

Original Article

Variations of Multifractal Structure in the Fetal Heartbeats

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Several procedures for evaluating fetal well-being are in clinical use. The cardiocotograph is mostly used as a non-invasive procedure to measure fetal well-being in clinical settings. The cardiocotograph displays the fetal heartbeat counts that vibrate. This variation has been classified into 2 categories. We investigated this variation by a novel method, in which we analyzed the change of structure of the attractors in the phase spaces according to the time course. We adopted the global spectrum, which means the distribution of fractal dimensions, for that structure. In this procedure, we discovered a new variation in which the cycle is much longer than the 2 types of known variabilities. Although loud noises such as white noises with a magnitude 1/4 times as large as the standard deviation of the original data were added to the original data, the variations were still detected. The variation is very difficult to detect by Fourier or wavelet transformation, however, because it changes very slowly. Through this new way of analyzing the vibration phenomena, we obtained a new perspective on the biological information available.

Key words: chaos, fractal, heart, complex system, variability

Examinations using ultrasound procedures for mothers and fetuses, such as the cardiocotography and the ultra-sonography, are in common use because they are not invasive procedures. Nowadays, the cardiocotograph, which can be obtained by ultrasound, is usually used to monitor fetal well-being in the clinic. Comparison of the simultaneous direct electrocardiograph and the cardiocotograph has shown that the latter provides reasonable statistical measures of heart period variation, and also of accelerations and decelerations, provided that signal losses are taken into account [1, 2].

Recently, complex systems that exist generally in nature have been analyzed using the chaos-fractal theory. Therefore, our purpose was to obtain new biological information by applying the chaos-fractal theory to the analysis of fetal heartbeats.

Materials and Methods

We used the Fetal Monitor 116 (COROMETRICS Medical Systems, Inc., Wallingford, CT, USA) and digital memory LRR-03 (sampling rate: 1 kHz) (GMS Co., Tokyo, Japan). Our subjects were 13 fetuses (Table 1). In the course of pregnancy and vaginal delivery, each mother and her fetus had no complications and abnormalities. Moreover, each mother was not in labor. We

Table 1 Statistics of maximum values of the global spectra

Age	Gestational weeks on examination	$\alpha(0)$	$f(\alpha(0))$	Covariance	Number of α - $f(\alpha)$	Sex	Birth weight (g)	Apgar score (1 min/5 min)
23	38	1.660 ± 0.167	1.618 ± 0.182	0.0300	39	M	2978	9/10
28	38	1.691 ± 0.297	1.641 ± 0.295	0.0868	12	M	2786	9/10
23	37	1.990 ± 0.156	1.964 ± 0.167	0.0260	24	F	3252	9/10
27	40	1.977 ± 0.244	1.940 ± 0.253	0.0563	12	F	3065	10/10
21	39	1.886 ± 0.217	1.849 ± 0.227	0.0491	15	M	3211	9/10
29	37	1.765 ± 0.212	1.710 ± 0.219	0.0455	11	F	2788	9/10
31	40	1.756 ± 0.194	1.714 ± 0.206	0.0395	23	M	2725	9/10
24	39	1.891 ± 0.242	1.860 ± 0.258	0.0624	19	M	3085	9/10
28	37	1.773 ± 0.208	1.733 ± 0.225	0.0466	19	F	3223	9/10
29	37	1.869 ± 0.246	1.832 ± 0.260	0.0638	12	M	3216	10/10
27	38	1.735 ± 0.297	1.695 ± 0.297	0.0877	18	F	2735	9/10
27	37	1.688 ± 0.239	1.651 ± 0.249	0.0590	17	M	2789	9/10
26	38	1.843 ± 0.250	1.808 ± 0.245	0.0604	19	F	2923	9/10
26.4 ± 2.9	38.1 ± 1.1	1.798 ± 0.242	1.760 ± 0.253	0.0607	240		2982.8 ± 204.0	

Each value represents the mean ± SD.

obtained the data by sending information from Fetal Monitor 116 to the LRR-03.

We developed an original source program using the Mathematica 4.0 Macintosh version (Wolfram Research, Inc., IL, USA) for the chaos-fractal analysis in order to investigate the cardiocograph. We used a PowerMac G4 (Apple Computer, Inc., CA, USA) for our calculations.

The time series data from nature has a variety and complexity that changes with the passage of time. In this study, we analyzed the changes of attractors according to the time course. Therefore, as the complexity, we set the following indices on the fractal measurements as the distribution of the fractal dimension [3-5].

