Chapter

mDFA Detects Abnormality: From Heartbeat to Material Vibration

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Abstract

Modified detrended fluctuation analysis (mDFA) is a novel method to check abnormality of heartbeat which is developed recently by the author. mDFA can characterize any oscillation such as heartbeat by the scaling exponent (scaling index, SI). Healthy heartbeat shows SI = 1. Dying heart's SI sifts toward 0.5. Ischemic sick heart experimentally showed an SI way over 1.0 approaching 1.5. Random vibration, such as FM-radio noise and idling car-engine, shows SI = 0.5. Quietly running motor generates an SI almost equal to zero. Using mDFA, it is possible to check potential risk based on SI values. This chapter shows empirical results quantifying various signals from heartbeat to material vibration.

Keywords: mDFA, heartbeat rhythm, material vibration, quantifying risks, scaling exponent

1. Introduction

System failure—ischemic disease of the cardiac system (CS), highway bridge crash, earthquake, space rocket launch failure, and so forth—leads to catastrophic consequences. Watching abnormality by testing toughness is important for preventing disasters. We want to detect early warning sign. But how? We have an idea. The method is modified detrended fluctuation analysis (mDFA).

In this chapter, we show examples of mDFA computation. First, we show mDFA results on the CS, then results on the nonliving, material system.

The CS is composed of the heart and the brain, that is, a pump and a controller. Evolutionally, all creatures have evolved from a common ancestor. If the CS was innovated long ago, "hearted" animals follow fundamental laws of physics (and chemistry and biology). In fact, it is known that all "hearted" animals carry the same DNA for making the heart: development of vertebrate heart is controlled by a common genetic code (a DNA sequence called Nkx, a homeobox, and a cardiac-specific homeobox). However, not only vertebrate heart but also invertebrate heart is controlled by the same genetic code: development of insect heart is regulated by "tinman DNA," which is Nkx family gene. Surprisingly, Hydra, a simple animal, that exhibits "pumping movement," has Nkx-like gene (see [1]). Therefore, the pumping-heart design is evolved since Hydra [2]. If we find a primordial basic rule in a simple creature, it is applicable to humans.

In this chapter, we first show experimental results on crustacean animals (crabs and lobsters), on which we have long worked [3]. In the second place, we present human heartbeat analysis, and lastly mechanical vibration analysis. Throughout

the study, we use an analytical method, mDFA, which is recently developed by our group [1]. We explain mDFA in the later section.

2. Physiology of animal heart

Circulation failure is absolutely a life-threatening event. Unpredictable cessation of blood flow is the worst-case scenario. For studying the problems, we need physiology, and it is necessary to record heartbeat data from freely moving animals.

Figure 1 shows how to record electrocardiogram (EKG) from invertebrate animals. Two permanently implanted metallic electrodes (+ and −), touching the surface of the heart with extreme caution, were used to record EKG. We used DAM50 C-R coupled AC amplifier (World Precision Instruments, USA) and Power Lab (ADIntrument, Australia) for digital EKG data sampling at 1 kHz.

Nervous regulation of the crustacean heart is well documented by great scholars [1]: Carlson (1904), Alexandrowicz (1932), Maynard (1961), and so forth. The heart receives two kinds of nerve fibers. One is acceleratory nerve (CA) and the other is inhibitory nerve (CI) [3]. The nerves are always active and discharge frequency is ever-changing. Moreover, the brain releases slowly functioning cardio-active substances (peptide) via the nonneuronal hormonal method [6]. As a result, the heart never beats at a steady pace. Heart rate exhibits a dynamic change all through life. Heartbeat interval time is never stable, never regular, and is always fluctuating.

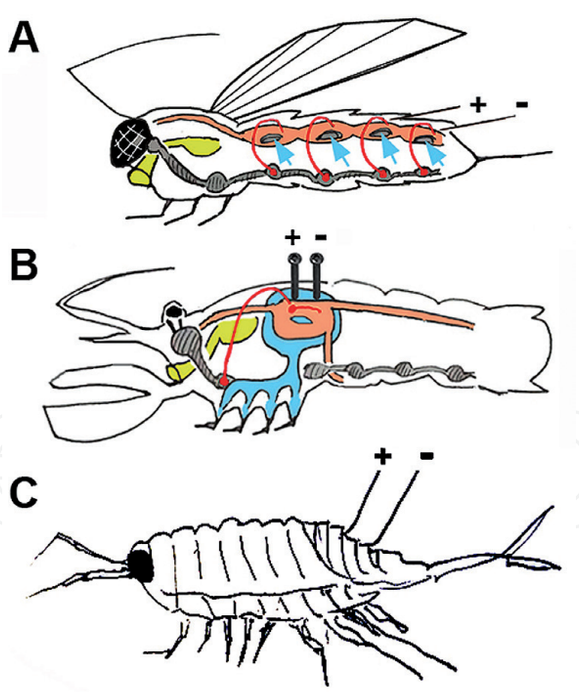

Figure 1.
Diagrammatic representation for EKG recording from insect (A), lobster (B), and isopod crustacean Ligia (C).

3. Analysis of heartbeat

Mechanisms of cessation of heartbeat could be studied by mathematical methods. We believed that the method might be the frequency analysis because heartbeat is a cyclic behavior. The other candidate method is heartbeat-interval time series analysis. Whichever, we need natural data, EKG. We prepared two specimens,

intact and isolated hearts. We tested two different analytical methods. One is the power spectral density analysis (PSD) and the other is mDFA [5, 6]. As a result, we found that PSD did not well distinguish the difference between the two heartbeats [5, 6]. In contrast, mDFA was powerful and quantitative to represent the inherent state of the two hearts [4].

PSD is well known worldwide. People who use PSD implicitly suppose that a complex-look signal is a sum of cosine waves at various frequencies such as 10, 20, 30, 40, and 50 Hz. Real world data, such as heartbeat and material-vibration signal, carry hidden information that PSD might not capture.

With this consideration, the mDFA program was invented by a master-student, Tanaka (see [7]), and an author (TY) tested and verified it [1]. It is about 20 years since then.

We repetitively confirmed [1, 4, 5] that freely moving animals' heartbeat exhibits the scaling exponent (SI, scaling index) of around 1 (SI = ~1.0). In turn, isolated heartbeat data exhibit the SI of around 0.5 (SI = ~0.5).

4. Animal heart experiments

At a very early stage of the study, we learned that mDFA well distinguishes between intact and isolated hearts as aforementioned. We got an idea: mDFA can be a helpful tool in pathophysiology, because cardiac disease is one of the major causes of death worldwide.

We began to record long-term EKGs from model animals. The recordings were started from fresh healthy specimens and were kept continued to the end of their life. Sometimes, the recording period length exceeded 2 years, which is extremely long and painstaking (**Figure 1B**, lobster). In turn, it was, at one time, only 2 h (**Figure 1C**, isopod Crustacea).

Figures 2 and **3** show example EKGs at terminal conditions.

Figure 2 shows coconut crab EKG. This specimen was captured in March at a Japanese tropical island, south-west Okinawa. We transfer it to Tokyo in a hand-carried baggage. Long-term EKG was recorded in Tokyo instead of the south, tropical zone. The animal eats apples and dry fish meat and lived longer than we expected. Climate in Tokyo got colder in autumn and the tropical crab ended its life in October: non-air-conditioned environment at natural room temperature. SI values in March were ~1.0 (data not shown). The SI values (around 0.9) continued to September.

In **Figure 2**, one can see that SI values decrease when dying. It is of interest that after the cessation of pumping heartbeat, fibrillation remained (**Figure 2**), which indicates that heart muscles still try to contract.

Many other specimens tested, including crayfish, crabs, insects, and clams, show a SI-decrease-phenomenon when dying (data not shown). We found it typical that when dying, animals show diminished movements and decremental SI-shift toward 0.5.

At the terminal condition, the brain is not likely to regulate the heart any longer, although the heart is still pumping like the isolated heart. We consider that the terminal condition accompanied by a low SI is a state of brain death.

If we look at dying crab specimens, our intuition tells that relevant specimen is likely to pass away soon. We define this as "natural death."

In the meantime, we encountered an unforgettable specimen that died unpredictably (**Figure 3**). At time zero in **Figure 3**, EKG trace looks normal. After checking EKG on PC screen, an author (TY) left Tokyo, setting out on a journey to see a hospitalized family. Two days later, TY returned and looked at PC and discovered that the crab

