Basic Principle and Applications of a Single Square Voltage Pulse Method
A Novel Skin Electro-Impedance Measurement

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Abstract: A single square voltage pulse method (SSVP) has been used as an effective tool to study a great variety of human biophysical information and mind effects. The basic principles of this skin impedance measurement method can be understood in terms of an equivalent electrical circuit model and power function for responsive current waveform. There are two biophysically important parameters, AP and BP in this method. AP is related to the autonomic nervous system and BP is correlated with the blood flow. Many applications of a single square voltage pulse method is presented, some examples of which are responses to various kind of stimulus, audiovisual effects, color effects, biological rhythms, autonomic nervous functions, Zen and Qi-gong.

Keywords: single square voltage pulse method, skin impedance, autonomic nervous system, blood flow, biofeedback, time series analysis, Qi-gong, Zen, consciousness

1. Introduction

The human skin can be regarded as a very important interface between the human body and the outside world. Although its function is complicated, electrical measurements of skin provide important biophysical information about both the human body and mind.

The single square voltage pulse method (SSVP) is a unique and powerful skin impedance technique which deals with electrical phenomena that occur in microseconds when a voltage pulse is applied to the body [1,2]. Electric responses in the 1 MHz frequency region provide novel biophysical information, including that of the functional balance of internal organs and body fluids. Two advantages of SSVP are that there is almost no interference with the subject and negligible polarization effects on the electrodes used, since the electrical pulse imposed on the body is only 256 μs in width and 3 V in intensity. As subtle and biologically important electrical signals can be measured by SSVP, application of voltage pulse on the spots on meridian lines reveals the balance of the body, health states and even mental effects through mind-body correlation. Interesting results [3] were obtained by the SSVP method, for example, as responses to various stimuli [4], biological rhythms or fluctuations [5], biofeedback [6], image recollection [4,7], function of the autonomic nervous system and a variety of conscious states [8] including sleep or altered states. Mental effects such as those induced in Zen [9,10], Qi-gong [8,11] or meditation are also challenging targets for the SSVP method. It is especially worthwhile to note that this method holds promise for studying the autonomic nervous system, which to date has only been elucidated [12] by indirect approaches.

2. Principle

In the SSVP method, voltage pulse imposed on the body is 256 μs in width and 3 V in intensity. When this pulse is applied between active gel electrodes at the tips of the finger (i.e., the tsubo) and inactive ones on the wrist, a very fast responsive electric current is observed. An example of the current decay waveform with maximum peak at 500 ns is shown in Fig. 1. The waveform analysis was carried out [13] which gave the responsive current function as a power function represented by the following formula, where B is 3 μs.

$$ I(t)=A/(t+B)^3+C $$ (1)

Application of the scaling rule of Koyama's complex...
Brownian motion theory [14] to the responsive current resulted in a fractal skin impedance model. An equivalent electric circuit, which behaves as the power function in equation 1, is depicted in Fig. 2. It consists of an infinite number of elements in parallel—each element being resister and capacitor in series. On the other hand, it is reported that most of DC current is on the epidermis which is independent of distance. The hard part of the epidermis is highly resistive, and in fact DC resistance greatly decreased when 20 cell layers of the epidermis were removed. Consequently, the fractal scaling impedance is attributed to the epidermis.

Taking into consideration the skin structure and its nature, the electric current generated by SSVP first penetrates the hard layer and epidermis and then flows mainly through the dermis. The dermis is relatively thick and rich in water with low resistance. The fat layer under the dermis is highly resistive and works as an insulator. The fast component of the responsive current, which has maximum peak at 500 ns, shows a distance dependency. However, surface effects characteristic of high frequency is negligible in the 1 MHz region in this case.

From discussion noted above, the total impedance model of the skin involves hard layer and epidermis leak impedance and scaling impedance connected in parallel and a low impedance of the dermis connected to them in series as shown in Fig. 2. In other words, the responsive current of the SSVP is explained as an equivalent electrical circuit of the skin and a power function formula [13].

