Analyzing the effect of moxibustion treatment using the maximum instantaneous frequency of photoplethysmogram signals based on Hilbert–Huang transforms

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Abstract
Moxibustion is a treatment in traditional Chinese medicine that can promote human health. In order to study the effect of moxibustion on cardiovascular function, photoplethysmogram signals were obtained from acupoints at st 36 (zusanli), sp 6 (sanyinjiao), and li 11 (quchi) during moxibustion. The test data were collected from six volunteers of average weight for 6 days of treatment. The effect of moxibustion treatment was determined by comparing amplitude–frequency characteristics of the instantaneous frequency in the power spectrum after Hilbert–Huang transformation of the pulse signal before and after treatment. It was found that after moxibustion, the maximum energy frequency of the photoplethysmogram would increase, but the amplitude would decrease. The results show that moxibustion therapy has the dual benefit of the infrared effect and acupoint stimulation, which can improve cardiovascular health and has a positive effect on metabolism.

Keywords
Hilbert–Huang transformation, moxibustion, photoplethysmogram, power spectrum, fEmax

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Introduction
The photoplethysmogram (PPG) is a low-cost and non-invasive method capable of analyzing blood pressure, heart rate, and other physiological information. It is widely used for diagnosing physical health and has important medical research value.¹ A PPG is produced mainly by irradiating human vascular tissue using light with a wavelength of 900 nm and collecting changes in light intensity through a receiver. Due to the continuous expansion and contraction of blood vessels in the human body, the internal blood volume changes periodically, which leads to a difference in the amount of light absorbed by the blood and a change in the

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intensity of received light. A PPG signal is formed from photoelectric conversion, which reflects the change in blood vessel volume and the health of the cardiovascular system.\(^2,3\) PPG signals express many biological information.\(^4\) After the decomposition and reconstruction of PPG signals, a potential relationship can be studied between different PPG signal characteristics and cardiovascular health in humans. The effects of the sympathetic and parasympathetic nervous system on cardiovascular regulation can also be analyzed.\(^5–8\) Considering that the effect of moxibustion treatment is difficult to define directly using biochemical indicators, PPG signal analysis is a promising method for quantitatively defining the relationship between moxibustion treatment and human cardiovascular health.

Moxibustion is a type of traditional Chinese medicine (TCM) treatment that can benefit health by adjusting far-infrared (FIR) radiation. It is practiced by burning moxa cones on the acupoints of the body, thereby influencing physiological and biochemical functions. Moxibustion has far-reaching influence in Asia and around the world, and it represents a non-pharmaceutical intervention that has long-term applications in clinical practice.\(^7\)

Moxibustion can promote cardiovascular function and improve the regulation of the nervous system by stimulating the acupoints. Fang and Zhou\(^9\) found that after electrical stimulation of acupoints such as st 36 (zusanli), sp 6 (sanyinjiao), and li 11 (quchi), the mean arterial pressure (MAP) of animals recovered rapidly, and myocardial ischemia and cardiac function recovery were improved, thereby protecting the myocardium. Liu\(^10\) studied the literature on the treatment of cardiovascular diseases and found that the stimulation of st 36 (zusanli), sp 6 (sanyinjiao), li 11 (quchi), and other acupoints played an important role in the recovery of cardiovascular function. Peng et al. studied the regulation of endocrine function by vascular endothelial cells and found that the generation and clearance of oxygen free radicals when moxibustion treatment is used lowers the blood pressure of patients with hypertension. Therefore, moxibustion stimulation on acupoints such as st 36 (zusanli), sp 6 (sanyinjiao), and li 11 (quchi) can promote the recovery of brain cell function; improve the working ability of cerebral cortical cells; improve heart function; regulate heart rhythm; and increase red blood cell count, white blood cell count, blood sugar, blood oxygen saturation, vasodilation, blood rheology, and neumodulation, all of which have significant effects.\(^11\) Coyle et al.\(^12\) applied moxibustion for patients with chronic obstructive pulmonary disease (COPD) and achieved positive therapeutic effects. Ni et al.\(^13\) conducted studies on the effects of acupuncture and moxibustion on patients with thoracic arteritis, and research results showed that acupuncture combined with moxibustion could regulate humoral immunity and cellular immunity. In addition, moxibustion stimulation on acupoints such as st 36 (zusanli), sp 6 (sanyinjiao), and li 11 (quchi) can promote cerebral function; improve the working ability of the cerebral cortex cells; benefit heart function; adjust the rhythm of the heart; increase the counts of red blood cells and white blood cells; and bring about significant changes in the neumodulation of blood sugar, blood oxygen saturation, blood vessels, diastolic blood pressure,\(^14\) and blood rheology.