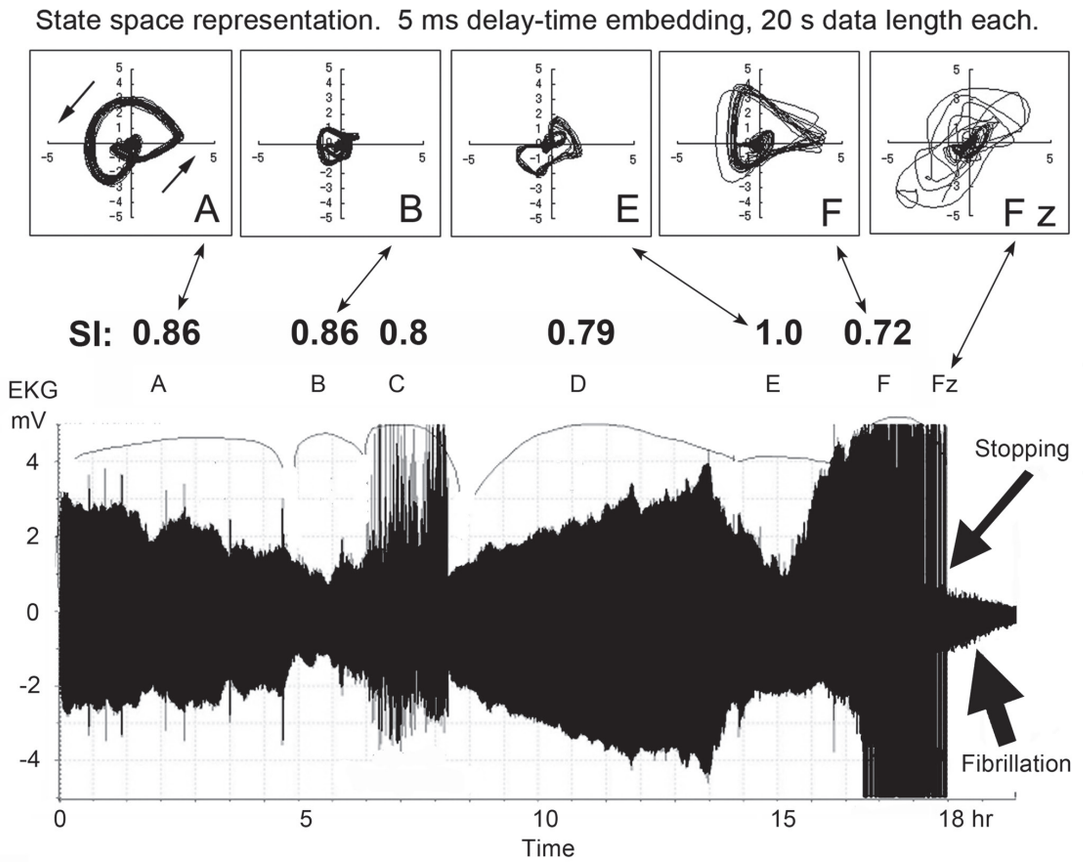

Figure 2.
A long-term EKG from coconut crab (Birgus latro) with state space representation. Recording for 18 h. Inset: SI values for the corresponding period from (A) to (F). Note: fibrillation after beating stops. State space representation of cardiac action potentials shows a normal action potential shape in (A), gradually changing to distorted pattern (B, E, F), and finally becomes erratic and unstable at the end (Fz). Modified from Yazawa [10], Chapter 2.

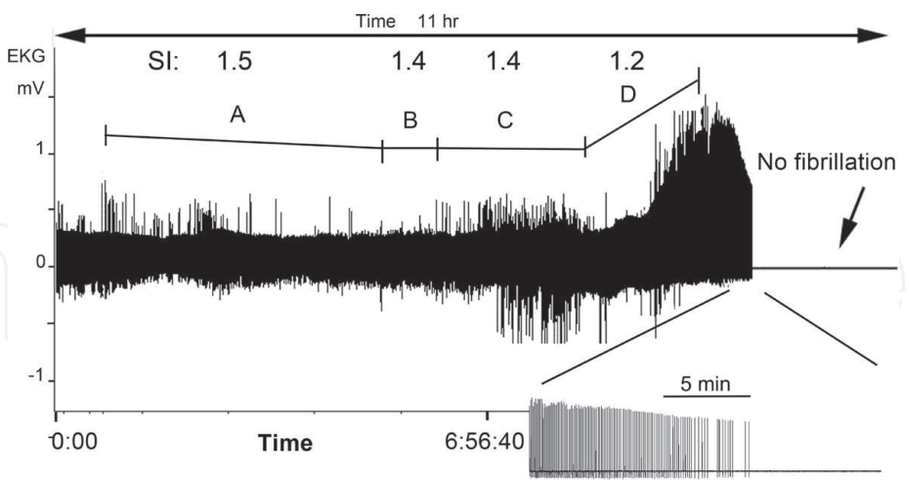

Figure 3.
A long-term EKG from "Mokuzu" crab (Eriocheir japonica). Recording for 11 h. Inset: SI values for the corresponding period from (A) to (D). Note: No fibrillation remained after beating stops: cf. **Figure 2**. *Inset: spike configuration not distorted. Modified from Yazawa [10], Chapter 2.*

heart stopped its beating 11 h after TY left (**Figure 3**). We define this "unpredictable death." Unpredictable death is a rare event among ~1000 specimens. We always check and dissect all specimens' body after the death. In case of **Figure 3** animal, dissection revealed that the myocardium of relevant crab partially got slightly injured by an EKG electrode (see the electrode in **Figure 1B**). It is the fault of researchers. We are very sorry that the innocent specimen suffered from the human-caused heart injury for 2

weeks, although we did not know that. From this rare case, we learned that little injury of myocardium causes sudden death. Only partial damage of the heart is life-threatening. It is comparable to a human health problem, well known ischemic heart disease. We found it crab's "unpredictable death."

Results of **Figure 3** surprised us, the suffering crab's SI values "always" exceeded 1.0 (see **Figure 3**, SI = 1.5, 1.4, 1.4, 1.2). We have never seen before. A hypothesis came into my head: "injured heart has a very high SI." This hypothesis is unproven as far as we know. We have seen many dying specimens that showed reduction of SI-value as shown in **Figure 2**.

The results suggest that "the scaling exponent methods" distinguish damaged heart from unhurt heart. We biologists consider that medical profession should test mDFA on human hearts. We sent a short abstract to a medical congress in Europe, but the application was rejected immediately. We ourselves began to study human hearts.

5. Biophysics

5.1 Quantitative analysis

In 1982, Kobayashi and Musha reported that healthy hearts exhibit 1/f spectrum [8]. Mathematically, 1/f slope is almost equal to SI = 1.0, while not 100% equivalent. This metric analysis based on SI is not fully proven as far as we know. The criterion-based strategy is better than qualitative research for diagnosing the CS.

For the quantitative expression for the CS state, we need computation. However, in the 1980s, we did not have a PC to calculate SI. Poor biologists found difficulty to use a computer that was installed in a building of a top university. It took until 2001 to prove the idea of mDFA by ourselves. The Windows XP machine was introduced in the year 2001. XP-PC helped us calculate mDFA on the second time scale.

What we liked was Kobayashi-Musha's concept that one (SI = 1.0) is "healthy" [8]. There is a fixed baseline for diagnosing the heart system, that is, healthy or not.

In the 1990s, Peng and Goldberger and others demonstrated that healthy hearts exhibit the scaling exponent ONE (1.0) by detrended fluctuation analysis (DFA) [9] [DFA is not mDFA (see below)]. These results add critical evidence to the issue of Kobayashi-Musha's concept.

Moreover, Peng and Goldberger's group reported that sick hearts exhibit a higher SI, which is SI = ~1.2. It sounds like providing evidence that a sick heart was consistently higher in the scaling exponent. But they only suggested. The truth was unclear. At least we were excited about our crab's high-SI discovery (**Figure 3**) because it coincides with it.

Most of the data in [8] and [9] were obtained from in-hospital patients. Peng and Goldberger's group did not extend their detailed experiments to general population as far as we know.

One is a baseline number for the health. This is testable hypothesis. We began to examine EKGs on general population and model animals. Currently we have ~500 individuals' EKG and ~1000 animal data. Some EKGs are collected from long-term follow up. Some subjects have passed away. We take medical record with all data including animal data. We never use website data. Physiological interpretation of data is impossible without medical record based on our own physiological observation.

5.2 Accurate data sampling

EKG signal was captured by two commercially available Ag/AgCl electrodes and a lab-made amplifier that can damp undulatory noise. The amplifier has a short input-time-constant (*tau* = 0.1 or 0.22 s, depending on capacitor used, 0.01 or 0.022 μF). The *tau* value for EKG-machine in hospital-use is set at about 10 s under the international regulation. A large *tau* amplifier makes signal-baseline drift when subjects move. We thus needed to make a small-*tau* amplifier in order to reduce "movement-induced noise and drift" (see **Figure 4**).

Peaks are captured automatically by a lab-made program. R-peaks are the time point at which V_{max} is attained over threshold voltage. Once R-peaks were captured, all peaks were 100% affirmed by eye observation on PC screen after the end of recording. If incorrect peaks are captured, or correct peaks are NOT captured, we

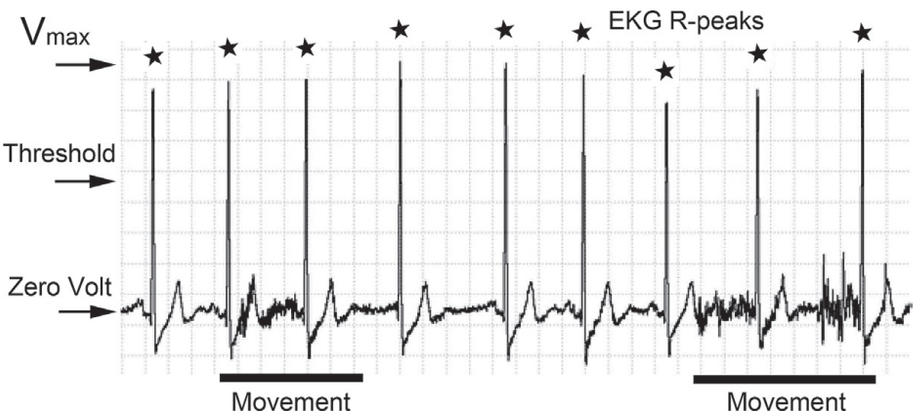

Figure 4.
Accurate peak detection. Human EKG recorded with a lab-made amplifier. A physician diagnosed this heart as a sinus arrhythmia, but not life-threatening; male age: 60s.