**Measurements of the SSVP method**

A Block diagram of the measurement system of the SSVP method is shown in Fig. 3. A single square voltage pulse is imposed between active electrodes on the tips of the fingers or toes and inactive ones on the wrist. Ag(film)-gel type electrodes with dimensions of 7x7 mm were used for active electrodes. These measured spots (Seiketsu) correspond to outlets of the 14 acupuncture meridians, which are significant electro-conductive points. 14 Seiketsu spots on left and right sides of both hands and feet together with the names of the meridian lines are shown in Fig. 4. The signals were AD

![Fig. 3 A block-diagram of measurement system for the SSVP method.](image)

![Fig. 4 Abbreviation of meridians. LU: Lung, LI: Large intestine, ST: Stomach, SP: Spleen, HT: Heart, SI Small intestine, BL: Urea bladder, KL: Kidney, HC Heart constrictor, TH: Triple heater, GB: Gall bladder, LV: Liver, KY: Kakuyu, HY: Hachiyu.](image)
converted in 1 μs with 10 bits resolution resulting in 256 (to 1024) digitized data values for each pulse, which were transferred to a micro-computer to determine parameters. A total of 28 spots on the 14 meridians on both sides of the body were measured in a certain order in one cycle of measurements. In the continuous measurements, this procedure was repeated every minute.

**Meaning of parameter** [1,2]

**BP**
The maximum peak current which flows immediately after application of external potential to the skin is called Before Polarization current (BP). Polarization means that of ions at the barrier membrane of the skin which is expected to be much slower than 1 microsecond. Physically BP indicates characteristic electrical conductivity of the measured systems. When BP is measured at spots called tsubo, the BP values reflect information of meridian systems. BP has positive correlation to blood flow, which was confirmed by simultaneous measurement of BP and blood flow at extremities when pressing upper arm artery [15]. Blood flow was measured by the laser doppler flow meter by attaching sensors at thumb of both hands.

**AP**
The steady state current, which is represented by term C in power formula, is called After Polarization Current, AP. AP flows even after polarization is completed and is 2 orders smaller compared to BP value. That is BP gradually decays by time converging to a constant value of AP during application of pulse voltage. AP is sensitive to pain or mental stimulus, and is related to the autonomic nervous system. There are many experimental evidence to support that AP increases when sympathetic nerve is excited and decreases when parasympathetic nerve is dominant. The simultaneous changes of psychogenic perspiration and AP were observed to have positive correlation between them [15]. AP decreases during sleep or in meditation.

3. Biophysical Reaction

3.1 Pain or thermal stimulus

By use of painmeter, a thermal stimulus was imposed on the subject at arm and simultaneously AP changes were monitored by the SSVP method on the finger of the opposite side of arm. The intensity of stimulus was controlled quantitatively by thermal radiation in mcal/s/cm². The AP began to rise immediately after the thermal stimulus forming a peak and decayed gradually in 40 to 60 seconds (Fig. 5). The AP peak height value plotted against thermal stimulus showed a relation represented by a convex curve upward, suggesting the threshold value of thermal radiation to be 60 mcal/s/cm². This experimental result is a strong evidence that AP increases when the sympathetic nerve is excited and AP decreases when parasympathetic nerve is dominant.

![Fig. 5 AP changes by painmeter based on the thermal radiational stimulus.](image)

3.2 Stress

The AP increased as a reaction due to invasion stimulus such as sudden temperature change by soaking arm into cold water under 15°C or hot water above 45°C. This is related to activity of C fiber of the sympathetic nerve. Physical strain such as pinching or stinging also increases AP by sympathetic nerve excitement.

The average AP distribution of 150 persons exhibits Lorenzian shaped graph (Fig.6). Approximately 60 % were in the range 20-30μA, with lowest limit at 10μA. The extraordinary high average AP values were that of Qi-healer whose Qi-gong is based on the martial art. The highest

![Fig. 6 Distribution of average AP, which is the mean average of 28 measured AP value for each subjects.](image)

average of 72.9μA was that of a subject who had symptom of so-called techno-stress at the measured time. The person who is always strained or under tension has a tendency to show higher AP, whereas a calm or often inactive person tends to show lower AP. Thus, abnormally high average AP value or large AP change can be a index of stress.
3.3 Biofeedback
The relaxation oriented biofeedback training regarding the activity of the sympathetic nervous system was performed by application of the SSVP method [6]. That means AP decrease is an indication of relaxation. Generally, not every subject can reduce their AP value easily at first, but probable reduction is 10-15%. For a very concentrated subject, AP decreased to about 30% (Fig. 7), which was 8 μA, notably smaller than usual limit of 10 μA.

