Analysis of acupoint bioelectricity based on wavelet entropy

Gai Shuping1,2, Liu Juntao1, Zhou Quan1,2, Kong Zhuang1,2, Wang Yang1,2, Xu Shengwei1,2, Cai Xinxia1,2

1 State Key Laboratory of Transducer Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, China
2 University of Chinese Academy of Sciences, Beijing 100190, China

Introduction

Acupuncture was well known in East Asian since two thousand years ago. It is an important therapy in the traditional medicine of China, Japan, and Korea. Based on the theory of traditional medicine, meridians and acupoints are closely related to the human body’s physiological state. Over decades, a great deal of investigators had shown great interest in the theory of acupoints.

The first claims for the electrical detection of acupoints could be dated to the 1950s, when Reinhard Voll (Germany) found that skin points electrical characteristics in traditional acupuncture points areas were different from other areas (1,2). Since then, lots of researchers and clinicians began using electrical devices to detect and monitor meridians acupoints (3), and mainly concentrated themselves on the measurement of the resistance (4), potential, capacitance and conductivity distribution. The traditional analysis methods about acupoints all belonged to linear analysis, which was very vulnerable to the signal quality and other outside interference, such as density of sweat gland, can dramatically alter results of the experiments (5).

Most doctors and clinics agreed that meridians possessed many distinctive ways for transferring signals and had a close relation with the internal organ. In the perspective of electronics, acupoint system (or meridian system) considered as an optimum path for transferring information including electrical information, was a non-linear system. But researches on nonlinear features of acupoint electrophysiological signals based on nonlinear dynamical methods were seldom involved. In this paper, we aimed to analyze the characteristics of acupoint electrophysiological signals with the concept of wavelet entropy. This work would provide some fundamental theory for the acupuncture technique research.

The discrete wavelet transform was proposed firstly in the 1980s. Osvaldo A adopted wavelet entropy to analyze short duration brain electrical signals and got cogent results in 2001(6). The value of entropy which can provide additional information of the signal with respect to its dynamical process (7), can also reflect the order or disorder of the signal. In this paper, entropy based on the orthogonal discrete wavelet transform (ODWT) was used to analyze the electrophysiological signals acquired from acupoints.

During the experiment, we chose ten acupoints and corresponding control groups to analysis their nonlinear features for the first time. Four adjacent non-acupoints around each acupoint were chosen as a control group in 400 trials on 10 volunteers aged 23-30 years to characterize the wavelet entropy (WE) of acupoint electrophysiological signals. The electrophysiological signals of acupoints and the control groups were recorded simultaneously. On one hand, by comparing the WE value of electrophysiological signals between acupoints and non-acupoints of healthy volunteers, we found that the WE value detected from acupoints was obviously higher than...
that from non-acupoints, which reflected the electrical signals of healthy person’s acupoints had a higher degree of disorder and were more complex than normal electrophysiological signal. On the other hand, we have not found this phenomenon in patients with kidney disease after more detailed analysis. According to the experimental results, we concluded that the meridian system may have some kind of special function affiliated with the internal organs.

Materials and Methods

Research subjects

In this study, for the purpose of more scientific and precise, we carried out the experiments by cooperating with a Chinese Medicine institution. Ten different acupoints scattered in upper and lower extremities were chosen, therefore, the results obtained from these acupoints were very representative. The ten chosen acupoints included ST 36 (or zusanli), SP 6 (or sanyinjiao), LI 14 (or binao), GB 39 (or xuanzhong), LI 11 (or quchi), GB 37 (or guaoming), LI 10 (or shousanli), SJ 5 (or waiguan), BL58 (or feiyang) and KI 9 (or zhubin). In addition, four non-acupoints around each acupoint were taken as control group.