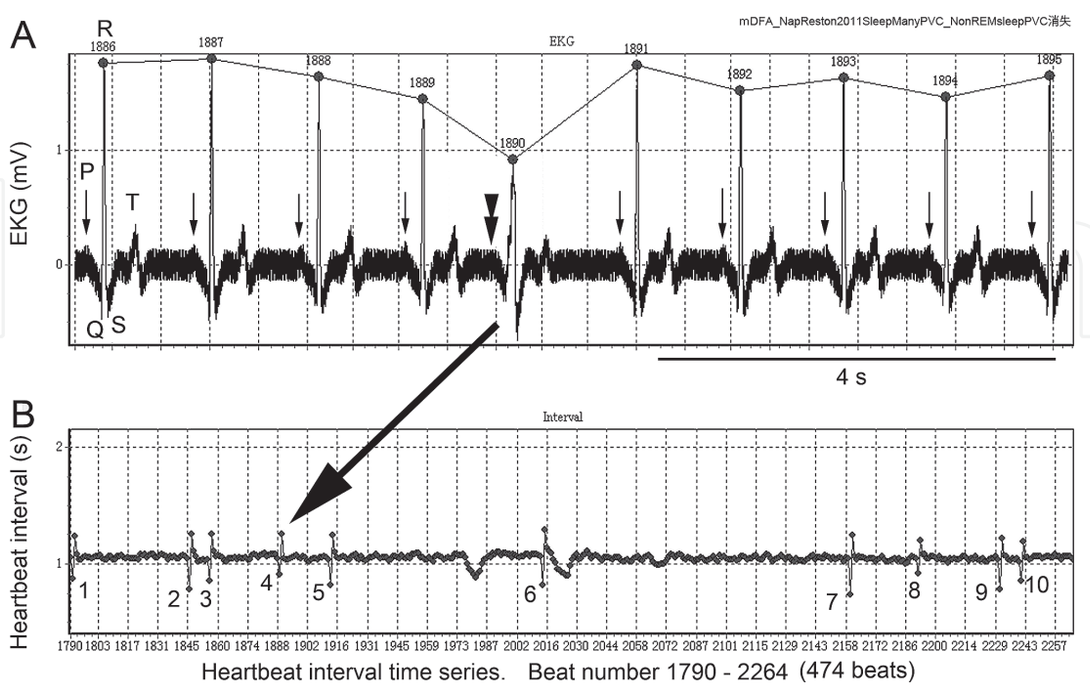

Figure 5.
Accurate data collection. Peak identification from EKG (A) and construction of time series (B). P, Q, R, S, and T peaks are indicated (see A). Small arrows in A point all the P-peaks. Double arrowhead indicates that there is no P-peak within one heartbeat period. Therefore, this is premature ventricular contraction (PCV). Within 474 beat time period, 10 PVCs are visible. **Figure 5** *was recorded 5 years before* **Figure 4** *from the same subject.*

manually made a correction on PC screen. As a result, all peak interval time series become accurate. It is time consuming work but inevitable for accurate interpretation of data. The sampling rate is 1 kHz for the heartbeat (20–40 kHz for material-vibration as shown in below sections).

Since we consider that accurate data sampling before analysis is paramount for later interpretation of results, skipping heartbeats and irregular heartbeats should not be deleted before analyzing, like someone does. However, any artificial spiky noise should not be counted as a pulse.

In summary, accurately recorded EKG without large noise, accurately captured R-peaks (stars in **Figures 4** and dots in **Figure 5A**), and accurate peak-to-peak time interval time series is important for performing accurate mDFA (**Figure 5B**).

5.3 Time series

Figure 6 shows the procedure of mDFA.

5.3.1 First procedure

We first construct an accurate R-R interval time series from EKG recordings, which is [*Xi*] (**Figure 6A**, abscissa axis, the number of heart beat *i*, and vertical axis, rate of beating in beat per min). **Figure 6** shows only 1 - 30 beats among 2000 beats. We use "heart rate" instead of "interval time." If we use R-R-interval time, which is an inverse of "rate," mDFA results are the same. To biologists, using "rate" is intuitively more understandable about physiology of the heart than using "interval." The seventh beat in **Figure 6A** shows an irregular beat.

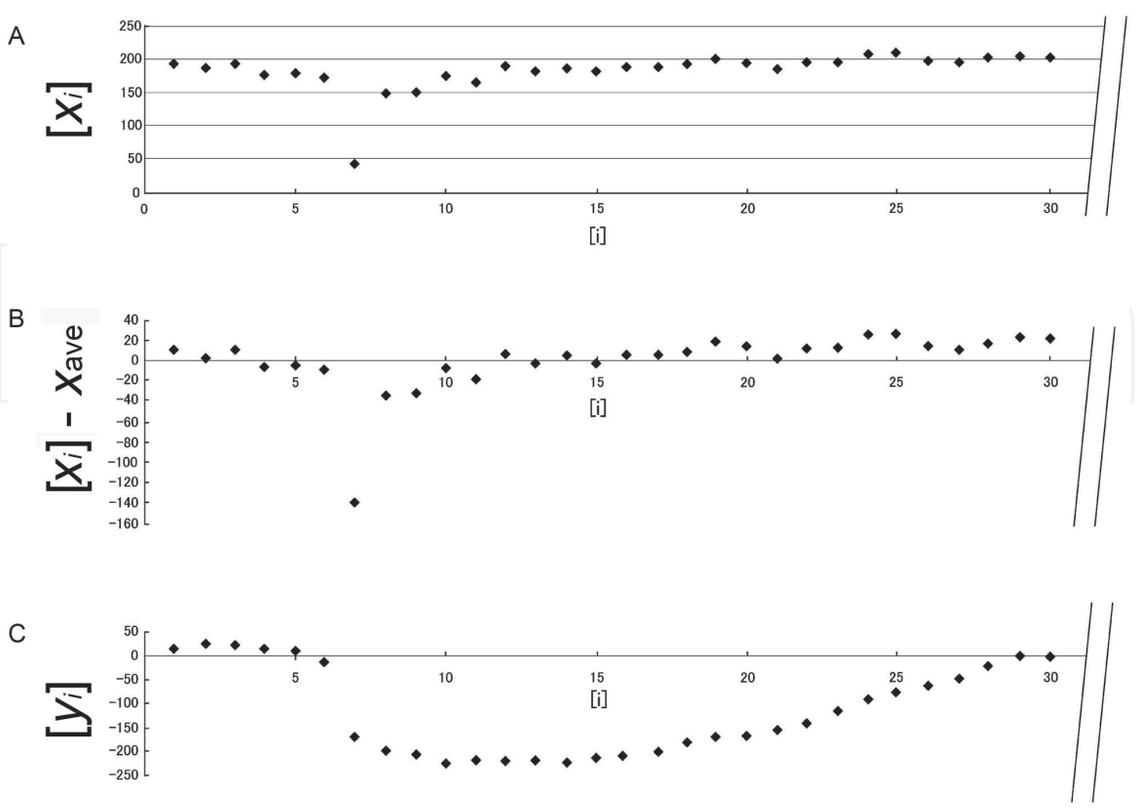

Figure 6.
A diagrammatic explanation of pretreatment of R-R peak data. Measuring a R-R peak interval time Xi, where i = 1, 2, 3, --- 2000 (A), obtaining an average of them, Xave, and thereafter subtracting it from Xi (B), and making additions of each values one by one (C).

For mDFA computation, we use 2000 heartbeat data. Both data shorter or longer than 2000 can be usable but we fixed it 2000 after testing [1]. Long data, such as 1 or 2 h data, does not have significant benefit for interpretation of physiological meaning of results. The reason is simple. The cardiac system (CS) never becomes a stable state. The CS is an ever-changing dynamic system, which is our temporary interpretation and we have had consistent results. Currently, we use 2000 beat data. A 2000 beat time period length is about 30–40 min [1].

5.3.2 Second procedure

Mean value from 2000 data is X_{ave}. By removing X_{ave} from each data (X), one can get a time series of pure fluctuation $[X - X_{ave}]$ (**Figure 6B**).

5.3.3 Third procedure

A computation $\sum_1^{2000} x$ makes a random-walk like temporal sequence $[y_i]$ (**Figure 6C**). Important concepts in mDFA are "averaging" and "sigma (summation of data, **Figure 6C**)."

5.4 Trend

Figure 6 demonstrates diagrammatically that the fluctuation property is expressed in connection with the average value. The sequence $[x_i]$ is heart rate time series in beat per min (**Figure 6A**). The sequence $[X_i - X_{ave}]$ expresses pure fluctuation (**Figure 6B**), some larger and some smaller than the average value. One can see that the seventh beat in **Figure 6A** shows a very small value. The seventh beat makes $[y_i]$ trace jump down (see the seventh dot, i = 7, in **Figure 6**). It is catastrophic happening; thus, this event is an arrhythmic heartbeat. This kind of event becomes a matter of life or death if extremely unlucky. In fact, a single event is not only life threatening but also not so happy of course. Therefore, the trait of fluctuation is directly linked to life or death.

In summary, the sequence $[y_i]$ expresses sigma (Σ) of each value. This $[y_i]$ is "trend." This is an explanation about the "pretreatment" of data before conducting mDFA. This $[y_i]$ is the data that mDFA analyzes. Both mDFA and DFA use $[y_i]$ for calculation, but the concept is different between them as shown below. See [1] for details.

5.5 Box size

In **Figure 7A**, 2000 beat long data are broken up into small length data; here it is 10 beat long (see three Boxes in **Figure 7A**). Box-size is freely changeable in program. In **Figure 7**, we show only box-size-10 as an example. We tested smaller box less than10 in box-size. As a result, it is not so useful than we thought. In our program, mDFA's box size ranges from 10 to 1000 [1]. In computing, mDFA automatically changes box-size, starting from box-size 10-beat. Then 11-beat, 12-beat, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, ..., 30, 31, 32, ..., 40, 41, ..., 50, 51, ..., 60, 61, ..., 70, 71, ..., 80, ..., 90, ..., 100, then 110, 120, and so forth [1].

5.6 Fitting curve

Figure 7B shows a fitting curve. They are linear fitting curves $y_v(1)$, $y_v(2)$, and $y_v(3)$ (**Figure 7B**). This example (**Figure 7B**) is linear fitting, just for the sake of ease. But, in practice, we must use biquadratic fitting [1] (see **Figure 8** caption).