A 33 years old man with essential hypertension underwent biofeedback training to decrease his AP. His usual blood pressure was 194/122 (max./min.) and 146 mmHg for average. His heartbeat was around 100 per minute and average AP was 31.0 μA. After several hours of practice, simultaneous measurement of the AP and blood pressure by noninvasive monitoring showed positive correlation. Namely, while AP decreased by 20 %, blood pressure and heartbeat decreased by 11 % and 15 % respectively. This trend was not observed, however, on the day when his blood pressure was relatively low and stable. That is, 161/109mmHg (max./min) and 128mmHg on average with mean AP of 20.4 μA.

3.4 Balance in meridian system
Meridian lines can not be attributed to some structural objects such as blood vessels or nervous systems, but are hypothetical pathways of bio-information or energy. However, there are several evidence that suggest the meridian system actually transfers physical information. When physical stimulus such as heat or electric voltage is applied to certain points on a meridian, reactional changes appear at other spots from the first spot on the same meridian line after some time. In fact, the speed of transfer of electric voltage has been measured to be 25 - 48cm/s [16] by placing several electric amplifiers on an arm along a meridian line.

The balance between the 12 main meridian systems and 2 special ones can be represented by a normalization of BP based on the average of 50 healthy people. The radial chart indicates the balance among 12 main meridians. In the case of healthy standard, the radial chart is a complete circle. The correlation of the internal organs and the associated meridians has not been strictly proven yet, but changes of the internal organs may well be expected to be reflected in the meridian lines. The accumulated experimental evidence suggests a strong correlation for some meridian systems such as stomach and liver. Sometimes certain characteristic patterns appear in the radial charts for certain diseases.

The heart meridian, heart constrictor, triple heater and small intestine meridians are regarded as related to circulation system based on the concept of the five elements of oriental medicine and phenomenal evidence. Fig. 8 shows a radial chart of a patient who was suffering from liver disease, showing abrupt drop at the liver meridian. Fig. 9 shows the radial chart of BP for the case of a panic syndrome and
heart disorder. The balance between the right and left sides and that among the different meridians are highly disrupted as can be seen from the chart. Fig. 10 shows the contrast between a healthy state and a mentally shocked state of the same person on different days. The radial chart of the shocked state indicates excitation of the digestion system (stomach and spleen meridian) and a stress reaction in the circulation system (heart and heart constrictor meridian).

4. Biological rhythm and fluctuation

The SSVP method can be used to measure subtle biophysical changes or fluctuations such as the 24-hour circadian rhythm of humans. Spectra analyses were carried out based on a time series of SSVP data measured every minute continually for 20 hours during sleep. That is, 28 spots were measured in a certain order every minute for 20 hours for data collection. The power spectra of BP, which is the peak value of the responsive electric current wave, in all the meridian systems were indicated to be $1/f$ fluctuation. On the other hand, different stages of sleep were found indicated by the presence of pulsations which form bursts for AP, autonomic nervous system related parameter (Fig.11). AP also seems to have essentially a $1/f$ fluctuation. Fig. 12 shows a power spectrum calculated with the maximum entropy method (MEM). The power spectral density was proportional to the inverse

Fig.10 (a) Radial chart of BP normal state in good balance, (b) Radial chart of BP in poor balance due to mental stress.

Fig.11 Time series data of AP (open circle) and calculated value (solid line) during sleep at stomach and heart meridians.
frequency to 5/3-th power, suggesting a Kolmogoroff spectrum. The MEM spectrum shows several peaks of different periods. The longest period of 355 minutes corresponds to the length of three bands of bursts. The long period variation is probably some kind of background variation which triggers the burst somehow. One possible source of this background may be the variation of the body temperature. The origin of the pulsation with time period of 9-12 minutes is unknown, but its certainly related to some variation in skin sympathetic nerve activity such as perspiration or blood flow. On the other hand, fluctuation with a time period of about 30 minutes can not be assigned to a specific biological rhythm, but may be related to some pattern of human consciousness. A child’s attention span is known to be about 30 minutes.