In order to find the functional specificity of acupoint, two types of measurement were implemented. Firstly, we carried out experiments on 10 healthy volunteers, and for each acupoint, 40 times repeated experiments were performed to assure clear and reproducible results. Then, we performed extra 40 times experiments at KI 9, which was belonged to kidney meridian, from ten volunteer patients who have kidney disease, trying to find the differences between them.

Experiment & instrument

Every volunteer was tested 4 times with an interval of a week. All the volunteers had signed informed consent before starting the experiment. They were told not to eat or take exercises at least 1 hour before the experiment. Before the signals started to record, keeping their emotions relaxed for 20 minutes. During the experiments, the volunteers were lightly clothed and supine comfortably. The environmental temperature was maintained at 25±1°C.

The electrophysiological signal was measured by three-electrode system (8). Two surface electrodes were taken respectively as the reference electrode and ground (9). Because of the low density of sweat gland, potential of the styloid process of ulna was stable. So we located the reference electrode on the right styloid process of ulna, while the ground on the right lateral malleolus.

It was known that the acupoints are underneath skin. In order to eliminate the individual skin differences, we used silver needle as working electrode, which were inserted into acupoints and control groups with a distance of 15 mm. Acupuncture was operated by a doctor of Traditional Chinese Medicine to guarantee the operation was accurate. The electrophysiological signals of acupoints and control groups were recorded synchronously. Sample rate was set to 1 kHz, and amplification factor was set to 1000.

Methods

Wavelet transform

Wavelet analysis known as ‘mathematical microscope’, which has advantages of multi-resolution analysis in both the time and frequency domain, provides a new powerful tool for the electrophysiological signal processing (10). For a given mother wavelet \( \psi(t) \), a scaled and translated version (wavelet family) \( \Psi_{a,b}(t) \) is the set of elementary functions generated of \( \psi(t) \):

\[
\Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{t-b}{a}\right)
\]

Where, \( a \) is the scale parameter, \( b \) is the translation parameter, and \( t \) stands for time, respectively. For a given signal \( x(t) \), the continuous wavelet transform (CWT) of \( x(t) \) is defined by,

\[
CWT(a, b) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{|a|}} \psi^*\left(\frac{t-b}{a}\right) dt
\]

Calculation of wavelet coefficients at every possible scale is computationally very expensive task. Instead, if the scales and translations are selected based on dyadic scales and positions, the wavelet analysis will become much more efficient. By selecting the discrete set of parameters \( a = 2^{-m} \) and \( b = 2^{-m}k \), the wavelet family \( \psi_{j,k} \) and the discrete wavelet transform (DWT) of signal \( x(t) \) can be obtained through,

\[
\psi_{j,k} = \frac{1}{\sqrt{|2^j|}} \psi(2^j(t-k)), j,k \in \mathbb{Z}
\]

\[
DWT(j, k) = \frac{1}{\sqrt{|2^j|}} \int_{-\infty}^{\infty} x(t) \psi^*(\frac{t-2^jk}{2^j}) dt
\]

Wavelet decomposition and wavelet entropy

Mallat put forward an efficient wavelet decomposition algorithm for implementing discrete wavelet transform in 1989, which adopted the orthogonal wavelets to decompose the signal under different scales (11). It is equivalent to recursively filtering a signal with a high-pass (HP) and low-pass (LP) filter pair named as quadrature mirror filters, which generates the detailed components and approximation components, respectively. In the first step of the DWT, the signal is simultaneously passed through an LP and a HP filter with the cut-off frequency being the one fourth of the sampling frequency. The output signals
having half the frequency bandwidth of the original signals can be down sampled by two according to Nyquist rule (12). The same procedure can be repeated for the first level approximation coefficients to get the second level coefficients (13). At each step of this decomposition process, the frequency resolution is doubled through filtering, while the time resolution is halved.

After a discrete signal \( x(n) \) \( (n=1, 2, \ldots, N) \) signal passing the fast wavelet transform by using Mallat’s method at scale \( j \) and instant \( k \), it has a high frequency component wavelet detail coefficient \( cD_j(k) \) and a low-frequency component wavelet approximate coefficient \( cA_j(k) \).

