Chapter 25
Quantifying the Mind: Worry, Tension, and Anxiety

Toru Yazawa

Abstract To quantify non-linear behavior of physiologic system such as the cardiovascular control system, we first used lobsters because we are invertebrate neurobiologists. After finding that the lobsters can display its emotion by changing the pattern of heart-beating, we extended the method to human: The heartbeat represents momently varying emotional tension. We show that this variation of the inner world is detectable and quantifiable using a long-time electrocardiogram (EKG). In each investigation, we captured 2000 heartbeats without missing a single beat. The heartbeat interval time series was analyzed by "modified detrended fluctuation analysis (mDFA)" technique, which we have recently developed by our group. The mDFA calculates the scaling exponent (SI, scaling index). A normal healthy heartbeat exhibits an SI of around 1.0. The heartbeat recorded from subjects who have stress and anxiety exhibited a lower SI. The values of SI changed one right after the other when circumstances and atmospheres surrounding subjects were changed. We report that the mDFA technique is a useful computation method for checking the mind and health.

Keywords Anxiety · EKG · Electrocardiogram · Fear · Heartbeat-interval time series · Modified detrended fluctuation analysis · mDFA · Quantitative measurement · Tension

25.1 Introduction

Nonlinear regulatory systems for controlling the organs, such as the heart, is operating in the state far from equilibrium: i.e., its functioning is not stable but dynamic. Maintaining constancy is not equivalent to maintaining equilibrium. This means that physiologists need another theory instead of a classical homeostasis theory.

T. Yazawa (✉)
Biological Science, Tokyo Metropolitan University, Minami-Ohsawa,
Hachioji, Tokyo 192-0397, Japan
e-mail: yazawa-tohru@tmu.ac.jp; yazawatorujp@yahoo.co.jp

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Researchers have tried to characterize the fluctuation of the heartbeat by a scaling exponent (SI, scaling index), and demonstrated that SIs were altered with disease and aging [1].

Goldberger et al. [1], Ivanov et al. [2] and Peng et al. [3] suggested that their method is applicable for the diagnosis of human heart disease, because they succeeded to show the difference between healthy and sick human subjects, although they did not study the transitory phenomena of subjects who were healthy in the past but are presently not healthy. Demonstrating the detection of long-range correlation [2] and multi-fractal analysis [3], they eventually proposed that the scaling nature of heartbeat fluctuation is potentially usable for the diagnosis. However, for a practical application, for example, predicting when in the near future the heart stops its beating, more experimental approaches are necessary [4].

Our approach is to make an index system that can describe the condition of the cardio-vascular system by a quantitative way. It is believed that beat-to-beat variations of the heart rate reflect modulation of cardiac control center [5]. If one has such a quantitative description method in hand, he/she can predict forthcoming illness. We consider that we hope to find the way for distinguishing sick conditions from normal conditions, based on electro-physiological heart data, electrocardiogram, (EKG, abbreviation after Willem Einthoven).

Not only in vertebrate animals like human, but also in invertebrates such as crustaceans, they have the heart. One may think that there are big differences between vertebrate and crustaceans in the anatomy of the cardio-vascular system. However, the heart is a pump that propels blood, and that is equipped with acceleration and breaking devises, the control of nerve fibers. Those are common features for both, in vertebrates and invertebrates. Therefore, fundamentally, all the cardio-vascular system operates in the same mode; ontogenetically designed as a pump equipped with positive and negative feedback controllers. Both vertebrates and invertebrates have a very complex cardio-vascular system in structure, function and regulation. Beneficial points for adopting invertebrates are; there are less-ethical problems and there exists a large amount of accumulated knowledge about the heart evolution, and all the hearts must have the same evolutional origin.

From above arguments we may conclude that there are common features between vertebrate (human) and invertebrate (lobster). Basic architecture of the heart and of its control mechanism could be fundamentally identical for all ‘hearted’ animals. Crustaceans supply, thus good model specimens, for the research on neurodynamical control of the heart.

We have observed that a healthy-looking crustacean heart stop unpredictably resulting in a failure of heart’s pumping-blood function [6]. This can happen to a human. It would be the worst-case scenario for the cardio-vascular system. Generally, cardiac failure has a principal underlying aetiology of ischemic damage arising from vascular insufficiency [7].