**Time series analyses**

The time series data during sleep were analysed by autoregressive model of Box-Jenkins type to indicate its order to be 2nd [5]. Analyses of 10 different meridians were carried out using following formula

\[ y(t) = ay(t-1) + by(t-2) + x(t) \]

where response series \( y \) are deviation from the mean values and the term of \( x(t) \) represents residual. The coefficient parameter \( a \) of each meridians were determined to be 0.767 to 0.978 and \( b \) in the range 0.004 to 0.506, suggesting major influence of the 1st order. That means influence of one prior time series data is dominant. Table 1 lists parameters for 10 meridians and their standard deviations are around 0.0294.

**Peak Fitting by the Steepest descend method**

As shape of peaks which form bursts are all the same, function formula of a single peak was determined by the steepest descent method. Then peaks fitting of the bursts were carried out with parameters of peak height and gradual background function [5]. The basic idea is that the phenomena of repetition peaks generation forms burst whose time intervals are indicated by peaks position. Time relation between intervals of peaks generation was also analysed by autoregressive model (Fig.13). The results that 4th order model fitted best indicates that peak generating time reflects influence of 4 to 5 prior intervals, or in other words biological individual has memory of 4 to 5 prior time intervals.

![MEM Spectrum](image)

Fig. 12 Power spectrum of AP based on the time series data suggesting Kolmogoroff spectra.

<table>
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<tr>
<th>Meridian</th>
<th>a</th>
<th>b</th>
<th>Mean</th>
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</thead>
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<td>TH-R</td>
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<td>0.0662</td>
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<td>0.0506</td>
<td>10.866</td>
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<td>-0.0292</td>
<td>16.000</td>
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<td>0.0041</td>
<td>17.835</td>
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<td>ST-L</td>
<td>0.978</td>
<td>0.0514</td>
<td>19.477</td>
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<td>0.0092</td>
<td>32.498</td>
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<tr>
<td>KI-L</td>
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<td>0.0414</td>
<td>25.222</td>
</tr>
<tr>
<td>BL-L</td>
<td>0.767</td>
<td>0.1957</td>
<td>19.929</td>
</tr>
</tbody>
</table>

**Table 1 List of parameters for 10 meridians.**

![Interval between x-th and (x-1)-th pulse peaks vs. x](image)

Fig. 13 Interval between x-th and (x-1)-th pulse peaks vs. x. The interval of AP peaks was analyzed based on an autoregressive model.

5. Sensitivity Information

5.1 Audiovisual stimulation

The effects of audiovisual stimulus were investigated using an instrument called a brain energizer (Innerquest-9110), which introduces different states of mind by flickering of LED and sound [4]. This instrument was made base on the brain wave research. The results indicated a strong
suggest that music effects appeared to be related mainly to respiratory function. Also, except for techno music, a large increase of BP was seen especially in the meridians of heart, heart constrictor and triple heater, which are related to the circulation system.

5.3 Color effects

Color effects of bright red, yellow, green, blue, purple and pale pink were measured by SSVP method [17]. Subjects were asked to sit on the chair facing colored wall and light emitting the same color and try to imagine that color. AP was the lowest for either red or its complementary color green, and the highest for very bright blue by 90%. Blue also exhibited largest BP for 80% of subjects. Yellow the complementary color of blue in some cases showed large BP. That meant owing to its color image and physical effects, blue excited the sympathetic nerve system and increased blood flow and resulted subject in the relaxed state. The complementary color relation of red-green and blue-yellow showed similar tendency in AP and BP, respectively. These experimental facts (Table2)