The generalized dimension [6]; D_q , defined by

$$D_q = \lim_{\epsilon \rightarrow 0} \frac{1}{q-1} \frac{\ln \chi(q, \epsilon)}{\ln \epsilon}$$

where

$$p_i(q, \epsilon) = \lim_{N \rightarrow \infty} \frac{N_i}{N}, \quad \chi(q, \epsilon) = \sum_i p_i(q, \epsilon)^q$$

where N_i is the number of time series which visits the i -th box (the length of a side is ϵ) which is divided in a q -dimensional phase space. α and $f(\alpha)$ were calculated using the next equation. ($\rho(\alpha)$ is the weight function, and $\epsilon^{-f(\alpha)}$ means the number of elements that have local dimension α in a q -dimensional phase space),

$$\chi(q, \epsilon) = \int \rho(\alpha) \epsilon^{-f(\alpha)} \epsilon^{q\alpha} d\alpha$$

where

$$\int \rho(\alpha) d\alpha = 1$$

Then, we obtained the following formula,

$$D_q = \frac{1}{q-1} \left\{ q\alpha(q) - f(\alpha(q)) \right\}$$

Thus, given D_q , we can know α , $f(\alpha)$. Finally, a basic statistical analysis was performed on the map of the α - $f(\alpha)$.

In order to obtain the effective attractor, the effective embedding dimension should be determined. An effective embedding dimension of the signals is often defined when the convergence of the correlation dimension with the embedding dimensions increase is less than half of the embedding dimension. In fact, the convergence is difficult to determine. Therefore, we devised a new efficient method to determine the convergence using information theory. Entropy in the information theory; H , defined by

$$H = - \int p(x) \ln p(x) dx$$

where $p(x)$ is set to the probability density function when the domain of the random variable x includes $p_i(2, \epsilon)^2$ ($i = 1, 2, \dots, N$).

We decided on an effective embedding dimension by using ϵ when H , in other words the quantity of information, reached its maximum. Then the effective attractor was finally reconstructed in the phase space.

Results

In this study, we analyzed the α - $f(\alpha)$ map every 512 beats. The α - $f(\alpha)$ map was demonstrated in Fig. 1. Thus, we were able to present the map using the multifractal structure mapping.

It is natural that the data included noises. For the purpose of proving that the data contains adequate effective biological information in order to make an analysis, we prepared the following 2 data sets, the phase randomized data and the shuffled data. The phase randomized data was obtained by inverse Fourier transformation after the randomized only phase constants of the original data. Therefore, the phase randomized data and the original data have the same power spectrum in the frequency analysis. The shuffled data was made by the randomized only order of the original data. Therefore, the shuffled data and original data have the same mean and variance.

We are also confident of the accuracy of the data, because the series of noise data was generated by adding white noise to the original data. The magnitudes of the ranges of the white noises were the mean of the original data multiplied by 2^{-1} , 2^{-2} , 2^{-3} , 2^{-4} , 2^{-5} , 2^{-6} , 2^{-7} and 2^{-8} to the original data.

When the noises were 2^{-6} times of the mean that is equivalent to 2^{-2} times of the standard deviation of the original data (*i.e.*, 6.32×10^{-3} sec), the variation that we revealed was observed to be at 0.01 of the significant level.

The α - $f(\alpha)$ mappings as a function of time are shown

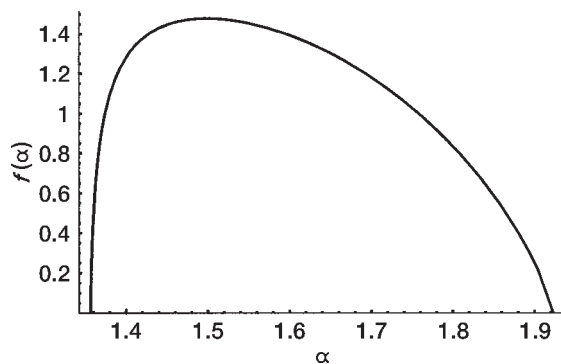


Fig. 1 The first 512 beats were extracted for the analysis of the fractal structure. α means the local fractal dimension, and $f(\alpha)$ shows what number of elements had fractal dimension: α was transformed into the capacity dimension. The map of α - $f(\alpha)$ shows the general tendency of the attractor.