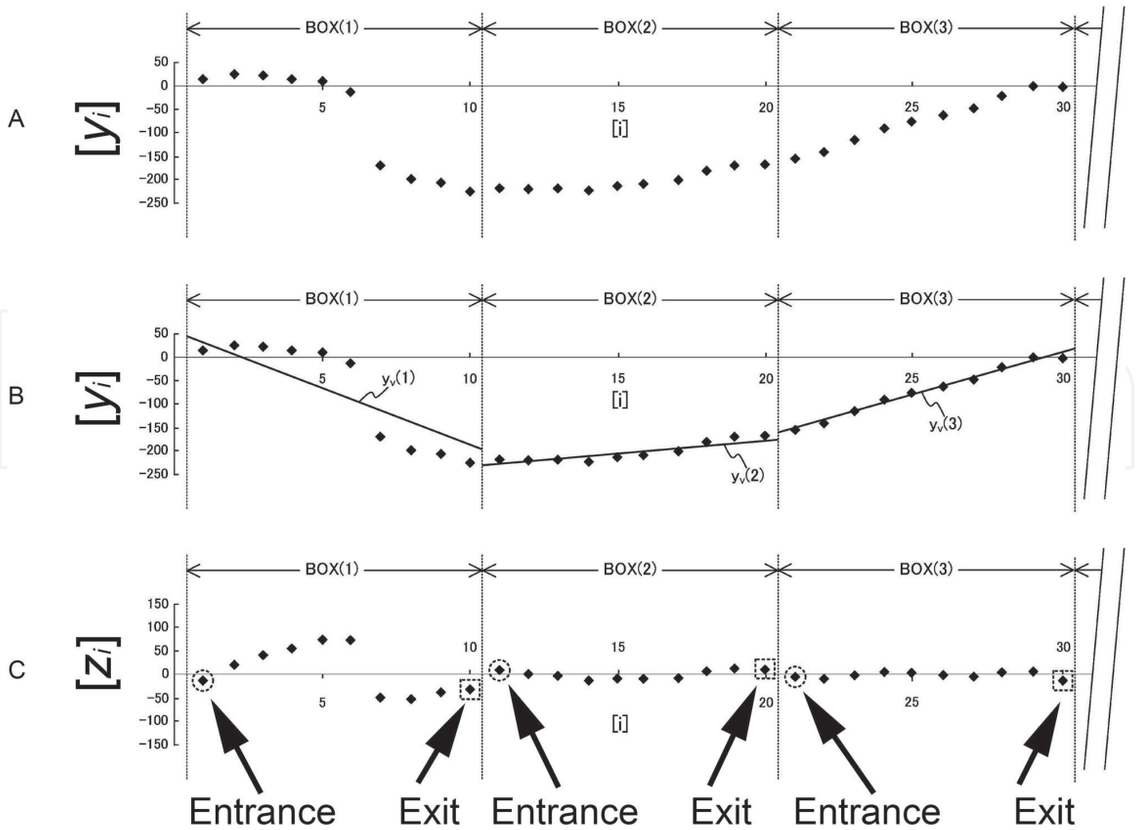

Figure 7.
Diagrammatical representation of the "detrending" procedure. A series shown in ***Figure 6C*** *is broken up into 10-beat-long box (A), drawing a fitting curve in each box (B), and thereafter executing detrending (C). See text.*

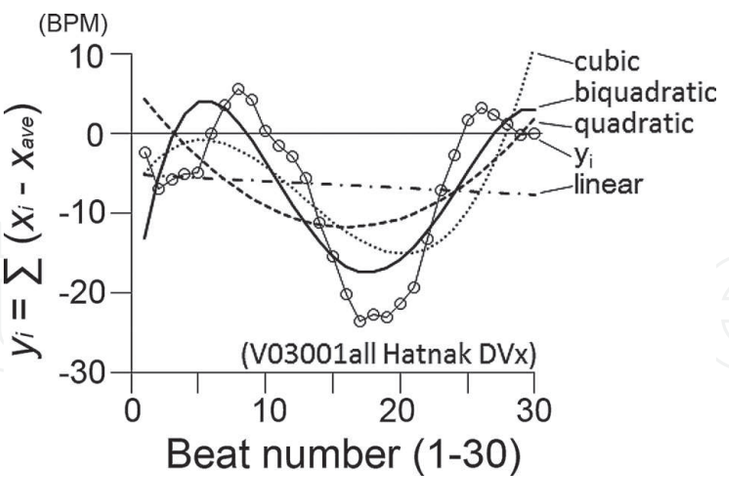

Figure 8.
Several kinds of fitting; real human data. The [y_i] curve shows raw data. We tested fittings, linear, quadratic, cubic, biquadratic, and further. As a result, less than fourth order computation does not return a stable/unvarying SI value. mDFA uses quadratic fitting.

5.7 Detrending

A fitting y_v curve is given by a PC computation as shown in **Figure 7B**. Next computation is making a detrended curve that is given as $z_i = y_i - y_v$. After this procedure, true fluctuation remains. This is "detrending." The [z_i] sequence is important.

5.8 DFA and mDFA

In **Figure 7C**, arrows point two values: "entrance value" and "exit value" in each box (**Figure 7**). mDFA uses entrance and exit values obtained by detrending procedures.

In turn, Peng's DFA uses all 10 values in each box (see **Figure 9**). But the detrending procedure is a common concept between mDFA and DFA.

For convenience, a portion of **Figure 7C** (from the 1st to the 16th) is enlarged in **Figure 9**. Peng's DFA measures vertical differences between fitting curve and real data (**Figure 9**). Thus, Peng's DFA looks at "critical phenomena" according to physicists. But mDFA does not do those measurements: mDFA looks at 10 heartbeats at once (**Figure 9**).

Peng's DFA looks at individual heartbeat one by one (**Figure 9**). What mDFA looks at is how much [z_i] sequence has proceeded over time within a box, sometimes up and sometimes down. Therefore, mDFA can see ever changing undulation or fluctuate in each box (**Figure 9**). Fluctuation is not always stochastic noise. Rather, fluctuation carries previously unknown hidden information. It is sometimes hidden threat. It is sometimes high-risk information.

One might think that both, Peng's DFA and mDFA, have a similar calculation concept. But, mathematically, there is a gap between their concepts. According to Peng's paper and successor's publications, there is a tipping point (changing point and critical point) at the box-size11-beat. Peng et al. labeled the scaling exponent as alpha-1 and alpha-2. Alpha-1 corresponds to box-size ranges smaller than 11. In turn, alpha-2 corresponds to box-size range greater than 11. However, mDFA does not detect this tipping point. We found that box-size smaller than 30 (30-beat-box-sise) does not carry physiologically significant information. mDFA program begins computation from 10-beat-box-size and goes to 1000-beat-box-size (see **Figure 10**) but draws regression lines from box-size greater than 30 (see next section).

5.9 Scaling

Figure 10 shows typical mDFA results from heartbeat data of a crab (**Figure 10A**). mDFA makes a log-log plotting graph. Abscissa axis, which is box-size and ordinate is shown in variance (**Figure 10B**). If a clear slope can be seen in the graph, mathematically, the slope represents scaling property buried in heartbeat signal.

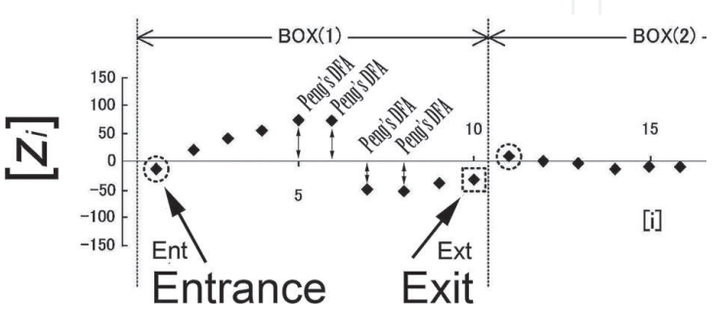

Figure 9.
Diagrammatic representation of the difference between Pang's DFA and mDFA. Pang's DFA calculates vertical difference between data and zero-line (four small arrows). Peng's DFA computes average of 10 data in a box. Total data length is 2000-beat. There are 200 boxes of 10-beat-box. Peng's DFA thus can get 2000 data in one-box-size-calculation. In turn, mDFA computes the difference between Ent and Exit (Ext – Ent). mDFA thus can get 200 data. After finishing box-10 computation, the program increases box-size and repeats calculations cyclically: box-11, box-12, box-13, and so on.

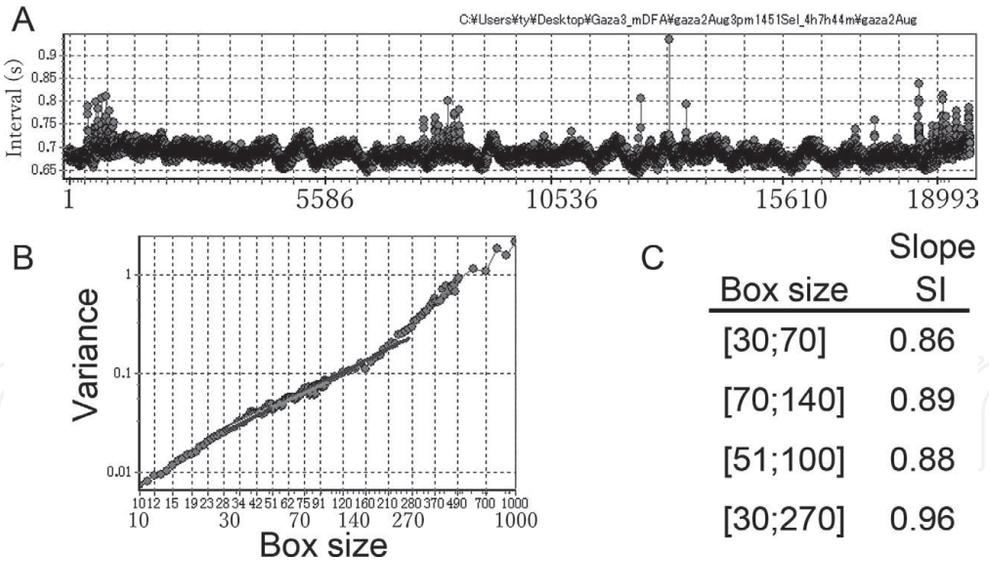

Figure 10.
An example mDFA. (A) Heartbeat interval time series; Gazami crab. (B) mDFA graph, box size versus variance; slope determines the SI. (C) Four box-size-ranges and corresponding SI. Crossover can be seen at two points, at a box-size of ~30 beat and ~200 beat. Physiological interpretation is under study. In this computation, 20,000-beat data were used, although 2000-beat data produce similar results (not shown).

