Invisible Emotion, Anxiety and Fear: Quantifying the Mind Using EKG with mDFA

Toru YAZAWA
Biological Science, Tokyo Metropolitan University
Hachioji, Tokyo, 192-0397, Japan

ABSTRACT

Fluctuation or variation of the heartbeat represents momently varying inner emotional tension. Can this psychological variations of the inner world, anxiety for example, is detectable and even quantifiable? Our answer to the question: Using a long-time electrocardiogram (EKG), we quantified them. We recorded EKGs by our own EKG amplifiers. The amplifier has a newly designed electric circuit, which enable us to record a stable EKG. The amplifier made it possible to record a perfect EKG where the EKG trace never jump-out from the PC monitor screen. Using this amplifier, we captured approximately 2000 heartbeats without missing a single beat. For the analysis of the EKGs, we used "modified detrended fluctuation analysis (mDFA)" technique, which we have recently developed by our group. The mDFA calculates the scaling exponent (SI, scaling index) from the time series data, i.e., the R-R interval time series data obtained from EKG. Detecting 2000 consecutive peaks, the mDFA can distinguish between a normal and an abnormal heart: a normal healthy heartbeat exhibits an SI of around 1.0, comparable to the fluctuations exemplified as the 1/f spectrum. The heartbeat recorded from subjects who have stress and anxiety exhibited a lower SI. Arrhythmic heartbeats and extra-systolic heartbeats both also exhibited a low SI ~0.7, for example. We propose that the mDFA technique is a useful computation method for checking health. The functional capabilities of various internal systems, such as the circulatory system and the autonomic nervous system, can be quantified by using mDFA.

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

1. INTRODUCTION

A healthy-looking heart can stop suddenly. It is the worst-case scenario for the cardio-vascular system. Generally, cardiac failure has a principal underlying aetiology of ischaemic damage arising from vascular insufficiency [1]. Meanwhile, various stimuli from environment cause dynamic changes of our internal world: for example, depression is a typical psychological mental states and unfortunately almost incurable disease. This study try to quantify the internal world using long-time electrocardiogram (EKG, abbreviation after Willem Einthoven who invented) recordings. We have recently made a novel method for EKG analysis, which is the modified detrended fluctuation analysis (mDFA) [2]. 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, it is helpful for checking health status as we exemplify in the present paper.

2. HEARTBEAT RECORDING AND ETHICS

To record heartbeats, we used a Power Lab system (ADInstruments, Australia), which is designed and used at the medical school's student-lab classroom worldwide. To record a biological signal, EKG, we used a set of three ready-made silver/silver chloride disposable EKG electrodes (positive, negative, and ground) (Vitrode V, Nihon Koden Co. Ltd., Japan), which is commercially available worldwide. Wires from the EKG electrodes were connected to our lab-made amplifier [2], which is activated by two button batteries at the voltage of 3.0 volt. The battery is commercially available even at a convenience store. This home-made equipment do not need 100 volt electric power souse although it has no special circuit for the prevention of electric shock. 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. Finger pulse recordings were also used with 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).

3. HEARTBEAT RECORDING AND ANALYSIS

We made a computation method mDFA [2] as followings: (a) Recording EKG at a sampling rate 1 kHz, obtaining 2,000 heartbeats without any missing heartbeat. A commercial disposable Ag/AgCl electrode for EKG monitoring. (b) To avoid miss recording, we newly made an EKG amplifier that mounted an in-put circuit with a short time-constant (tau); the ideal tau would be, $\tau < 0.22$ s. (c) An appropriate box size for the mDFA was [30; 270] in beat per min (BPM), which means that mDFA computes a routine regression line from 30 BPM to 270 BPM. (see Peng [3] for greater detail about regarding DFA instead of mDFA). This automatic computation well distinguished two different heart conditions, an isolated heart and an intact heart of lobsters [2]. EKGs were taken at the sitting position for about 30 min, in the afternoon, from the volunteers.

