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A Comparison Study on Arterial Blood Pressure and Pulse Data of Condenser Microphone*

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1. Introduction

Recently, [Wang et al. 1989; Young et al. 1989, 1992; Jan et al, 2003; Wang Lin et al, 2004; Kuo et al, 2004; and Hsu et al. 2006] developed the resonance theory that each arterial bed in the vascular system is oscillated by the pressure waves at its own resonant frequency. They reported that ligating the renal, gastric, splenic or superior mesenteric artery of Wistar rats for a short duration could cause specific changes to the individual harmonics. They also showed that the ligation effects of different systems were linearly additive: as the renal artery and the superior mesenteric artery were simultaneously ligated, the change in the pulse spectrum was similar to the direct addition of two spectra resulting from the two individual ligations. They came to two important conclusions: First, the organ spectra can be used as parameters to elucidate the physical status of the specific vascular beds. Specifically, the magnitude of a harmonic mode reflects the amount of blood spent by the corresponding organ. Second, as the physical properties of a specific arterial bed change, the amplitude of the corresponding resonant mode changes more than that of the others. However, the corresponding resonant frequency will be approximately maintained by the heart rate control system to minimize the energy loss [Jan et al. 2003]. Most of their experimental data used pressure transducers to collect tail arteries of Wistar rats.

Based on this theory, Yu and Wang developed an artery blood pressure pulse acquisition system to take the wrist arterial blood pulse pressure data via a commercial microphone [Yu & Wang, 2006]. Unlike the experimental data of Wang et al., the sensor of the sonocardiography system of Yu and Wang are non-invasive and were more convenient to collect data than most existing systems. However, the interested frequency range of the wrist pulse data of the traditional Chinese medicine is lower than the announced range of most commercial microphone, say 20-20kHz. In [Jeng & Lee, 2008; Jeng, et al., 2011], it was proven that, if the acoustic signal source, pressure waves and small air cell containing the diaphragm of the electret condenser microphone are properly confined to a small air

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chamber, the lower bound of the effectively frequency response can be as low as 0.5Hz. The environment of signal confinement is equivalent to the situation that one firmly presses the microphone to the measured skin. In other words, the system using an electret condenser microphone is a potential tool to re-study the human organ-meridians which had achieved great achievement in the traditional Chinese medicine.

The above discussions confirm the fact that the arterial signals picked up by the sonocardiography system are closely related to the human organ-meridians. An interested problem is whether the microphone arterial pulse data also closely relates to the modern medicine data such as the well known invasive ABP and ECG. The ECG and ABP are the two commonly employed physiological parameters to monitor patients in the setting of critical illness [Civetta et al. 1992 & Marino 2007]. They offer the basic information of how the circulatory system performs in complex clinical conditions.

In order to look into complicated information embedded in signals of microphone's arterial pressure, ABP and ECG, both the FFT [Brigham, 1998] and time-frequency transform should be simultaneously used [Jeng & Lee, 2008; Jeng, et al., 2011]. The FFT provides a spectral parameter representation and the time frequency transform even give us the possibility of revolving the temporal varied amplitude and frequency of a wave component. In this study the Gabor transform will be employed.

In some sense, the ECG data reflects the input command, whereas the ABP signal reflects the corresponding vascular response. In case of homeostasis, the circulatory system should behave as a linear transfer function in the spectral band of the heart beat mode that the variation of ABP should be highly correlated with that of ECG. When the system is not properly functioning, the correlation may be violated such that the person may have healthy problem. From this view point, the correlation between variation of ECG and ABP can be a potential biomarker of human health assessment. However, continuous ABP data is usually only conveyed in critically ill patient with invasive intra-arterial measurement. Being non-invasive and more easily applicable, microphone pressure sensor is an alternative choice to get the continuous pulse signals. If we can prove that the microphone arterial signal's heart rate mode can be used to provide the index, the preventive medicine would become a practical issue for the general population. Moreover, the connection between the ancient Chinese and modern medicines will become more solid in near future.