5.10 Scaling range

By drawing a strait regression line, mDFA computes SI (**Figure 10B**). But the length of the regression line, from where to where, is unsolved. Default mDFA program draws six lines at once in a log-log graph. Each slope corresponds to the respective SI value. In **Figure 10C**, four SIs are computed. Standard six box-size ranges include: [30; 70], [70; 140], [51; 100], [30; 140], [130; 270], and [30; 270] (**Figure 11**). In our studies, unless otherwise specified, the six set is not changed for the sake of NOT to create confusion, while it can be changed infinitely. **Figure 11** is the final style after testing a variety of ranges. We have been using this "unaltered program" made by former master student, Tanaka [7] for over 10 years.

Meanwhile, those who have the skill of programing can easily make his/her own program. It is a high school level mathematics. Scaling range can be determined by the person who makes it. Other mathematical procedures, such as averaging, square root fitting, and drawing a scaling line, are not complicated tasks.

So, we can guaranty that any mDFA program surely captures cardiac scaling properties. mDFA works in physiology. Thanks to great names, William Harvey (1628 Circulation), Marcello Malpighi (1653 Medical Dr., Capillary), Ludwig Traube (1872 Alternans pulse), Willem Einthoven (1903 EKG), and Anton Julius

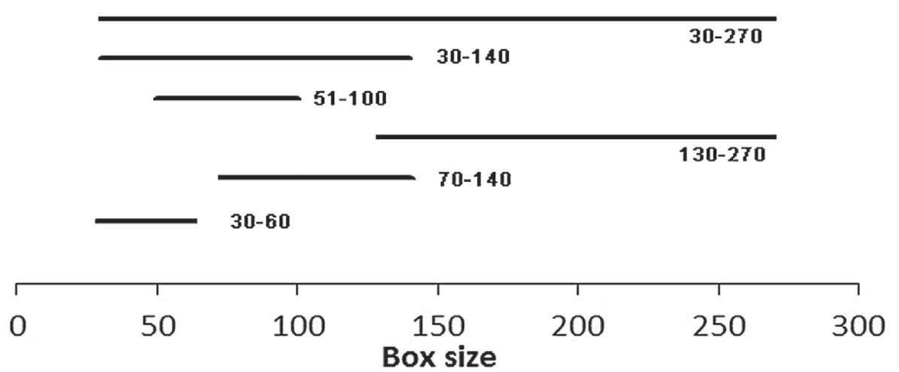

Figure 11.
Standard six box size range.

Carlson (1904 Heart physiology on model animals), for example, basics of physiology would never change forever.

If two persons have their own mDFA program, then they analyze the same data, and then one can say, "my computed SI is 1.10" and the other can say, "mine is 0.93." This kind of "contradiction" can happen. But it is NOT a big deal. We need to overlook the details. Both are around 1.

Regarding mDFA computation, please see the following sections that show what we calculate from heartbeat data.

EKG signal is generated by the cardiac system. Elements in the system are linked to each other. The system cannot work properly without feedback connections. If one can find a scaling-line in the graph (**Figure 10B**), the heart system is working properly. If a line is bending or winding, something is wrong in the body system. We guaranty so. And if a subject is healthy, mDFA tells you that the SI-value is around 1 (1.0).

As far as we know, this scaling property of the heart system was first documented in 1982 [8] and then in 1990s [9]. They proposed this nice metric theory. They used a well-known mathematical idea. We must say we moved it forward. But mDFA is based on different concepts—this is the novelty of this research—than Peng's concept as shown below. We just use the scaling property that the cardiac system inherently has.

5.11 Physiological interpretation

After finding the slope, linear fitting is necessary to determine SIs. We draw a regression line from box-size 30-beat to 270-beat as the best range for interpreting physiological meaning of heartbeat data [1]. In our study for more than 10 years, SI is "always" obtained from the regression line ranging from box-size 30-beat to box-size 270 beat (**Figure 10B**).

A 30-beat time length corresponds to about 30 s. A 270-beat time length is approximately 3–5 min. We feel sure that life prefers "3–5 min" period length: boxing round fighting time, for 3 min; hit song one musical performance, for 3 min; instant noodles cooking time, for 3 min; and a pain killer medication, coming on 3 min after taking it. We found that it seems convenient and correct that mDFA draws a line within a box-size range [30; 270] (**Figure 10C**) to check if the body system is alright or not.

6. Human general population

6.1 Ethics

We try to record EKGs of general population including people in the classroom, in the exhibition hall, company-employees, university-employees, and people at a scientific conference venue [1]. Every experimental subject was treated as per the ethical control regulations of universities (Tokyo Metropolitan University; Tokyo Women's Medical University; Universitas Advent Indonesia, Bandung; Universitas Airlangga, Surabaya, Indonesia).

6.2 SI: reproducibility

All our data are collected by the author [1, 5, 6]: invertebrate heart study since the 1980s, human data since approximately 2000, and materials data since 2010. The mDFA program was made by a former master student Tanaka [7] in about 2004.

mDFA results are reproducible and consistent. We found stratification phenomena that provide evidence for the quantitative measure SI links to various physiological phenomena in a one-to-one manner [1, 7, 10–12]. Arrhythmic heartbeat decreases SI [11]. Non-REM sleep decreases SI [12]. Premature ventricular contraction (PVC) decreases SI [11]. Alternans (harbinger of death rhythm) decreases SI [7]. Anxiety, fear, and worry decrease SI [10]. University president, vice president, president-secretary, and dean professor all have a low SI [1] but teaching-only professors have a healthy SI (SI = ~1.0) [1]. A happy content housewife has a healthy SI too [1].

Meanwhile, we encountered some healthy looking but non-healthy-heart subjects in general population [1]. We found that these subjects have had received cardiac surgery. Their myocardium is indeed injured like the crab specimen shown in **Figure 3**. All of them had a high SI. A person who has an implantable cardioverter had SI = 1.22 [1]. A person who has stent-replacement had SI = 1.26 [1]. A person who had bypass-surgery had SI = 1.38 [1]. A person who had a surgery due to ventricular septal defect had SI = 1.41 [1]. However, until today, we have never met any person, in general population, who keep maintaining a high SI and later passed away.

Ergometric exercise increases SI [1]. We think that hard exercise is probably NOT a healthy behavior for normal humans.

Heartbeat is repetitive muscle contraction. It is a cyclic behavior. It is oscillation. It is a fluctuating event. SI can quantify these unstable movements. SI can tell us the cardiac system's condition. If SI is around 1, there is no health problem regarding the heart and its control. However, if your SI is high or low, maybe I say, "Better see a doctor." But the research has only just begun.

We would like to declare that mDFA can sense warning sign although mDFA cannot identify what is wrong or what is going on.

7. Nonliving material

7.1 Introduction

We learned that mDFA detects abnormality of the heart system. Especially, we learned that a system failure increases SI up from the basic value 1.0. The failure of the heart is generally myocardial cell damage. Myocardial cells are the elementary structure of the system. Analogically, it is like a material that is made by granulated elements [13]. We expected that mDFA might contribute to nonliving system because mDFA works well in the heart.

In **Figure 3**, when a crab heart's cells were damaged by an electrode, the damage caused a significant shift of SI (toward SI = 1.5) (**Figure 3**). In human heart cases, a person who had a surgery due to ventricular septal defect, the cardiac surgery might be a major cause that pushed SI up from normal SI [1] (see a large SI, 1.41, in Section 6.2).

Materials have different properties, meaning each has its own quirks when processing [13] like the hearts.

7.2 Abnormal vibration

In nonliving material experiments, we use a piezoelectric sensor for vibration detection. It is a mechanical monitoring device made for a cardiac pulse sensor (ADInstruments, Austuraria). The sampling rate is 1 kHz in our heart experiments. The heart beats at about 1 Hz in rate. In turn, a motor rotates ~3000 times per min.

It is 50 Hz oscillation. We set the sampling rate (ADIinstruments) at 20–40 kHz in non-living material experiments. After recording vibration signal, we capture peaks and conduct mDFA as usual.

We use consecutive 2000 peaks for the analysis. We obtained vibration data lasting for about 40–60 s. The methods for both living and nonliving vibration are fundamentally the same.

7.3 Electric motor

A motor has a design that will safely operate for a long time. We realized that a running motor did not break easily [14]. We therefore covered the motor by glass wool to enhance overheat (**Figure 12**).

We monitor vibration wave travelling through the fixed base by a piezoelectric device. Vibration was analyzed by mDFA, like the heartbeat analysis. **Figure 13** shows results, which demonstrate that abnormality is captured by mDFA. We used a box-size range [30; 270] as in the heartbeat analysis (**Figure 13A**). SI is around 0 when running without overheating (see the periods designated as P–U, **Figure 13**). **Figure 14** shows an example of mDFA.