Figure 1 shows the mDFA-computation. An interval time series $\{x_i\}$ was obtained (Graph 1 in Figure 1). Graph 1 only shows 90 beats. Real data involved as 2,000 beats. An average interval time of the 2,000, $<x>$, was obtained (Graph 2 in Figure 1, a dotted line). A computation of x_i - $<x>$ gave a time series that fluctuate around zero line (Graph 3 in Figure 1). A computation of qi,

$$q_i = \sum_{k=1}^{i} (x_k - \langle x \rangle) \qquad (1)$$

was conducted (Graph 4 in Figure 1). This "random walk" like signal was cut into "box" (Graphs 4 and 5 in Figure 1). Please note that, here, "box size" is 30 beat as an example. mDFA program repeats computation cyclically with changing box size from 10 to 1000 (see Figure 3).

Within each box, a regression line was made by the least mean square method (Graph 5). In Graph 5, a linear regression line is shown. But, in the real mDFA, we use biquadratic regression line. Then, "difference" between the regression line and data were calculated (Si, Graph 6). This is "detrended" procedure that Peng et al. [3] have introduced for EKG analysis.

Peng et al. [3] measured all the difference (Graph 8), but mDFA computes "how many steps proceeded" that is, "difference" between the first value and last value of regression line of a box (Graph 7). Graphs 9 and 10 shows that box size is 40, for example. Peng et al.'s DFA and mDFA is thus different. Subsequent algorithm is the same as Peng's (see [3]). By changing box size, we can see the scale invariant property, i.e., a self-similar process at different scale.

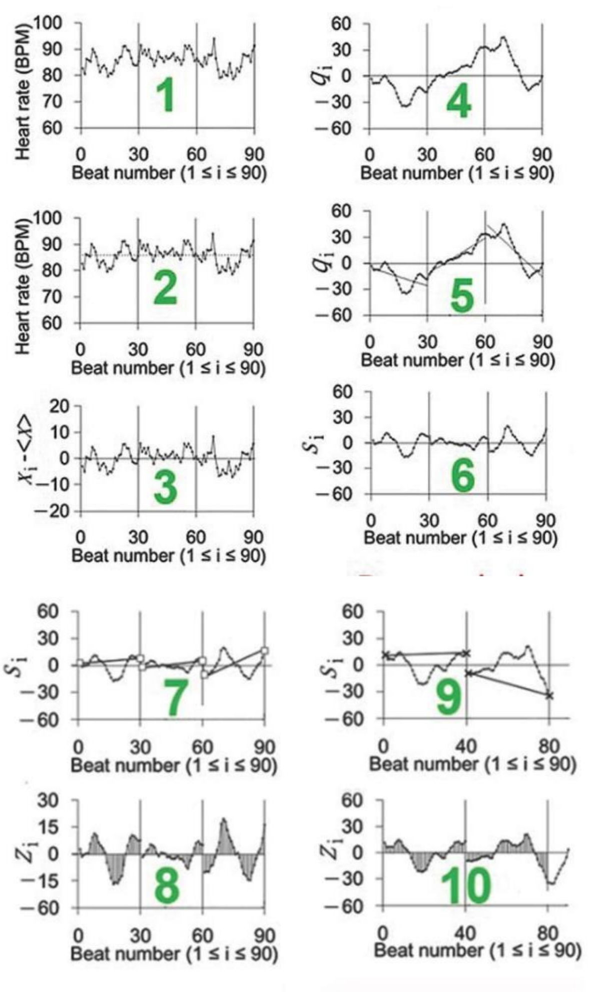

Figure 1. Ten key procedures explaining mDFA computation (Graphs 1-10).

4. BOX SIZE IN ROUTINE mDFA

We always use a routine mDFA [2]. Our routine works include: (1) obtaining a baseline-stable EKG at 1KHz sampling rate, (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. A 2000 beat length of EKG is corresponding to a time period for about 30 min. We tested a longer recording period, for example EKG for 2 hour,. 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 hours. 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 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.

