysis on the HRV.

Our results suggest that the HRV is a chaos-like behaviour, because the maximal lyapunov exponent was positive, and the lyapunov dimension took uninteger values in all subjects.

Furthermore the present study could confirm that the chaotic indices reduced with respect to the advancing age and positively correlated with SDHR.

From the above observations it is concluded that the HRV shows a chaotic characteristics but it complexity could be reduced with advancing age as same as the SDHR. Further investigation will be needed for this problem.

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