2. Data and method

2.1 Theoretical development

Because the time series picked up by the microphone system, ECG or ABP may involve drift and/or trend, it frequently involves a monotonic non-periodic part. Therefore, a time series data string, $y_j = y(t_j), j = 0, 1, 2, \dots, J$, can be written in the following form [Jeng et al. 2009]:

$$y_j = \sum_{l=0}^{J-1} \left[c_l \cos \frac{2\pi t_j}{\lambda_l} + d_l \sin \frac{2\pi t_j}{\lambda_l} \right] + \sum_{n=0}^N a_n t_j^n, \quad 0 < j < J-1 \quad (1)$$

where $t_{j+1} - t_j = \Delta t = \text{constant}$, l is the mode index, and $\lambda_l = J\Delta t / l$ is the wavelength of the l -th mode, the second summation represents the non-sinusoidal drift and/or trend and N represents the largest power for which $a_n \rightarrow 0$ for all $n > N$. For most engineering applications, $N = 250$ is a reasonable value. The non-sinusoidal trend is interpreted as the sum of monotonic parts and all the Fourier modes whose wavelengths are longer than the

data span $T = J\Delta t$. This study uses the iterative Gaussian smoothing method in the spectral domain to serve as a high-passed filter. It can be proven the resulting response takes the following form [Jeng et al. 2008, 2009, 2011]:

$$y'_{j,m} \approx \sum_{l=0}^J [1 - \exp[-2\pi^2\sigma^2 / \lambda_l^2]]^m \left[c_l \cos \frac{2\pi t_j}{\lambda_l} + d_l \sin \frac{2\pi t_j}{\lambda_l} \right] + O(\Delta t^2) \quad (2)$$

$$\bar{y}_j^m = y_j - y'_{j,m}$$

where $y'_{j,m}$ and \bar{y}_j^m represent smooth and high frequency responses after applying the iterative Gaussian smoothing method for m cycles and $[1 - \exp[-2\pi^2\sigma^2 / \lambda_l^2]]^m$ represents the attenuation factor, in which σ is the smoothing factor of the Gaussian smoothing method and $m > N/2$. In this study, the iteration parameter m and smoothing factor σ use the value of 127 and 0.8seconds, respectively. These parameters means that the filter's transition zone is $\lambda_2/\lambda_1=2$ and $\lambda_1 \approx \sigma/0.772 \approx 1.036$ seconds. More specifically, all wave modes of y'_m with wavelength $\lambda \leq 1.036$ seconds are almost the same as that of original data and those wave modes with wavelength $\lambda \leq 2.072$ seconds are removed. Now the trend is ultimately removed. Because this result is principally derived by assuming the data span running from $-\infty$ to ∞ , small errors are thus induced by the missing data beyond the two ends. Next, the zero crossing points around the two ends can be located by a search procedure and interpolation formula. After dropping the data segments beyond the two zeros, a monotonic cubic interpolation [Huynh, 1993;Jeng et al. 2009, 2011] is used to redistribute the data into uniform spacing whose points equal an integer power of 2. Subsequently, the odd function mapping is used to double the data span. Finally, the FFT [Brigham, 1998] will generate a Fourier sine spectrum. This spectrum reflects many details in the low frequency region because the trend has already been removed and all the required periodic conditions are ensured by the odd function mapping.

In this study, the following Gabor wavelet transform using the Gaussian window (with a given window width a on the time domain) is used for the sinusoidal data y'_m :

$$G(f, \tau) = \frac{1}{\sqrt{a}} \int_0^T y'_m(t) e^{-2i\pi f(t-\tau)} e^{-(t-\tau)^2/(2a^2)} dt \quad (3)$$

in which τ denotes the central time instant of the Gaussian window and f is the central frequency index on spectral domain. By scanning both f and τ over the desired range of time-frequency domain, the desired two-dimensional Gabor wavelet coefficient plot or the spectrogram can be obtained. It can be proven it is about equal to the following form [Jeng et al. 2009, 2011]:

$$G(f, \tau) \approx \sqrt{\frac{a\pi}{2}} \sum_{l=1}^{J-1} \{ [d_l - ie_l] e^{i2\pi f_l \tau} \exp[-2a^2\pi^2(f_l - f)^2] \} \quad (4)$$

where $d_l \approx (1 - 2\pi^2\sigma^2 / \lambda_l^2)^m b_l$ and $e_l \approx (1 - 2\pi^2\sigma^2 / \lambda_l^2)^m c_l$ are Fourier spectrum of y'_m . These relations indicate the wavelet coefficient is just an inverse FFT of a finite spectrum band specified by an associated Gaussian window whose window width is $1/(2a\pi)$ and is

centered at the frequency of f . For the sake of completeness, the procedures are summarized below [Jeng et al. 2009, 2011].