The above studies have expounded the relationship between the effect of moxibustion treatment and the change in cardiovascular function in the human body from the perspective of medical science. However, this research can only give a rough description using the change of pulse signal speed, and it is difficult to use real-time human physiological information data for characterization because these measurements lack objectivity and convenience, which limits the clinical application of moxibustion. A study confirmed that PPG signals reflect changes in blood pressure.\(^15\) In order to further study the relationship between moxibustion treatment and human health, it is necessary to use PPG signals to analyze the influence of moxibustion on the amplitude and frequency of pulse signals. A research method for analyzing the frequency corresponding to the maximum energy \(f_{\text{fmax}}\) value of pulse signals based on the Hilbert–Huang transformation (HHT) is proposed here. The objective is to collect the digital pulse signals of the human body before and after moxibustion treatment, reveal the effect of moxibustion treatment through the instantaneous frequency characteristic change corresponding to the maximum amplitude of the PPG signal, and study the effect of moxibustion on cardiovascular regulatory function.

**Basic theory and methods**

**HHT and HT power spectrum analysis of PPG signals**

Since the pulse wave signal is a non-linear and non-stationary physiological signal, it is difficult to extract the correct signal characteristics and analyze the real-time physiological signal through the traditional Fourier transform and wavelet transform analysis.\(^14\)

In recent years, with the development of HHT, the application of HHT for pulse waves has been analyzed.\(^16,17\) The HHT is a time–frequency signal analysis method proposed by Huang et al. in 1998, and it mainly studies the signal frequency characteristics through the signal’s intrinsic mode function (IMF), which is obtained by empirical mode decomposition (EMD). Since the IMF is able to provide a quantitative analysis of energy changes at different frequencies, its results are more accurate than the wavelet or Fourier transform, highly efficient and adaptive, and have
important applications in the study of energy–frequency–time distributions.\textsuperscript{18,19} Therefore, the HHT can overcome the problems of non-adaptive functions and allow for non-linear and non-stationary signal analysis.

In the HHT process, EMD is first used to obtain the IMF and find the instantaneous component of the signal associated with the pulse wave transform. Then, the analytic function is constructed through the Hilbert transform (HT) to calculate the instantaneous frequency and amplitude of the signal and then analyze the information contained in the signal.

For example, Huang et al.\textsuperscript{20} applied this method in their study on the HHT and Poincaré plot analysis (PPA) heartbeat segmentation algorithm, and Yimin et al.\textsuperscript{21} studied the relationship between pulse signal and cardiovascular status. Haidong\textsuperscript{22} researched the frequency behaviors of the Hilbert spectrum and Hilbert marginal spectrum (HMS) to estimate the spectral traits of heart rate variability (HRV) signals.

The HHT is based on the instantaneous frequency obtained using EEMD (Ensemble Empirical Mode Decomposition), and the HT of the IMF component signal $x(t)$ is defined as

$$H[x(t)] = y(t) = \frac{1}{\pi} \int \frac{x(\tau)}{t - \tau} d\tau$$

It can be expressed in polar coordinates as

$$z(t) = \alpha(t)e^{i\theta(t)}$$

which includes

$$\alpha(t) = \sqrt{x(t)^2 + y(t)^2}$$

$$\theta(t) = \tan^{-1}\left(\frac{y(t)}{x(t)}\right)$$

where $\alpha(t)$ and $\theta(t)$ represent the instantaneous amplitude and phase of the analytic complex signal, respectively. The instantaneous frequency $\theta(t)$ of the signal is obtained from the instantaneous phase $\omega(t)$

$$\omega(t) = \frac{d(\theta(t))}{dt} = \frac{y'(t)x(t) - y(t)x'(t)}{x(t)^2 + y(t)^2}$$