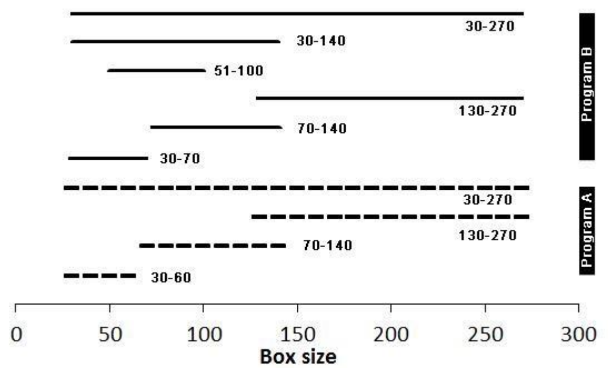

Figure 2. mDFA box-size-range (a slope measurement from which box size to which box size).

Program A	53							
10	11	12	13	14	15	16	17	18
	19	20	21	22	23	24	25	26
	27	28	29	30	40	60	70	80
	90	110	120	130	140	150	160	170
	180	190	200	210	220	230	240	250
	260	270	280	290	300	400	500	600
	700	800	900	1000				
Program B	136							
10	11	12	13	14	15	16	17	18
	19	20	21	22	23	24	25	26
	27	28	29	30	31	32	33	34
	35	36	37	38	39	40	41	42
	43	44	45	46	47	48	49	50
	51	52	53	54	55	56	57	58
	59	60	61	62	63	64	65	66
	67	68	69	70	71	72	73	74
	75	76	77	78	79	80	81	82
	83	84	85	86	87	88	89	90
	91	92	93	94	95	96	97	98
	99	100	110	120	130	140	150	160
	170	180	190	200	210	220	230	240
	250	260	270	280	290	300	310	320
	330	340	350	360	370	380	390	400
	410	420	430	440	450	460	470	480
	490	500	600	700	800	900	1000	

Figure 3. mDFA box-size at which we computed variance and mDFA.

We performed mDFA computation at various range of box-size. In 2006, we first made program A (see Figure 2), which included box-size-ranges [30; 60], [70; 140], [130; 270], and [30; 270]. This four ranges were automatically computed at once but we are able to compute any box-size-range manually if we need. Then, we increased the number of box-size-range, which is program B (see Figure 2). The program B includes box-size-ranges [30; 70], [70; 140], [130; 270], [51; 100], [30; 140], and [30; 270]. Until now, we used both program A and program B. Existing EKG data at present (before 2006 as well) were all computed by both programs.

Program A computed at 53 points of box (Figure 3) and program B computed at 136 box (Figure 3). This increase in box-number was decided because calculation speed of a Windows PC was improved.

Once again, in our empirical studies in biomedical investigations key points include: (1) a recording length approximately 2000 beats, which is roughly, say, from 1990 beats to 2200 beats, and (2) mDFA main box size range, i.e., a key box-size-rage is [30; 270] unless otherwise mentioned. The period length 30 min is a maximum period for human to keep stable.

It is of interest to note: The period length of the special box-size-range that we found, a 270 beat length, is an unique period-length that has been mysteriously chosen by "man" in our history (i.e, it is about three minutes for us to keep a steady state, I would explain so), For example, (1) the period-length for the boxing game one round, (2) the period length for that one can wait until a noodle soup can be finished up. Cup ramen (also called instant ramen) is now sold all over the world, and (3) the song length of a single RCA-music forty-five seven-inch records; Elvis, The Beatles, Rolling Stones and many more.