Meanwhile, we know that our (human) heart function directly reflects psychology. The autonomic nerves can change heart function according to stimuli such as stress that we receive. Thus, such stimuli from environment cause dynamic changes of our internal world and changes the heart function as well.

This study is a challenge to quantify the internal world using long-time EKG recordings. We have recently made a novel method for EKG analysis, which is the modified detrended fluctuation analysis (mDFA) [6]. In the present study, we show that mental changes which occur internally can be measured with the combination of EKG and mDFA. Although mDFA is not a method well known to the public, we would like to introduce mDFA, which is helpful for checking health and the mind as we exemplify in the present paper.

25.2 Heartbeat Recording and Ethics

We used a Power Lab system (ADInstruments, Australia) to record heartbeats. For recording human EKG, we used a set of three ready-made silver/silver chloride disposable electrodes (positive, negative, and ground) (Vitrode V, Nihon Koden, Japan), which is commercially available. Wires from the EKG electrodes were connected to our lab-made amplifier, which is activated by two button batteries at the voltage of 3.0 V. This equipment is only used in the "university laboratory condition" with a certificate of consent written by all subjects. The EKG signals were passed to the Power Lab system. Over 500 subjects have been tested so far, but no electrical accident has happened by the home-made amplifier recording.

The human heartbeats were recorded outside of a hospital, in for example university laboratories and convention halls (The Innovation Japan Exhibition). All subjects were treated as per the ethical control regulations of following universities (Tokyo Metropolitan University; Tokyo Women's Medical University; Universitas Advent Indonesia, Bandung; Universitas Airlangga, Surabaya, Indonesia).

25.3 Heartbeat Recording and Analysis

A computation method mDFA [6] is described in the paper appeared in the conference proceedings WCECS 2017 [8].

Briefly, we always use a routine mDFA [6]. Our routine works include: (1) obtaining a baseline-stable EKG at 1 kHz sampling rate (a lab-made amplifier with an input time-constant < 0.22 s), (2) detecting peaks of heartbeat, (3) measuring peak to peak interval (such as R-R peak interval of conventional EKG), (4) constructing inter-heartbeat interval time series, and (5) analyzing the time series using mDFA program.

mDFA uses a consecutively recorded ~2000 heartbeat data. The number 2000 could be ideal number of heartbeat if one wants to use mDFA. We tested a longer recording period, for example EKG for 2 h. Long data is not adequate to use, because subjects are NEVER stable. Nobody can keep a steady state, i.e., keeping sitting posture for 2 h. And more importantly, the heart seems NOT to keep staying at a stable condition for such a long period. Instead, the heart control by the brain is very

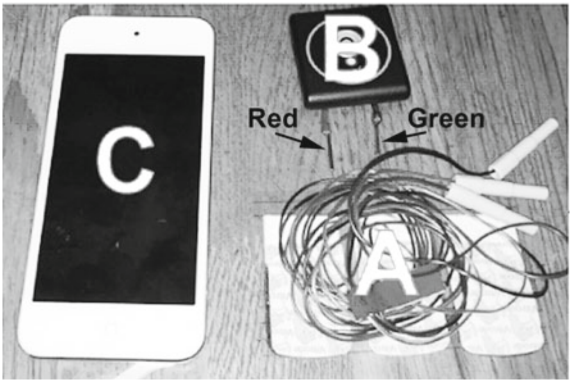


Fig. 25.1 Electrocardiogram recorder and mDFA calculator

variable and thus dynamic. We therefore fixed our data length for about 30 min or so, which is a period length for about 2000 beat. A ~2000 beat is key length of mDFA technology.

25.4 EKG-Recording-Computing Device

Figure 25.1 shows our data logging and mDFA computing devices. Figure 25.1a shows three individual electrodes for EKG recording, commercially available, in-hospital use, using for a prematurely-born baby in an incubator, Vitrode V, Nihon Koden, Tokyo, Japan. Figure 25.1b shows an EKG-amplifier, heartbeat interval calculator, and Bluetooth radio transmitter. Red and green end terminals (see arrows in Fig. 25.1) are lab-made input terminals from the EKG electrodes. Figure 25.1c shows an iPod (Apple, USA) which has a computation program, i.e., mDFA, that we made and was incorporated in it.