Therefore, the real part of the signal $x(t)$ can be written as a time-dependent function using the amplitude and instantaneous frequency

$$x(t) = Re\{z(t)\} = Re \sum_{i=1}^{n} a(t)e^{i\theta(t)}$$

where $Re\{z(t)\}$ represents the real part of the complex signal $z(t)$. To preserve the physical relevance of the instantaneous frequency obtained from equation (5), the instantaneous phase $\theta(t)$ must be a single-valued function over time as a function of a single group. The instantaneous phase $\theta(t)$ is derived from the HT as shown in equations (3) and (4). Therefore, it must be a single-valued function. In equation (3), the amplitude and instantaneous frequency are presented in the form of a three-dimensional diagram, and the amplitude is represented by the height of the time–frequency plane. The resulting time–frequency distribution is called the Hilbert–Huang spectrum, $H(\omega, t)$

$$H(\omega, t) = Re \sum_{i=1}^{n} a(t)e^{i\int w(t)dt}$$

Accordingly, the marginal spectrum $h(\omega)$ can be defined as

$$h(\omega) = \int H(\omega, t)dt$$

**Definition of frequency extreme point**

According to the Sadrawi et al.,\textsuperscript{17} $f_{E_{\text{max}}}$ is the frequency corresponding to the maximum energy point in the selected IMF of the PPG signal. In order to obtain the correct frequency range of the PPG signal, EMD is required to obtain the corresponding IMF function.\textsuperscript{23} The $f_{E_{\text{max}}}$ of the PPG signal can be obtained by the HT from the IMF function. In this process, in order to effectively solve the modal aliasing problem in the EMD process, different white noises can be added to the original data before IMF decomposition, which is called the EEMD decomposition.\textsuperscript{24,25}

In Figure 1, the IMF component of the PPG signal obtained by EEMD before moxibustion (Figure 1(a)) and the marginal power spectrum of IMF components after HT (Figure 1(b)) are shown. The frequency corresponding to the maximum energy in the figure is the value of $f_{E_{\text{max}}}$. Previous studies have shown that characteristics of the power spectrum can reflect human vascular function.

**Experimental results**

**Experimental test**

**Research subjects.** Six healthy young volunteers (five males and one female) were recruited in the study. People with known systemic diseases as well as those with smoking and drinking habits were excluded from the study. All participants were required not to drink alcohol or coffee for the 24 h before the test. In addition, all the volunteers’ basic personal information (including age, gender, weight, height, body mass index, etc.) was recorded. All of the volunteers had not received moxibustion treatment in the month prior to
the test. Test participants were informed of moxibustion therapy, including experimental devices, stimulation methods, treatment intensity and frequency, and possible adverse events. Each participant signed a written consent form. The agreement and procedure of the study are in line with the principles of Helsinki Declaration and approved by the medical ethics review committee of Ningxia Medical University.

**Equipment and data acquisition.** In the study, the signal of decomposed short-time PPG was acquired using a self-developed device designed for human fingers. The volunteers’ index fingers were selected as the data acquisition object. In order to get better accuracy of data, the signal frequency was chosen at 500 Hz, and each data record lasted for 20 min. The collected data were uploaded to the computer through the analog-digital acquisition card-USB-6009 DAQ (National Instruments, Austin, TX, USA). LabVIEW 2014 and MATLAB 2015 are used for data acquisition and processing operations.

The acquired PPG signal was decomposed by EEMD and then used to calculate the IMF because pulse parameters could be measured accurately and reliably in the PPG signal. In order to ensure that the data were not affected by the environment, all PPG signals collected within 1 min before and after the collection are discarded. The remaining data were decomposed by the HHT at 6-s intervals. The data involved in HHT decomposition were 3000 points. In total, 180 time decomposition processes were implemented, and 180 instantaneous frequencies were obtained. On this basis, 15 maximum values and 15 minimum values of all instantaneous frequencies were discarded, and the remaining 150 maximum instantaneous frequencies were averaged as the $f_{E_{\text{max}}}$ of the test.