A sound "bang" occurred at the time of the end of U, and smoking started. It is hazardous. We stopped running the motor at about 10 min (**Figure 13C**). After the bang sound, one can see that SI significantly increases. The motor still ran till 10 min at the same speed although overheated. In **Figure 13C**, one can see that amplitude of signal significantly decreases. We estimate decreased stiffness and durability. It might be plastic's inherent weakness. We later opened the motor. Overheat caused softening of plastic parts inside the motor, especially plastic materials surrounding the brush. Softened plastics may absorb vibration energy more than hard-cold one. **Figure 13B** demonstrates wave patterns. U is much noisier than Q although running speed does not change. It is an induction motor (200 V, 50 Hz).

We found that a box-size range [30; 270] seems to work properly as in the heart. However, the box-size range [130; 270], which is a much narrower range, seems to contribute greatly to capture "warning sign" about "failing" motor (see # in **Figure 13A**). The plotting "130–270" indicates that the "time-window size [130; 270]" detects malfunctioning earlier than other "window sizes" (**Figure 13A**). Moreover, the SI value (see the plotting of "window-size 130–270") increases rapidly in number earlier than the "bang" sounds (**Figure 13A**). This is beyond doubt. But we must say that details are not known for explicit interpretation.

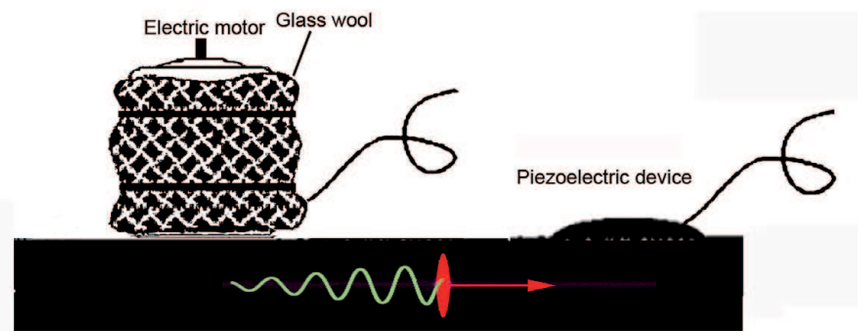

Figure 12.
Schematic image of electric motor experiment. A hand-dryer motor (in this study 100 and 200 V tested) is set on a base. A piezoelectric device monitors vibration. The sensor is connected to a logger (ADInstrument). It is the same analysis method as the EKG study, except for a higher sampling rate (20 or 40 kHz).

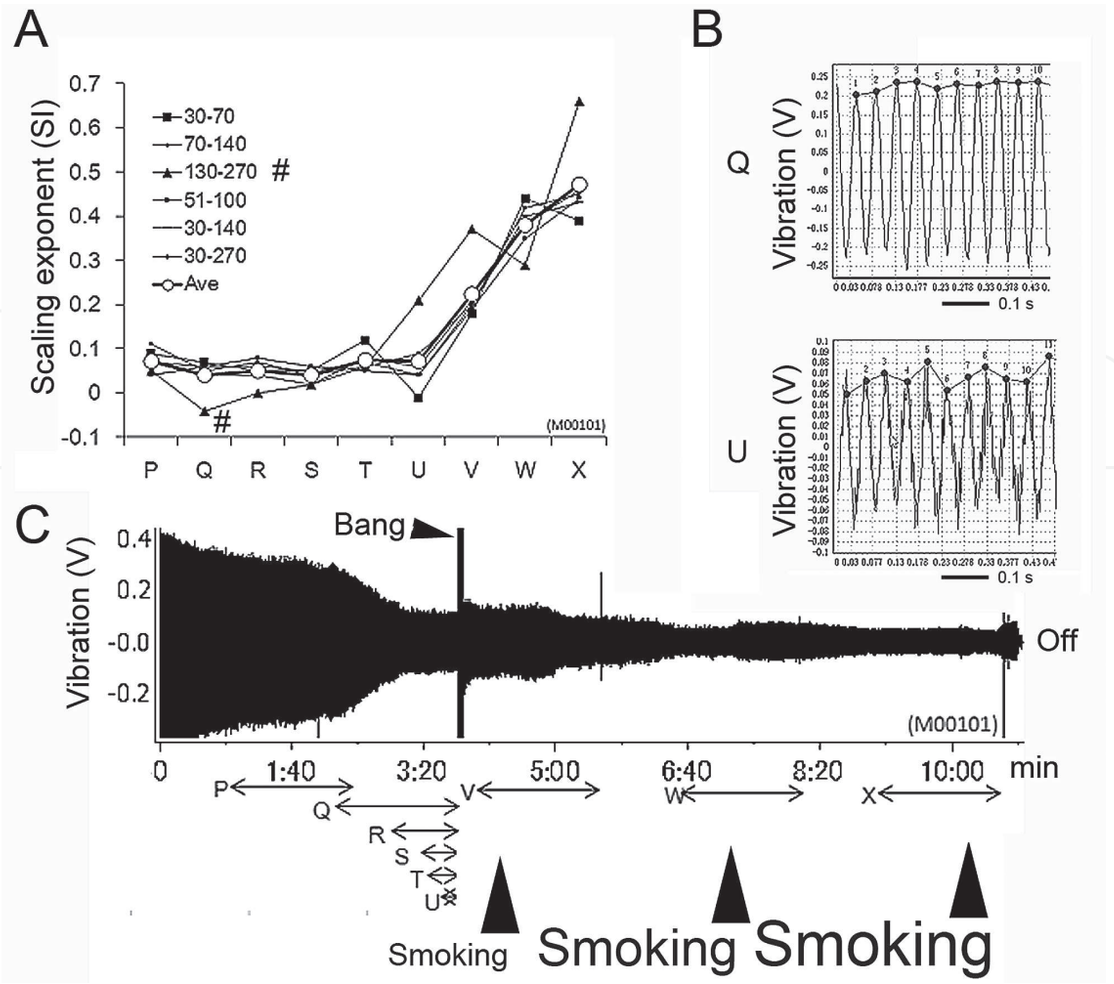

Figure 13.
A 200 V motor, overheating experiment. (A) mDFA results. (B) Example waves and peak-identifications. (C) Time zero, run motor. The time period P, heating up is insignificant. Q, Amplitude of signal decrease. Between U and V, a bang sound. Then smoking is started and gradually become worse, then the room was filled with smoke. Motor was stopped before igniting (see Off). It is perhaps fair to say that the time period lengths of R, S, T, and U are not identical. One thus can ignore R, S, T, and U, which do not interfere interpretation of data. The surge of large increase of SI occurs after Q.

7.4 Aluminum bar

We test material's toughness or the fracture toughness by changing stress intensity. **Figure 15** shows a diagrammatic image of fracture testing. We set a cantilever. A bar was tightly set on the fixed base (see W, in **Figure 15**). Vibration was applied by a speaker (see S, in **Figure 15**). Vibratory wave was monitored by a piezo device. We apply downward pressure to one end of the bar (see caption of **Figure 15**).

Figure 16 shows the summary of results. There is no load during the time period P. After P, an increase of a load is started. The bar distorts reversibly (Q, R, S in **Figure 16**). At time T, a catastrophic event, an irreversible fracture occurred (TU in **Figure 16**).

Figure 16C shows that, at normal state, SI is near 0.5 instead of near zero (**Figure 17**). This is not like motor (**Figure 13**).

Before the fracture event, **Figure 16C** shows unique results: SI attains a very high level, 1.2–1.4. This high value of SIs reminds us of ischemic heart disease's SI [1] (see Section 6.2). It is hidden threat. It is a high-risk state.

In summary, mDFA can monitor shear stress. Q-R-S periods are a period of reversible deflection. Among them, R-S periods are special. It is at a risky time: an elastic state shifts suddenly into an irreversible condition, which is catastrophe.

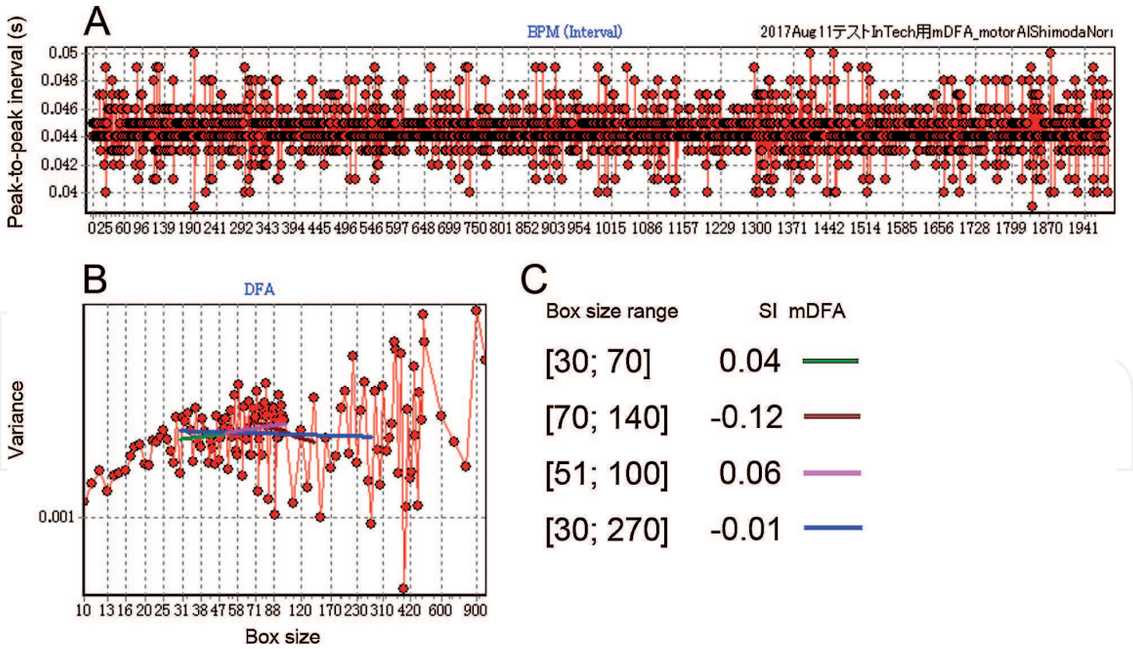

Figure 14.
An example mDFA. Running motor. (A) An interval time series. (B) mDFA graph, log-log plotting and fitting lines. (C) mDFA results. Note that slopes are vertical, meaning a normal healthy motor has an SI around 0. (Supplement note: if the testing motor is set on unstable fixed base, such as the automobile engine in the car, giving rise to a resonance with the surroundings, then SI becomes approximately 0.5, like stochastic noise. Undescribed in this article).