Figure 25.2 shows a practical view of iPod touch screen. To start recording, an operator can touch the rec button (Rec), and then after completing capture of 2000 beats, it automatically computes SI. As can be seen in the figure, it computes. SIs are computed from various box size ranges (see the reference [6, 8] in detail), [10; 30], [30; 70], [70; 140], [130; 270], [51; 100], [30; 140], and [30; 270]. For the final SI-result, we use the last one, here it is 0.531390, as explained in the reference [6, 8].

25.5 Results

Case 1: Driving safely

Volunteer (a man in his 60s) drove a car from his home to a town 150 km away to see his mother-in-low who is hospitalized. He has been driving the road so many

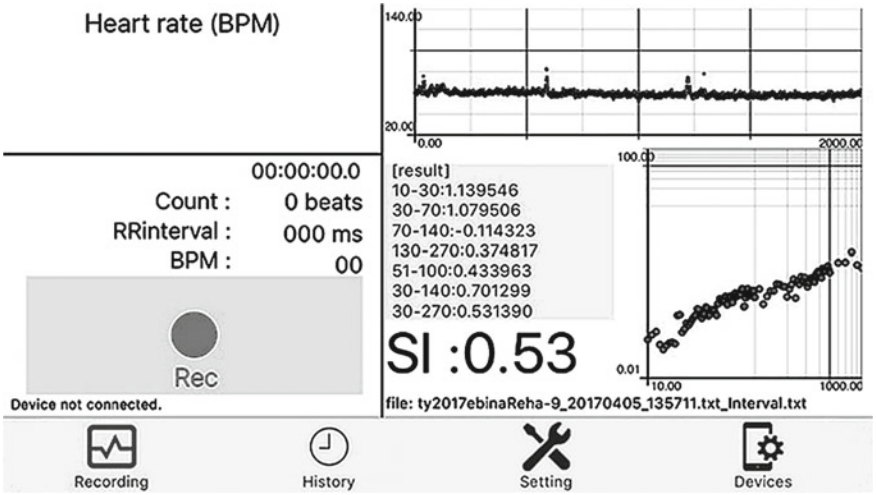


Fig. 25.2 An example screen view of iPod (lab-made, not for sale)

time, thus he is familiar with the road conditions every corner. Furthermore, he drove safely as possible as he can by obeying the speed limit. We recorded his EKGs while driving, computed the scaling exponents by the device (Figs. 25.1 and 25.2).

Driver's heart rate was monitored (Fig. 25.3a, b). Figure 25.3d shows an example result of mDFA computation. Figure 25.3b represents a 2000 beat recording. Figure 25.3a shows an expanded time series of heart rate recording (see arrows). The program instantaneously computed the scaling exponent (SI) (Fig. 25.3c). Figure 25.3d shows a summary of the characteristics of the data {i.e., the file-name, 37 min and 0.2 s recording in total-time for the 2000 beats, R-R interval value in the end of recording, 1046 ms, and heart rate (57 beat per min, BPM) of the last heartbeat.} Figure 25.3c indicates that it was proved that driving safely gives a perfect healthy scaling exponent near 1.0. Here, the SI is 0.99.

Table 25.1 shows an example of EKG-heart-rate monitor and the scaling exponent (SI) computation during the driving for many hours. We confirmed that we can indeed quantify the mind of driver, or internal world of any human-subjects, such as the vehicle-driver, because we consider that the heartbeat reflects the mind or that the heart is the window of the brain [6, 9].

In Table 25.1, when starting driving, SI showed a low value (SI = 0.84, see Data No. 1). This can be explained that the driver solved many worries about fuel Gas, driving route and so force. When taking express way, the driver kept its speed limit and enjoyed blue sky of a spring morning day (SI = 1.03, Data No. 2). Many vehicles over-took his car one right after the other although only some cars were followed his car. He continued driving safely (from No. 3 to No. 8). One can see that his safe-driving gave good SI, i.e., near 1.0 as can be seen the SI values from No. 2 to No. 8.