5.2 Musical effects

The SSVP method was employed to measure the effects of 5 different categories of vocal music [17]. These five musics are Mongolian Xoomie, Japanese gidayuu, Opera (Magic flute of Mozart), Gregorian chant and digital rock techno music. Subjects listened to one of the five music categories randomly chosen for 15 minutes by headphone and then immediately after that measured by the SSVP method. The BP, which indicates electro-conductivity at extremities of the body, showed largest increase after listening to Mongolian polyphony Xoomie music (Fig.15). The average increase of BP by Xoomie was 8% and the maximum increase was 21%. The increase of BP is related to the larger blood flow, suggesting largest relaxation by Xoomie. The balance among BPs at different meridian became better also. Opera and Gregorian Chants showed similar effects in some cases. The only exception was the case of techno music when BP decreased slightly, suggesting that it induced stress rather than relaxation. Comparison was made between meridian systems by weighting each BP increase and summing up the total. The lung meridian showed the largest BP increase among other meridian, which seems to
Table 2. Color effects measured by the SSVP method. Colors with maximum and minimum AP and BP are listed for ten subjects. R: red, Y: yellow, G: green, B: blue, Vt; purple, Pk: pink. Meridians are LU: lung, LI: large intestine, BL: urea bladder, GB: gall bladder.

<table>
<thead>
<tr>
<th></th>
<th>AP (High)</th>
<th>AP(Low)</th>
<th>BP(High)</th>
<th>BP(Low)</th>
<th>Large color splitting spots</th>
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<tbody>
<tr>
<td>A ᵃ 22</td>
<td>B, Y, G</td>
<td>R</td>
<td>B, G</td>
<td>Vt, Pk</td>
<td>LU</td>
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<tr>
<td>B ᵃ 21</td>
<td>B, Pk</td>
<td>R</td>
<td>B</td>
<td>Vt</td>
<td>LU, LI</td>
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<tr>
<td>C ᵃ 22</td>
<td>B, Pk</td>
<td>R, G</td>
<td>B, Pk</td>
<td>G</td>
<td>LI, LU</td>
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<tr>
<td>D ᵃ 22</td>
<td>Vt, Pk</td>
<td>R</td>
<td>B, Pk</td>
<td>Y</td>
<td>LU, BL, LU</td>
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<tr>
<td>E ᵃ 21</td>
<td>B, G</td>
<td>R</td>
<td>B, R, G</td>
<td>Vt, Y</td>
<td>BL</td>
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<td>F ᵃ 22</td>
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<td>G</td>
<td>B, Y, Vt</td>
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<td>G ᵃ 22</td>
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<td>G</td>
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<td>Vt, Pk</td>
<td>BL, LU, LU</td>
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<td>H ᵃ 22</td>
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<td>B, R</td>
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<td>I ᵃ 22</td>
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<td>J ᵃ 22</td>
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<td>R</td>
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</table>

correspond well with nature of color sensitive cell in color processing mechanism proposed by Boynton (Fig.16). It also implies that color information processing at retina membrane or at lateral geniculate nucleus (LGN) in brain is reflected in the color effects measured electrically at the extremity of the body.

The experimental results corresponded well with impressions that subjects had during the experiment.

Psychological effects should be also counted for, because color images of bright Miconos blue are free, refreshing, magnificent, far away or longing for. The lowest BP was found for purple for 60% of subjects. Although low BP indicate less blood flow, many subjects felt calmed by purple which is known as a healing color in color therapy. The subject may be feeling relieved and comfortable in purple with low BP in the states when depressed or in need of healing.

6. Oriental Mental Training

6.1 Zen

Biophysical changes during three different types of Zen were measured for the same subject who has been practicing Zen for 22 years [9,10]. Shikantaza is "just sitting without thinking", Mujisazen is "think of Mu or nothing throughout" and Koan-nentei is "trying to answer a Koan asked by Zen master with such nature that violates postulate logic. At the start of Zen, AP rose once and decayed converging to the steady state, which was common tendency seen in all three types of Zen (Fig.17a). This was especially eminent in the meridians corresponding to the digestion system measured at foot, suggesting that the parasympathetic nervous system is excited in those systems. As for AP measured in hand, it increased during Zen indicating excitement in sympathetic nervous system. It was especially eminent in triple heater meridian, which is related to circulating system, reflecting the special breathing of Zen. On the other hand, BP increased immediately after started Zen by 13% and stayed almost constant during Zen as shown in Fig.17b. This seems to be due mainly to right posture and stable mind of Zen meditation.