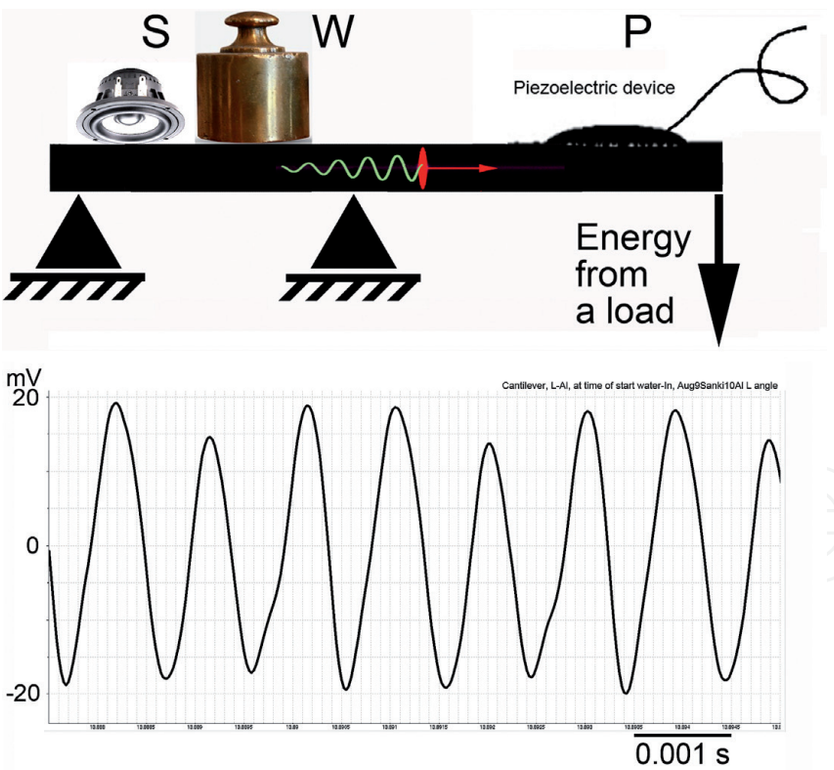

Figure 15.
Schematic image of cantilever set-up. A bar (black bar) set on a base by a weight (W). One end receives downward force accelerating at a constant speed (an arrow). A speaker (S) generates vibration. Fluctuation signal passes through the material bar and reaches to a piezoelectric sensor (P), which is connected to PowerLab 4/20 (ADInstrument, Australia). The recording method is the same as that of EKG-study as aforementioned, except for a higher sampling rate (20 or 40 kHz). Inset: PowerLab's recorded wave profile, without load.

For the safety, at the level where SI is about 0.6, inspectors are recommended to do their job for checking abnormality of materials, bridges, buildings, etc. However, it is just a biologist idea.

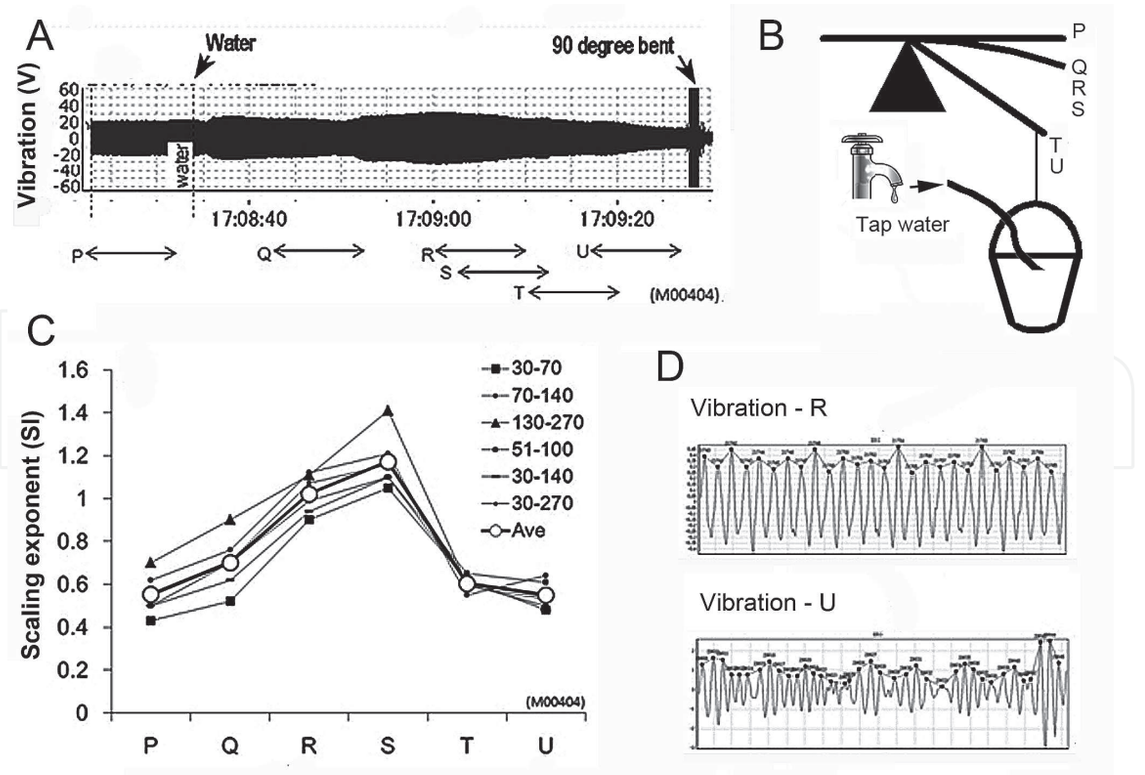

Figure 16.
mDFA results of cantilever experiment. (A) Vibration recording. (B) Diagrammatic representation of deflecting bar by a load. (C) SI value change over time. (D) Example waveforms. Material: aluminum L-shaped angle bar, cross section 3 mm thickness and 20 mm side. Load: tap water, flowing into a bucket at a rate approximately 5 L per min.

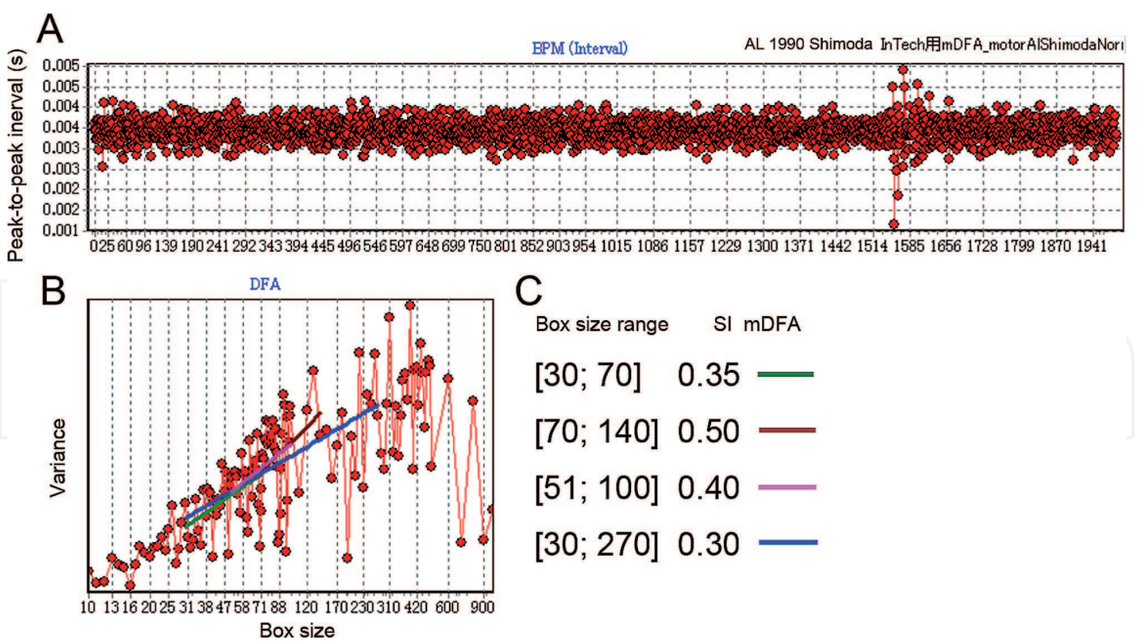

Figure 17.
An example mDFA. Aluminum bar. No load. See **Figure 14** *for comparison to motor tests.*

7.5 Earthquake

We consider that earthquake is fracture of rock structure underground, meaning fracture of materials. We expected that mDFA might help analyze these data. Ground vibration data are available from government institutions. We tested the idea.

Figure 18 shows a gigantic earthquake vibration, recorded by a seismometer at Narita in Japan, approximately 500 km away from the seismic center. The date was 11 March, 2012, afternoon.

We obtained raw seismic data (**Figure 18**) from the High Sensitivity Seismograph Network Japan. Two arrows in **Figure 18** show the time of the big event. A flat line before the big event is NOT a true straight line (see A1 in **Figure 18**). We magnified y-axis scale. The conversion discloses hidden small vibrations (A2 and A3, **Figure 18**).