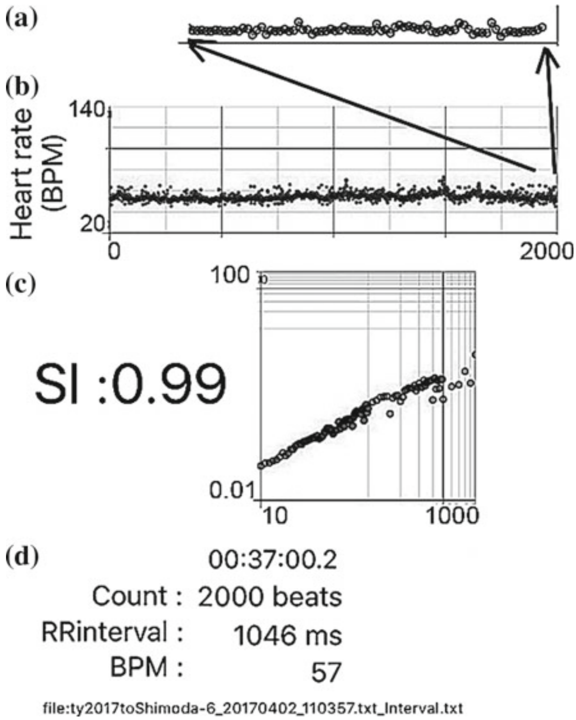


Fig. 25.3 EKG monitoring and mDFA results

We found that eating lunch decreased the SI value (SI = 0.61, Table 25.1, Data No. 9). We can explain this results as followings: the mind (his brain function, i.e., autonomic nerve function) concentrated to enjoy foods, digesting them in the stomach and even pay less attention to environment, the condition of which is a kind of state loosing dynamic response of the brain that momentarily controls the heartbeats every second.

We also confirmed that mDFA can capture anxiety/worry of a subject. One can see that nervous conditions put SI lower. Table 25.1 shows SIs of the subject who walked into the hospital and visited and stayed the room of his mother-in-law (see Data No. 10 and 11, SI = 0.64 and 0.53, respectively). After the hospital, the person's SI recovered during driving and shopping at the super market (Nos. 12 and 13).

And most interestingly, when meeting a new person (the drivers brother-in-low) to greet him, the SI showed a very low value (Data No. 14, SI = 0.77) again, which indicates that he is very nervous NOT to display an ungentlemanly attitude.

In conclusion, SI derived from mDFA can determine internal world (Fig. 25.4).

Technically before conducting mDFA, our three must do: (1) From heartbeat raw data, noise from power souse and body movement should be avoided. (2) But, skipping heartbeats and/or arrhythmic beats are not noise. Such irregularity is very important information for disentangling health care. We believe that this mDFA-technology can quantify acute psychological distress and/or jubilation although there

Table 25.1 EKG-heart-rate monitoring and mDFA results, SI

Data no.	Driving a car very safely to see relatives	SI
1	Talking about Gas and driving route	0.84
2	Driving legal speed, express way	1.03
3	Driving legal speed, local road	1.09
4	Driving legal speed, local road	1
5	Driving legal speed, local road	1.03
6	Driving legal speed, local road	0.99
7	Driving legal speed, local road	1.04
8	Driving legal speed, local road	1
9	Lunch, sweet-sour pork, special black vinegar	0.61
10	Visit hospital	0.64
11	Visit hospital	0.53
12	Driving, super market	0.84
13	Super market	0.99
14	Ggreeting brother-in-law	0.77