Fig. 16 Color perception model of Boynton showing responses of red-green and yellow-blue. S, M and L represent photoreceptor cone cell for blue (S), green (M), and red (L), respectively.

![Color perception model of Boynton](image-url)
6.2 Taimyaku Qi-gong

Qi-gong operation which uses special breathing called Taimyaku and Meimon breathing by a 44 years old Japanese Qi-healer was measured using SSVP method [11]. Difference between internal operation of Qi and external operation, that is healing others, was clarified in this case. Fig. 18 shows BP radial chart of the Qi-healer at internal Qi-gong operation together with that of normal state. The right side BP exceeds left side at all the meridian by 20% on average. This Qi-healer always intend to images discharge of Qi-energy only from the right hand. The experimental evidence agrees well with his saying. In both internal and external Qi operations AP of heart constrictor meridians and such related to circulation system increased, indicating sympathetic nervous system excited, whereas AP in stomach, liver, spleen and gall bladder meridian which are related to digestion system decreased, indicating parasympathetic nervous system excited. As for BP, it increased at all the meridian system on internal Qi operation, while decreased slightly on external Qi operation. Synchronous phenomena were observed between Qi-healer and receiver in 2 cases of continuous measurements. At Qi-healing the master can change his AP by 100 $\mu$A which indicates extraordinary case of self-regulation of the autonomic nervous system. Table 3 lists BP change of every meridian systems at Qi-healing operation by this healer for 15 subjects. The average increases of BP for 14 meridians after 10 minutes of Qi-healing are given in the bottom low for each subject. Eleven people out of fifteen showed average increase of BP to be more than 10%, the maximum case being 23.8%. The only person who had minus increase (K.K) had symptom of autonomic imbalance. In such a case, effects of Qi-gong may appear to vibrate balance at the early stage of healing. The increase of BP at circulation system related meridians were eminent for most of the subject, which can be estimated to reflect synchronous reaction with the Qi-healer.

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7. Conclusion

The responsive electric current of a single square voltage pulse was explained with an electrical equivalent circuit of the skin and power function formula. The main current flow pass seems to be the dermis.

The parameter BP, the initial peak current characteristic of the electro-conductivity of the measured system, is a good indicator of relaxation related to blood flow. The effects of music or color appeared as changes in BP. BP also reflects functional balance of the internal organs based on the meridian system. In fact, some typical diseases exhibited characteristic patterns of its balance. BP increase during the practice of Zen was most astonishing. The Qi-gong operation also increased the BP of Qi-receiver.

The AP parameter is related to activity of the autonomic nervous system and can be an indicator of stress. From responsive results to thermal radiation stimuli measured by the SSVP method, it became evident that AP increases when sympathetic nerves are excited and decreases when parasympathetic nerves are dominant. Relaxation oriented biofeedback was performed effectively using AP decrease as an indicator of relaxation. The decrease of AP in Zen is due to suppression of sympathetic nerves and activation of parasympathetic nerves, which also indicates deep concentration or depth of meditation. Application of audiovisual stimuli, which induces certain brain wave modes exhibited a strong correlation and synchronization between AP and brain wave frequency range. This indicates that audiovisual stimuli applied to central cerebral were converted to the extremities of body through autonomic nervous system which appeared as a change of AP value. Similar effects were also observed for vocal music and color. AP decreased during sleep and the existence of different stages of sleep with bursts due to variation of sympathetic nerve was clarified. The power spectral density based on time series data during sleep was proportional to 5/3 power inverse to frequency, suggesting a Kolmogoroff spectra.

Thus, a single square voltage pulse method proved to be a very efficient and advantageous technique to study human life information science and mental effects.

8. Future Work

Sensory perception information, which is regarded as fuzzy, will become possible to measure by using the single square voltage pulse methods. Especially, objective evaluation of sensory susceptibility is required in order to understand mechanisms of information processing of auditory, visual or other sensory signals. However, there is scarcely any biophysical approach to this matter. Since SSVP method is unique and an efficient tool for detecting sensitive and subtle changes in both the human body and the mind, it opens up new opportunity in studying not only information processing but also mind-body states and their correlations in the future.
References


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