Linear y-axis is inconvenient for peak detection, because some are extremely large. We converted y-axis. We plotted it in a logarithmic scale. B2 shows the square of B1 (**Figure 18B2**). Then, we make it upside down (from **Figure 18B2, B3**).

After this pretreatment, we captured peaks by a lab made program (**Figure 18C**). We use the same program for R-R peak detection in the heartbeat study. The C1-trace shows a portion of C2-trace in enlarged time scale. The C3-trace shows an example of peak-to-peak interval time series.

Figure 19 shows mDFA results. The observation period is from 3 to 29 March, 2012. The scaling exponent on 4 March was around 0.5 (SI = ~0.5) (**Figure 19B**). This means the vibration is stochastic movement. Then, SI grows up and attains a "risky" level about of 1.0. Since we are NOT specialists of seismology, we are afraid to say that it is hidden threat or high-risk state. However, in terms of chaos dynamic theory, 1.0 means the system's behavior is dynamic. It is like the heart system. It is never stable.

We know that it is too hasty to mention: this mDFA result is very similar to that of aluminum bar fracture experiment shown in **Figure 16**. In the aluminum bar fracture, SI grows up during the elasticity period, that is, reversible deflection.

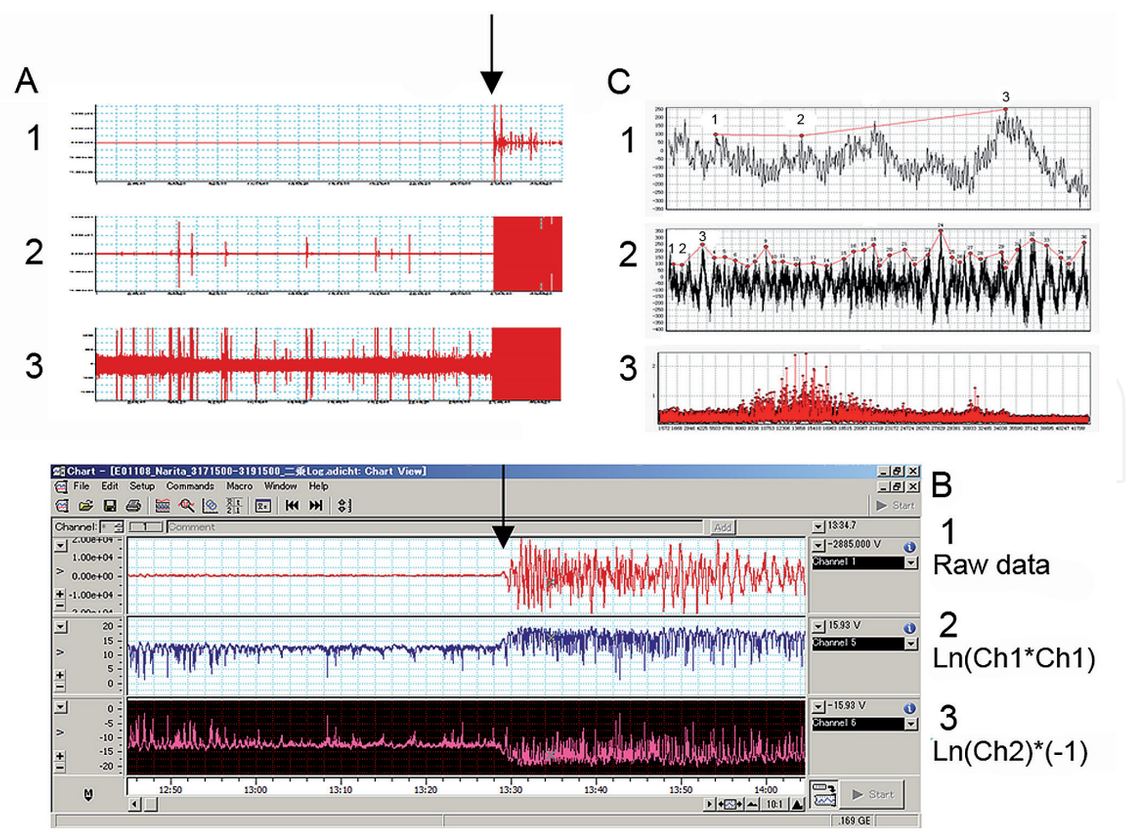

Figure 18.
Earthquake data and pretreatment for mDFA. A, Hidden vibration being exposed to view, a raw earthquake data (A1), an enlargement of Y-axis (A2), further enlargement of Y-axis (A3). B, An explanation of pretreatment procedures. A raw earthquake data (B1), logarithmic output of the square of B1, an inverse of B2 (B3). C, An example explanation of peak detection, with a faster chart speed (C1) and with a slower time (C2), accomplished peak-to-peak interval time series (C3).

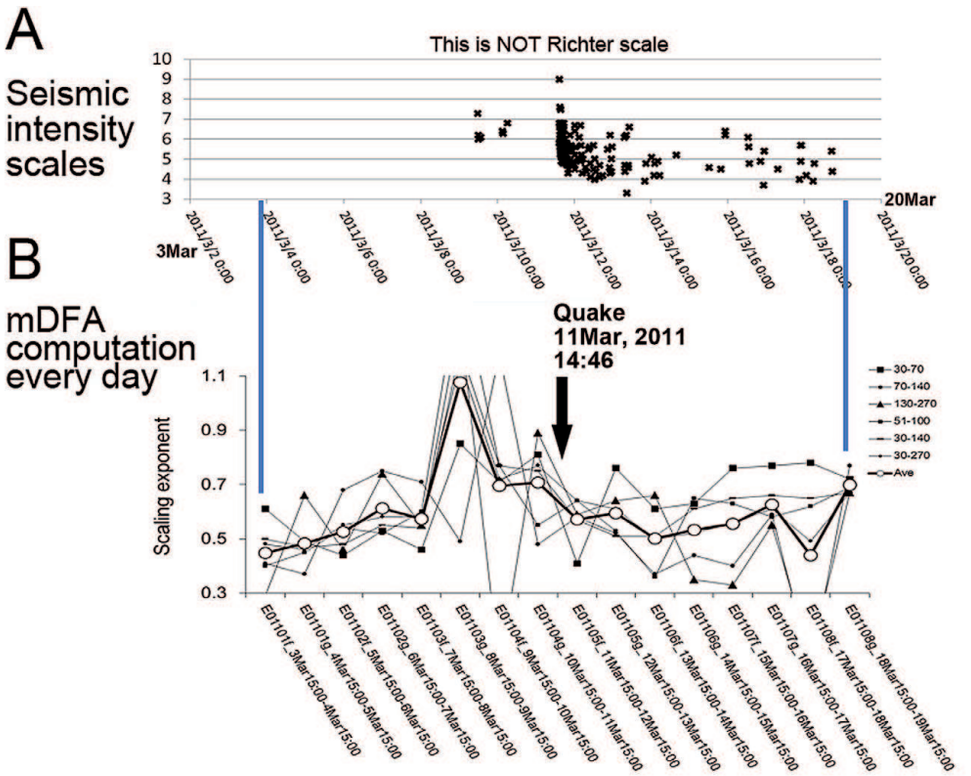

Figure 19.
mDFA results. Data: Narita seismometer. (A) Seismic intensities reported by Japan Meteorological Agency. The marks (X) indicate individual earthquakes. Five or six noticeable tremors before the big event are seen. (B) mDFA results. A plotting (marked -o-) represents averaged SI-value of all box-size ranges.

After the fracture event, aluminum's SI returns to a normal SI-value (around 0.5). **Figure 19B** shows similar trait in **Figure 16**.

This earthquake investigation using mDFA has just begun. We are not professionals, but **Figure 19B** results are remarkable. We hope that seismologists and engineers might possibly have an interest in mDFA.

8. Conclusions

mDFA computation is simple. It is high school level mathematics: first, constructing peak-to-peak interval time series [x]; second, calculating an average value x_{ave} using 2000 data; third, computing $\Sigma\ (x - x_{ave})$; fourth, cutting the time series into box; fifth, drawing a fitting biquadratic line in each box; sixth, finding the first data (Ent) and the last data (Exit) in each box; seventh, calculating the difference (Exit−Ent) in each box; eighth, calculating$\Sigma\ (\text{Exit} - \text{Ent})^2/2000$ then obtaining "variance" (statistics of root-mean-square); ninth, changing the size of box one by one, and repeating the statistics cyclically; tenth, making a log-log plotting graph that is box-size versus variance; eleventh, drawing a linear regression line; and twelfth, measuring slope of the line. At the end, the slop denotes SI.

A 2000 "interval" data are fundamental. This length of data is not always rigid. A 2200-interval, for example, produces similar results to that of 2000-interval.

We hope that many people can make their own mDFA program. The basics are averaging, root-mean-square computation, and fitting. It has never been proposed before.

In the present study, we extended mDFA to nonlife system. We then provide the comprehensive results by analyzing various real-world data, which include oscillation/vibration generated from materials. All our results are versatile; it could be applicable to the heart, a motor, materials, and possibly earthquake motion.

The heartbeat data and/or material-vibration are not static and ever-changing phenomena. They fluctuate momentarily. We did not expect that a nonlinear-way-of-thinking method (mDFA) can distinguish the states between "intact heart" and "isolated heart" when we started investigation without questioning. It was more than what we thought. Invertebrate experiments, that is, isolated heart experiments and unpredictable death experiments were a never-to-be-forgotten experiment to discover the power of the mDFA technique.

Peng's DFA and mDFA each has different scope and concept. Peng's DFA considers criticality. In turn, mDFA deals with characteristics of fluctuation embedded in signal that fluctuates over time. In the future, not only a biologist but also engineers and seismology physicists hopefully study much more data in their discipline, by using mDFA.

If we need to find abnormality of a system, mDFA always requires comparison with a baseline SI value. There is a baseline value. That quantification method makes mDFA reliable and versatile.

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