The frequency band range of \( D_j(k) \) and \( A_j(k) \) obtained after reconstruction is:

\[
D_j(k) \in (2^{-j+1}f_s, 2^{-j}f_s) \\
A_j(k) \in [0, 2^{-j+1}f_s], j = 1, 2, \ldots, M
\]

\( f_s \) is the sampling frequency, and the original signal \( x(n) \) can be represented by the sum of all components \( D_j(n) \) and \( A_j(n) \), that is:

\[
x(n) = D_1(n) + A_1(n) = \cdots = \sum_{j=1}^{M} D_j(n) + A_M(n) \tag{5}
\]

For unify, denote \( A_M(n) \) by \( D_{M+1}(n) \), then we get:

\[
x(n) = \sum_{j=1}^{M+1} D_j(n) \tag{6}
\]

Energy at each sampled time \( k \) is defined as:

\[
E_j = \sum_k |D_j(k)|^2, j = 1, 2, \ldots, M + 1
\]

Clearly, the total energy can be obtained by:

\[
E_{\text{tot}} = \sum_j \sum_k |D_j(k)|^2
\]

Then, after normalizing the values, the relative wavelet energy is:

\[
P_j = \frac{E_j}{E_{\text{tot}}} \tag{9}
\]

\( P_j \) represents the probability distribution of the energy for each resolution level. Obviously, \( \sum_j P_j = 1 \). According to the definition of Shannon Entropy (1948), we can define the wavelet entropy (Blanco, 1998) as:

\[
WE = -\sum_j P_j \ln(P_j) \tag{10}
\]

Wavelet entropy is counted to reveal the information content carried by different scales coefficients, which is a measure of the degree of order/disorder of the signal, and can indicate the potential dynamical properties of non-linear signals (14). This gives a suitable tool for detecting and characterizing feature in both time and frequency domains. In this way, it’s easy to find a marked difference between the acupuncture and non-acupuncture signals.

**Analytical methods**

Firstly, we got the electrophysiological signals through a band-stop filter to prevent 50Hz frequency interference from power system. As we could not tell the difference between the original signals recorded from acupoints and non-acupoints visually, we further analyzed the WE of them, trying to discover whether there were difference between acupoints and the control group. The electrophysiological signals data are pre-processed through DWT with Mallat’s methods to decompose into six sub-bands signals using fifth level decomposition (15) (Fig.2).

As Nyquist sampling theorem, the maximum useful frequency that could be applied is half of the sampling frequency. Since the sampling frequency was 1KHz, the effective frequency band of the signal ranged from 0Hz to 500Hz (16). According to wavelet analysis theory, the frequency band range of coefficient \( cDj(k) \) and \( cAj(k) \) is shown in Table 1.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>frequency band</th>
<th>Coefficient</th>
<th>frequency band</th>
</tr>
</thead>
<tbody>
<tr>
<td>cA5</td>
<td>0–15.625 Hz</td>
<td>cD3</td>
<td>62.5~125 Hz</td>
</tr>
<tr>
<td>cD5</td>
<td>15.625–31.25 Hz</td>
<td>cD2</td>
<td>125~250 Hz</td>
</tr>
<tr>
<td>cD4</td>
<td>31.25–62.5 Hz</td>
<td>cA1</td>
<td>250~500 Hz</td>
</tr>
</tbody>
</table>

After DWT, we calculated the wavelet entropy value of ten acupoints and their corresponding non-acupoints, respectively. Then, in order to demonstrate the difference of the electrophysiological signals distinctly, we averaged the wavelet entropy of each acupoint and non-acupoint.

Finally, a particular analysis on KI 9 acupoint was carried on by comparing healthy people with kidney patients. KI 9 acupoint belong to the kidney meridian, which is a commonly used acupuncture points in the treatment of nephropathy in China(17,18) and may has some relation with the kidney organ(19). For each volunteer, we computed the mean WE value of electrophysiological signals collected from KI 9 acupoint and adjacent point.