**Experimental test.** The temperature in the room was kept at 26°C, and a quiet environment was ensured. The testers were in a relaxed supine position and not affected by the external environment during the entire test. The PPG infrared sensor was used for data collection using the index finger of the volunteers’ left hand.

Before data collection, the volunteers rested for 5 min. Then, the data were collected for 20 min before moxibustion, recording approximately 600,000 numbers of signals. During the moxibustion process, professional doctors were responsible for sticking the moxa cone to the li 11 (quchi) point, st 36 (zusanli) point, and sp 6 (sanyinjiao) point and keeping it burning at the point for 5 min, and then instructing the volunteers to rest for 10 min. After the end of moxibustion treatment, the data were collected again after the moxibustion, with an acquisition time of 20 min.

During processing, both the amount of data collected before and after moxibustion was 600,000 signals. The obtained data were then filtered. The filtering method was mainly adopted from the method of subsection comparison: firstly, all data were statistically counted to find the data cycle benchmark, and then the data benchmark was compared with each group of data to remove the abnormally large local data and avoid data pollution. The filtered data segment length was 6 s of PPG signals with a sampling point number of 3000. After all the data was decomposed by EEMD, IMFs and residuals could be generated, as shown in Figure 2(a). By Hilbert–Huang spectral analysis, the instantaneous frequency of different energies corresponding to each IMF could be obtained, as shown in Figure 2(b).

**Results and analysis**

Based on the above research method, the moxibustion effect tracking study was carried out with the help of
six volunteers. The study lasted for 6 days and mainly involved recording $f_{E_{\text{max}}}$ changes of the human pulse before and after moxibustion every day. The effect of moxibustion treatment on human cardiovascular status was studied through the use of $f_{E_{\text{max}}}$.

In order to track the continuous change of cardiovascular status during the moxibustion treatment cycle, a volunteer was selected and observed to analyze the changing trend of $f_{E_{\text{max}}}$ during the moxibustion treatment during the first step. The test results are shown in Figure 3. In Figure 3(a), the horizontal axis represents the time, the vertical axis represents the value of $f_{E_{\text{max}}}$, and the red and blue lines, respectively, represent the changing trend of $f_{E_{\text{max}}}$ frequency before and after moxibustion. As shown in Figure 3(a), $f_{E_{\text{max}}}$ improved after moxibustion relative to $f_{E_{\text{max}}}$ before moxibustion. The change is more obvious in the later stage of the treatment, which was consistent with the subjective feelings reported by the volunteers regarding increased heart rate and sweating after the completion of moxibustion. In Figure 3(b), the horizontal axis represents the frequency, the vertical axis represents the amplitude, and the red and blue lines, respectively, represent the variation of amplitude before and after moxibustion. It is shown in Figure 3(b) that $f_{E_{\text{max}}}$ amplitude decreases rapidly after the test, indicating that the pulse amplitude gradually decreases in the frequency domain of IMF6 after moxibustion. From the perspective change of the whole frequency domain, each frequency domain of the PPG signal decreased by different degrees, and only the part of IMF9 was enhanced. As seen from the relationship between signals, IMF9 is the residual part of PPG signal decomposition, representing the long-term change of signals. Besides IMF9, the reduction of signal amplitude in each frequency domain means that moxibustion treatment can reduce the change in the high-frequency signal amplitude of the PPG signal, and all signal energies are more concentrated in the change in the low-frequency trend, which is consistent with the concept of gaining "qi" in the theory of TCM treatment.

In order to further study the effect of moxibustion on $f_{E_{\text{max}}}$, the $f_{E_{\text{max}}}$ data of six volunteers within 6 days of moxibustion treatment were compared, as shown in

![Figure 2](image_url)