5. RESULTS

Case 1: A wine party

Volunteers (a women's cooking group) invited us to a home wine tasting party held in Tokyo, and we were allowed to take their EKGs after lunch (Table 1). We recorded their EKGs for about 40 minutes, and computed the scaling exponents immediately after. Of the nine volunteers, two were in good health (subjects No. 8 and No. 9, Table 1). Subject No. 8 specifically exhibited a scaling exponent = 1.03: perfect health (see Figure 5). We have met over 500 subjects so far, and only about 10 percent had a healthy scaling exponent of "one." This was a typical group (Figure 4 and Table 1). We always observed subjects' behavior carefully. We noticed that the normal subject (No. 8) exhibited a typical pattern, a "healthy exponent creating behavior"—i.e., smiling a lot, talking, and possibly rich. Indeed, subject No. 8 (the scaling exponent = 1.03) was laughing, enjoying her EKG, and never stopping talking during the 30–40 minute recording. Meanwhile, some other subjects said that they need to work hard at part-time jobs (see Table 1). Some others also confessed that they were always worrying about their children's education, etc.

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.

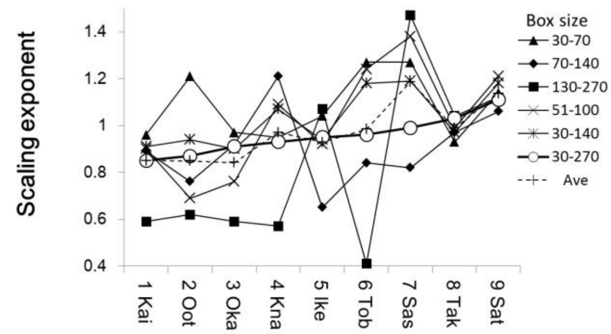

Figure 4. DFA results of nine subjects at a home party. In particular subject No. 8 showed almost perfect scaling exponent of one.

Table 1. Comparison of the scaling exponent and everyday life. (Subject 5 was a wine seller)

Subject number	Code name	Age	Sex	Scaling exponent SI [30; 270]	Arrythmic beat during recording	Medication for arrhythmia	Job work or house wife
1	Kai	46	F	0.85	PVC x2	*None*	Part time two days a week
2	Oot	48	F	0.87	PVC 24hr x400	Medication	Part time two days a week
3	Oka	48	F	0.91	PVC x1	*None*	Part time two days a week
4	Kna	52	F	0.93	*None*	*None*	House wife
5	Ike	61	M	0.95	*None*	*None*	Wine sales
6	Tob	47	F	0.96	*None*	*None*	House wife
7	Sas	52	F	0.99	*None*	*None*	House wife
8	Tak	46	F	1.03	*None*	*None*	House wife
9	Sat	41	F	1.11	PVC 40min x5	*None*	Work (caretaker)

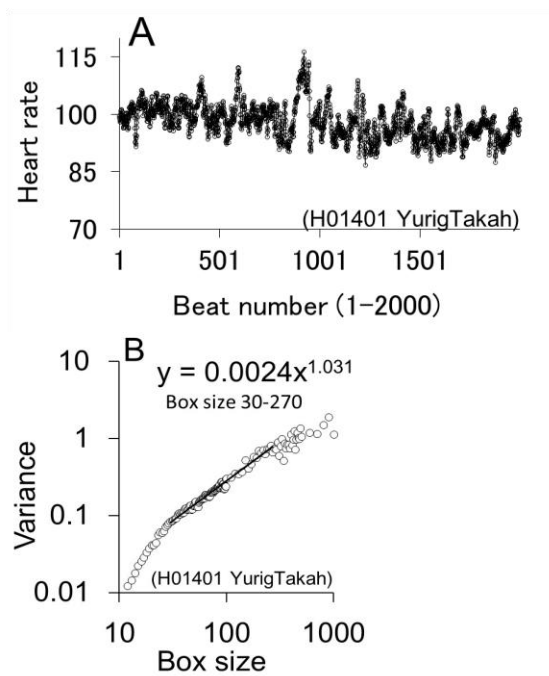

Figure 5. An example for the perfect health demonstrated by mDFA. Subject No. 8.

Case 2: Passenger airplane
This subject is afraid of high place since an accident. The person told us that she (age 60s) got a falling down accident from a steep slope during skiing in teen age at the Alps mountain in Germany.