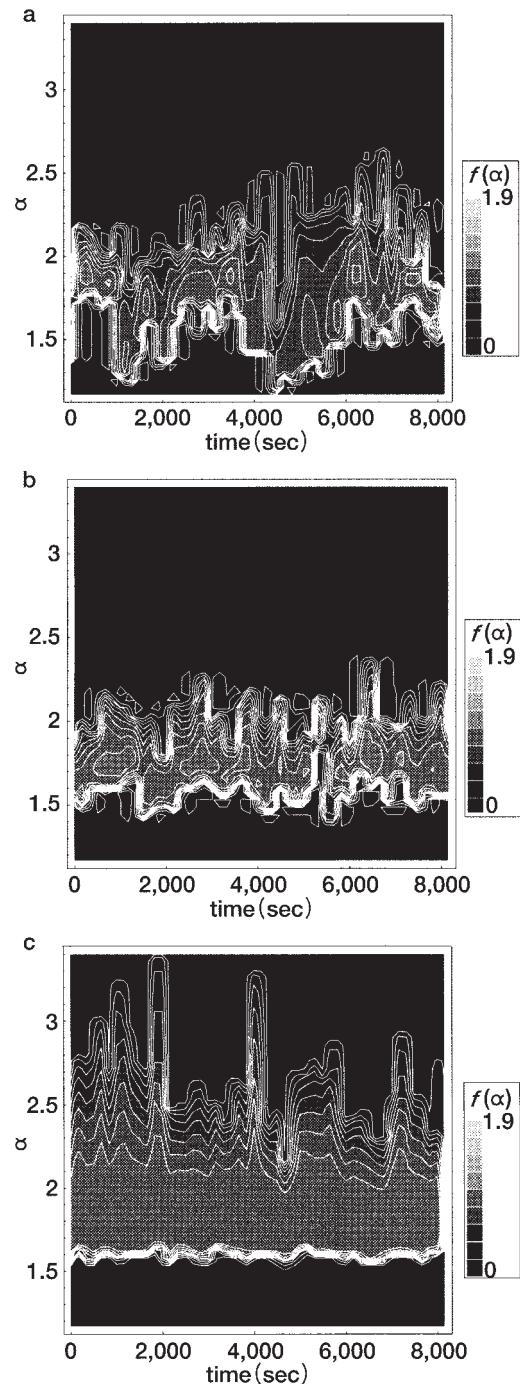


Fig. 2 The α - $f(\alpha)$ mappings as a function of time. The contour maps of the multifractal structure are shown. a, The original data. The multifractal structure varied in about 8 to 50 min (2.1×10^{-3} to 3.3×10^{-4} Hz). The structure varied and swung as time passed, as if it were a mountain range. The base, the edges, and the summit varied. b, The phase randomized data. In the slow variation, there were less variations than a. c, The shuffled data. There were less variations than a and b in the smaller side of α .

by contour maps in Fig. 2. In this case, we obtained the data one day before birth, and the number of data obtained was 19,968 beats. The figure reveals that the structure varied and swung as time passed, as if it were a mountain range. The base, the edges, and the summit of the range varied. This variation seemed to vary at about 8 to 50 min intervals, as shown in Fig. 2a. And we saw the variation in all cases (Table 1).

We analyzed the following indices: $\alpha(-\infty)$, $\alpha(0)$, $\alpha(1)$, $\alpha(2)$, $\alpha(\infty)$, the range of α , the skewness, the kurtosis excess, the mean of α by the invariant measure, the standard deviation of α by the invariant measure, D_0 , D_1 , D_2 , and each difference of them. We analyzed $f(\alpha)$ in the same way. Each mean and standard deviation of $\alpha(-\infty)$, $\alpha(0)$, $\alpha(1)$, $\alpha(2)$, $\alpha(\infty)$, the range of α , the skewness, the kurtosis excess, the mean of α by the invariant measure, the standard deviation of α by the invariant measure, D_0 , D_1 and D_2 were 2.17 ± 0.225 (mean \pm standard error), 1.66 ± 0.167 , 1.59 ± 0.191 , 1.57 ± 0.192 , 1.50 ± 0.172 , 0.674 ± 0.263 , $0.172 \pm 7.16 \times 10^{-2}$, $-1.03 \pm 6.19 \times 10^{-2}$, 1.80 ± 0.144 , $0.177 \pm 7.16 \times 10^{-2}$, 1.62 ± 0.182 , 1.59 ± 0.191 and 1.58 ± 0.192 , respectively. By the analysis of variance and mean difference test, the original data and 2 data sets, which consisted of the phase randomized data and shuffled data, were statistically different in terms of $\alpha(0)$, $\alpha(1)$, $\alpha(2)$, $f(\alpha(0))$, $f(\alpha(1))$, $f(\alpha(2))$, $\alpha(\infty)$, and D_0 , D_1 and D_2 ($P < 0.01$, respectively).

Discussion

Adding the large white noises as 2^{-6} times of the mean which is equivalent to 2^{-2} times of the standard deviation of the original data (*i.e.*, 6.32×10^{-3} sec) means that if the fetal heart had moved to generate a time lag (*i.e.*, 6.32×10^{-3} sec in a beat-to-beat time), the fetal heart would have had to travel to a location 4.83 m from its place in the body, because the velocity of sound is about 1,530 m/s in the body. This is actually impossible. Therefore, the data includes adequate biological information, even

though such a large noise was added to the data.

This is the first report of this variation. We named the variation super-long-term variability, to distinguish it from short-term and long-term variability [7].

Because the variation has a much slower frequency (2.1×10^{-3} to 3.3×10^{-4} Hz) than the frequency of the fetal heartbeat (about 1 to 3.3 Hz), it is probable that the Fourier frequency analysis and the wavelet analysis would both be very difficult to discover. The variation disappears when the data of the heartbeats is randomized. Therefore, the phase constants and the sequence of the time series data include biological information. This fact means that each impulse regulating the cardiac center in the neural system towards the heart is related to the past impulses. In other words, the cardiac center does not generate the impulses individually, or one-by-one. However, we cannot prove what this new variation means. We reasoned that the complexity of the neural system as a complex system makes this new variation.

It is probable that further investigation of this new variation will provide a new perspective on the neurological information through the regulation of heartbeats.

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