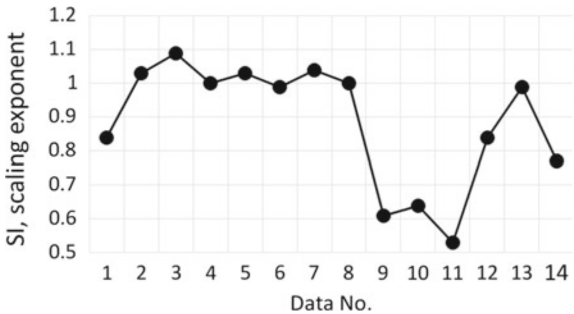


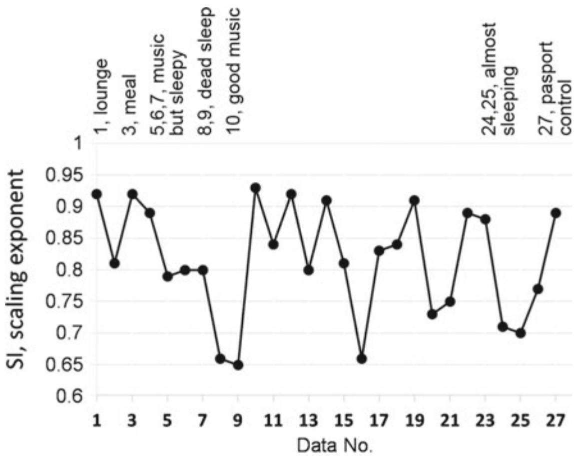
Fig. 25.4 SI derived form mDFA can determin internal world

are many more research questions. Irregular heartbeats should not be removed from raw data when constructing time series data. (3) We keep the size/length of data constant; a raw data must contain about 2000 beats, ranging from 1900 to 2100, or always exactly 2000.

Case 2: Overseas flight

Figure 25.5 shows 27 data while a volunteer (a man 66) traveled from the Narita-Tokyo Airport to the Washington Dulles International Airport to attend a conference held in the USA. Each analysis gives one SI from a 2000-beat-EKG as shown in Fig. 25.5.

Fig. 25.5 Scaling exponent records while traveling



We confirmed that the SI values can represent the internal world of the subject. This subject did not get enough sleep before taking oversea flight. Therefore, SI in Fig. 25.5 always less than 1.0—please compare with the case shown in Fig. 25.4, where the driver took good sleep before driving.

When the subject was at an aroused state such as staying in the waiting lounge, SI shows a "healthy" SI, i.e., here it is 0.92. (Data No. 1). Meal service, SI is 0.92 (Data No. 3). When he enjoyed "good days music, 70 s hit chart," SI is 0.93 (Data No. 10). While he was sleeping, SI goes down lasting for about one hour (Data No. 8 and 9, SI = 0.66 and 0.65, respectively). Good music but not so exciting as "good days music" makes SI a lower value (Data Nos. 5, 6, and 7, SI = 0.79, 0.8, and 0.8, respectively). While he was watching a boring program, feeling sleepy, SI gets a low value (Data No. 24 and 25, SI = 0.71 and 0.70, respectively). At passport control after landing, SI = 0.89 (Data No. 27). In summary, it is surely observed that sleepy state lowers SI.

In conclusion, happy life could fundamentally guarantee a healthy exponent. Anxiety and stress lowered the scaling exponent. mDFA might reflect psychological and physical internal bodily state. mDFA might look at internal state through the heart. The heart is the window of the mind.

25.6 Discussion

This study suggests that the scaling exponents computed by mDFA can quantify the mind such as stress.

Although we need much more comprehensive examples, we propose that mDFA is helpful computation tool in the research on emotion, particularly fear and anxiety disorders, understanding how emotion is encoded in the heartbeat time series, in animal models and humans.

If the body is tortured by stimuli from environment, and/or if some stimuli would harm us internally, which is invisible from outside, we would be upsetting for the nervous system, because we can realize that stimuli is distorting the autonomic nerve function, little of which has been understood by human being until today [4], although we spend everyday life under advanced science and technology. Using mDFA computation, we can numerically evaluate/quantify the state of our body, even it is invisible to us.

Although we (basic scientists, biologists) cannot make by ourselves, making a gadget is very rewarding. It is the right time to start making it. The gadget can work: (1) recording 2000 consecutive heartbeats without missing even a single pulse, (2) computing automatically the scaling exponent that can check the scaling exponent = 1.0, which is perfectly healthy state [6], and finally (3) the gadget would capture what is going on in front of, around, and inside our mind. It gives us health information, each time we use it, for example, on an everyday basis.

In the present paper, we would suggest that we have entered the world experiencing seeing inside without sight. Sometimes a new technology does not have to be supercomplicated. mDFA computation is a kind of high school level mathematics instead of sophisticated nonlinear measures and/or linear complex computation like the HRV, the heart rate variability. mDFA looks at how the brain communicate with the heart and also with the world. mDFA is a tool that enable us to explore previously uncharted territories.

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