She was a passenger of an airplane. We recorded her EKGs. during her airplane was heading to the Washington Dallas Airport, observing her conversation and behavior, and putting every noticed things into a laboratory notebook. EKG results and mDFA computations are shown in Figure 6. A 2000 beat data, from "a" to "f" in Figure 6A, were used for mDFA computation. Each data was shifted by 500 beats. During the periods, a, b, and c, the airplane gave us scary emotions because of shaky condition due to very bad weather. After the data "c," one can see that the airplane touched down the ground. When the airplane was shaky, the scaling exponents were way lower than 1.0 (Figure 6B, a, b, and c). After passengers can see successful landing, the scaling exponents went up (Figure 6B, d, e, and f). The difference of slope in mDFA computation can be seen from the slope graph shown in Figure 6C, where the slops are steeper in d, e, and f, compared to those of a, b, and c. After landing, the subject did feel less fearful, which is shown by numerical evidence, the varying scaling exponent (changes from a, b, c to d, e, f, in Figure 6B). The EKG tests revealed that the scaling exponents were able to tell us quantitatively how we feel fear.

The scaling exponents are always calculated determining the slop over the fixed range of box-size between 30 heartbeat and 270 heartbeat in our mDFA computations [2].

The subject (Figure 6) normally has a small number of skipping heartbeats (data not shown), which is benign, and is called PVC, premature ventricular contraction. During scary fearful condition, inhibition, the vagal nerve activity, could be vanished and acceleration, the sympathetic nerve activity, could be dominated in terms of physiology of the autonomic nervous function. In fact, one can see two PVCs [see two asterisks (*) in Figure 6A] during the last half period in the Figure 6A. In the anterior half, the subject had a scary feeling when the airplane was shaky and was descending approach to the landing strip. However, the scary feeling was gradually disappearing when the airplane is almost going to make a touchdown. Both EKG time series and mDFA results are helpful to interpret how the subject's mind varied while landing.

Case 3: Occupation and cardiac problem
Table 2 shows the results where human EKGs were analyzed using the same mDFA methodology. We collected EKGs data at seated position at the time length for 30 to 50 min with interviewing about subject's daily life, stress, medical history, and family history. In Table 2, one can see the SI (SI = the scaling exponents) differences between stressed and non-stressed individuals.

While we have not extensively studied thousands of human subjects (Table 2), people who have stress and conduct top management seem to have quantifiable degree of stress. Fundamental idea of the stress-quantification or stress-measurement was derived from crustacean animal experiments [2]. Cardiovascular system in various animals would be working under the same law, in terms of evolution of life on earth. The law is the scaling law of heartbeat time series. The law governs the simple system, i.e., the system is composed of two elements, a controller (the brain or the cardiac center in the brain) and a pump (the heart).

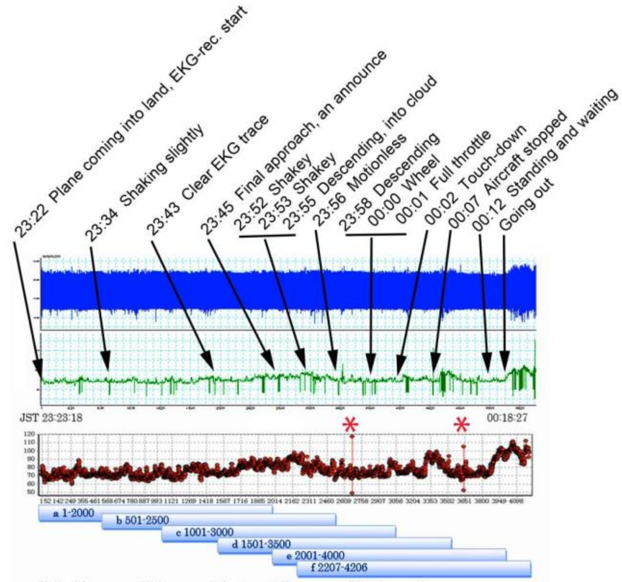

Figure 6A. EKGs in the airplane.