**Figure 2.** IMF and HT power spectrum decomposed from the standard PPG segment: (a) IMF intrinsic function of the volunteers’ pulse signals measured before moxibustion and (b) HT power spectrum of the volunteers’ pulse signals measured before moxibustion.
Figure 4. Figure 4(a) shows the changes of the mean $f_{E_{\text{max}}}$ of all volunteers' pulses before (solid red line) and after moxibustion, where the horizontal axis represents the time and the vertical axis represents the value of $f_{E_{\text{max}}}$. Figure 4(b) shows the increasing trend of the $f_{E_{\text{max}}}$ mean value during 6 days of being treated with moxibustion, where the horizontal axis represents the time, the vertical axis represents the value of $Df_{E_{\text{max}}}$, and the blue curve represents the changing trend of $Df_{E_{\text{max}}}$ in 6 days. After the moxibustion, the $f_{E_{\text{max}}}$ of the volunteers increased relative to that before the test, but the rate of increase was diminished. The changing trend indicates that during the entire process of moxibustion treatment, with the increase of human body adaptability, the range of $Df_{E_{\text{max}}}$ was relatively reduced, and the effect of moxibustion treatment on human cardiovascular health was gradually weakened.

In order to further study the correlation between $f_{E_{\text{max}}}$ and moxibustion, the data of the six volunteers were collected to calculate the $f_{E_{\text{max}}}$ before and after moxibustion. It can be seen that the value of $f_{E_{\text{max}}}$ before moxibustion was significantly less than it was after moxibustion ($N = 6$, $P = 0.0312$), as shown in Figure 5.

**Discussion**

According to the theory of TCM, the points of li 11 (quchi), st 36 (zusanli), and sp 6 (sanyinjiao) are important acupoints of human body. In this study, all participating volunteers recorded their pulse signals before and after moxibustion, and HHT was used to obtain $f_{E_{\text{max}}}$ in the spectrum. By comparing the changes of $f_{E_{\text{max}}}$ before and after moxibustion, the effect of moxibustion treatment on human cardiovascular health was studied.
The frequency information of PPG signal can reflect the state of blood vessels—distinguish between healthy people and diabetics. In the field of TCM treatment, relevant scholars have studied that the heat-sensitive moxibustion had neuroprotective effects against focal cerebral ischemia/reperfusion injury. In this study, $f_{E \text{max}}$ is used as an indicator to reflect the effects of acupuncture on human body’s nerve function.

During the 6-day experiment, the changes in PPG signals of the volunteers reflected the effects of moxibustion on the human body, both individually and as a group. The value of $f_{E \text{max}}$ increased after moxibustion relative to the value before moxibustion. As shown by the increasing trend, the $f_{E \text{max}}$ value changed the most on the first day of treatment. As the test continues, the difference gradually decreased. Considering that the gradual reduction of $f_{E \text{max}}$ is a result of the gradual change in the human body’s self-regulation ability during this period, moxibustion treatment can significantly increase the value of $f_{E \text{max}}$.

In addition, the amplitude of $f_{E \text{max}}$ decreased significantly after moxibustion, which indicates that moxibustion treatment can reduce the amplitude of PPG signals in all frequency bands except IMF9. The reduction of high-frequency signal amplitude means that the cardiovascular vibration ability is more concentrated in the low-frequency part, which verifies the effect of the “qi” phenomenon of moxibustion treatment on human blood vessels.

**Conclusion**

Through using the HHT, the effect of moxibustion treatment on $f_{E \text{max}}$ frequency and the amplitude of human PPG signals were analyzed to study the effect of moxibustion treatment. The stimulation of moxibustion on acupoints can be manifested in two aspects: the FIR thermal effect and the acupuncture stimulation. The energy generated by the infrared thermal effect can be absorbed by the proteins in organs and spread in the organ and tissue, causing the expansion of blood vessels and turbulence in the middle layer of the blood. The blood vessels expand and cause increased blood flow, which will cause the $f_{E \text{max}}$ to increase. Therefore, moxibustion at acupoints can result in the increase of $f_{E \text{max}}$. This numerical change process will gradually decrease with the increase in the times of exposure to moxibustion, which is also consistent with the experience of moxibustion treatment.

After moxibustion, the amplitude of human PPG signal (except IMF9) decreases, and the energy is concentrated from the high-frequency part of the human pulse signal to the low-frequency part, which is consistent with the idea that moxibustion can reduce the effect of organs on blood supply according to the theory of TCM. In the follow-up study, the plan for further research is to focus on the efficacy of moxibustion, improve the comparative test, study the comprehensive effect of different points of moxibustion on human and pulse signals, and get further confirmation on the actual efficacy of moxibustion.

**Declaration of conflicting interests**

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