**Results and Discussion**

**Original electrophysiological signals investigation**

As shown in Fig.3, the electrophysiological signals of acupoint and control points are synchronous and the pulse voltage amplitude is only on mV magnitude. The wave shape and amplitude is parallel, which suggests that the original electrophysiological signals recorded from acupoint (red line) and non-acupoint (blue line) are similar and make no difference in time domain. So we need wavelet entropy analysis for further detailed analysis with wavelet-domain.

**Mean wavelet entropy analysis**

For investigation of the ten points, we took the average value of electrophysiological signals wavelet entropy from ten healthy volunteers, respectively, to eliminate
the individual differences of volunteers. The results are as shown in Figure 4. The experimental data show that the mean values of the fifth layers of wavelet entropy at the ten acupoints are higher than that of non-acupoints. It reveals that the electrophysiological signals of healthy person’s acupuncture points have disperse characteristic, reflecting the meridian electrical signal sequence has a higher degree of disorder and is more complex than normal electrophysiological signal.

Wavelet entropy analysis on KI 9
Contrapositing KI 9 acupoint and surrounding non-acupoint, we further analyze the WE value of electrophysiological signals of 10 healthy men and 10 patients with kidney disease respectively. Analysis result of healthy volunteers is shown in Figure 5, while results of patients are shown in Figure 6. For healthy person, wavelet entropies of acupoint KI 9 are all greater than the corresponding non-acupoints. However, comparing the wavelet entropy of nephropathy patients, there are no clear distinction between KI 9 acupoint and non-acupoint. Therefore, we infer that there may be some deficiency of electrophysiological information transferring and expressing ability on KI 9 acupoint for the patients with kidney disease. Whether this can be a sign that the internal organs related to the acupoint potentially had some pathological changes, or the internal organs had lost their self-regulating ability to some extent (20), it relies on more further and comprehensive research.

As mentioned above, in our research, only acupoint KI 9 and patients with nephropathy were studied due to the limitation of experimental subject. To some degree, we’ve just scratched the surface on the relationship between acupoints and internal organs. Therefore, the medical principle and significance of this phenomenon need to be further studied.

Conclusions
With the development and application of traditional Chinese Medicine Science over two thousand years, medical practice has proved that acupuncture has an excellent clinical effect in certain diseases. As acupuncture is widely used in modern clinical applications, there are lots of researchers focusing on the characteristics of acupoints. Our research shows that acupoint electrophysiological signals can reflect the health condition of internal organs effectively, which indicates that analysis of acupoint electrophysiological signals has important implications.

There are three major findings in the paper. Firstly, we find that the original electrophysiological signals acquired from acupoint and adjacent non-acupoint are similar, making no distinction of the amplitude maximum and the waveform keep consistent. Secondly, the research shows that acupoints electrophysiological signals acquired from healthy person have higher WE value than nearby non-acupoints area, which imply a higher degree of information disorder. Finally, particular analysis on KI 9 shows that the WE values are neck to neck on their KI 9 acupoints and non-acupoints for patients with kidney disease, indicating that patients with nephropathy may have functional lack in transferring or expressing bioelectrical information. In summary, based on the findings of WE study, it suggests that healthy human acupoints system could be considered as an efficient way for transferring information including electrical information for internal organs. This article provides a new viewpoint for the clinical application of acupuncture and may have great significance to the study of traditional Chinese medicine.
Acknowledgements
This work is sponsored by the NSFC (No.61471342, No.61527815, No.31500800, and No.61501426), National Basic Research Program of China (2014CB744600), the Beijing Science and Technology Plan (Z141100000214002, Z141100003414015), and the Key Programs of the Chinese Academy of Sciences (No. KJZD-EW-L11-2).

References