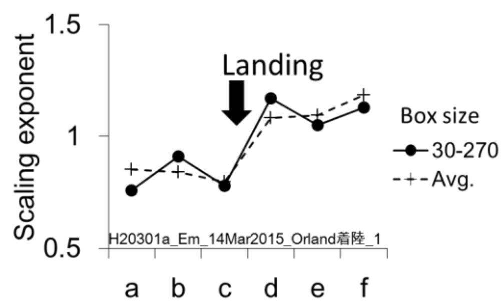

Figure 6B. mDFA results from the data in Figure 6A.

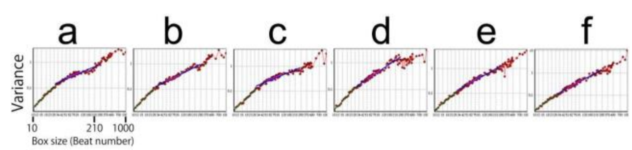

Figure 6C. mDFA slopes where we determine the scaling exponents.

This study suggests that the scaling exponents computed by mDFA can quantify stress. Furthermore, mDFA results were intriguing. The appendix in Table 2 shows that cardiac muscle injury can be detected using mDFA. Their SI, i.e, an ischemic heart has a high SI. (We have proven in animal models that an injured crustacean hearts exhibited a high exponent [2].)

In case one received a heart surgery, we can test the heart operation using mDFA. The operation was successful if the patient has SI = near 1.0. We have two good examples. EKGs recorded from professors, both have had "valve operation about a year ago; one EKG is from a Russian, age in his 40s, and the other is from a Japanese, age in his 60s. The professors, to whom the author met at a meeting (unpublished data), both told us that each surgeon informed professors after surgeries that the valve repair was successful. However, both professors honestly told us that they worry about that possible malfunction might be happen someday soon. Therefore, they asked us to check their heartbeats by mDFA. They said they had a relief after our mDFA proved they have a SI near 1.0.

Although we need much more comprehensive examples from "potential sick subjects" who are spending their life as a "person on the street" instead of an "inpatient," we can conclude that the injured heart exhibit an extremely (over 1.2 by our criteria) high exponent [2].

Table 2. Comparizon: Stress level and exponent value (Indonesia, 2012, working with Prof. A. Hutapea)

Categories	Age	Stress level (Interview)	SI
Business owner (a company) No. 1	50s, Male	Fairly low	1.03
Business owner (a company) No. 2	50s, Male	High	0.72
Top management, President of a Univ.	60s, Male	High	0.84
Top management, Vice President of a Univ.	40s, Female	High	0.84
Middle management, Dean	40s, Male	High	0.72
Middle management, Secretary of president	40s, Female	High	0.76
Ordinary employee, Teaching only professor, No. 1	50s, Male	Fairly low	1
Ordinary employee, Teaching only professor, No. 2	50s, Female	Fairly low	0.98
Appendix: Cardiac disease	Age	Daily life	SI
Patient with stent-placement	60, Male	OK	1.26
Patient with bypass-surgery	45, Male	OK	1.38
Patient with inplantable cardioverter	53, Male	OK	1.22
Ventricular septal defect (20 y ago operation)	48, Female	OK	1.41
Healthy representative, housewife	46, Female	OK	1.03

6. DISCUSSION

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 [2], 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.

Detrended fluctuation analysis (DFA) is not our own invention, but Peng's in early 1990s. DFA has solid foundations in quantitative science. Peng's DFA focused on "critical phenomena" natural data. Peng's DFA is well accepted worldwide. However, We needed to modify and make our own program because Nicola Scafetta and Paolo Grigolini [5] pointed out that Peng's DFA is appropriate for Gausian time-series data but not appropriate method for the data that is derived from a system of non-Gausian distribution. Therefore, we tried to make our program and tested how it works upon natural data by our own empirical EKG studies [2].

ACKNOWLEDGMENTS
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