1. Use the iterative Gaussian smoothing method to remove the non-sinusoidal part and a fraction of several lowest modes whose wavelengths are ranged from λ_L to T , where $T=J\Delta t$ is the data length.
2. Find the Fourier sine spectrum : find the zero around the two ends; discard data segments beyond the zeros; redistribute the data via a proper interpolation method so that the data point is an integer power of 2 ($= 2^{**k} > 2L$, where L denotes the original data size); make an odd function mapping with respect to one end; employ in an FFT.
3. Choose the frequency resolution $f_i = f_0 + i\Delta f$ and $a = 2c / \Delta f$ to evaluate the band-pass limited spectrum via the Gaussian window with window width c , where f_0 is the lowest frequency employed to plot the spectrogram and c is an user specified parameter (e.g. $c = 1.5$).
4. Find the inverse FFT of the band-pass limited spectrum, which is the real part of the spectrogram coefficient corresponding to the f_i mode. The corresponding amplitude distribution with respect to time is then evaluated by applying the Hilbert transform.
5. Scan all f_i s and plot the spectrogram.

Note that the resulting wavelet coefficients (spectrograms) are subject to the blur effect of the uncertainty principle [Goswami & Chan, 1999; Mallat, 1999; Jeng et al. 2009, 2011]. At most one obtains the best resolution with certain compromise between the temporal and spectral scales. In practical application, an approximate optimal resolution can be achieved via a few trial and error procedures by varying the parameter c in the third step.

A careful inspection upon Eq.(2) reveals that one can simultaneously remove the trend and obtain the high frequency spectrum by merely calculating in the spectral domain. Moreover, one can further obtain a single mode or a band-pass-limited spectrum by imposing a suitable window upon the spectrum of the high frequency part.

In this study, the relation between the microphone pulse data, ECG, and ABP is assumed to be determined by the cross-correlation of two wave components of the heart rate mode. The following familiar method directly calculates the cross-correlation coefficient [Bendat & Piersol 2000] between two wave components $y_1(t)$ and $y_2(t)$ is employed.

$$c = \frac{\int_{t_0}^{t_f} y_1(t)y_2(t)dt}{\left[\int_{t_0}^{t_f} y_1^2(t)dt \int_{t_0}^{t_f} y_2^2(t)dt \right]^{1/2}} \quad (5)$$

where t_0 and t_f are the initial and final instances of the two wave components. The associated time series wave component, say $y_1(t)$ or $y_2(t)$, is obtained by the inverse FFT algorithm of the spectral band. For convenience, only two Fourier modes are considered here.

In order to eliminate the phase lag induced by the pressure wave propagation along the artery wall, one of the two wave components will be shifted, say $y_1(t \pm \tau)$ or $y_2(t \pm \tau)$. The parameter τ is the amount of time shift which achieves the maximum absolute value of c in Eq.(5). For a person not in critical state, his heart beat modes of ECG and ABP should be highly correlated in this sense.

For a patient in an intensive care unit, the modern medicine provides many effective supports and treatments. He may still survive even if his heart beat modes of ECG and ABP are not correlated. The reason is Eq.(5) principally depends on the phase lag between these modes. With the strong support of the intensive care unit, it seems that the correlation between the envelopes of these ECG and ABP modes is also an important index for such a patient. The envelopes, which represent the energy or amplitude of these modes, are believed to be roughly reflected by the shapes of corresponding wave components in spectrograms of amplitude [Jeng & Cheng, 2007].

According to the above discussions, in addition to Eq.(5), a partial information of the cross-correlation between two sinusoidal data strings is roughly considered to be the similarity of wave components in the spectrograms of amplitude. It is clearly that, as two wave components are partially correlated, the phase lag may or may not occur. If the phase lag is insignificant, it is certain that $|c| \geq 0.6$. If a large phase lag exists between two wave components with partial energy correlation, their correlation coefficient calculated by Eq.(5) may be low, say $|c| < 0.5$. To explain this state, consider the correlation between the heart rate modes of ECG and ABP of a patient as an example. Suppose their temporal amplitude and frequency distributions are similar so that energies of their corresponding wave components are correlated. The command of the heart (ECG) is transferred to the point of measuring the wrist pulse (ABP) via the pressure wave propagation through a series of vascular tubes. Due to some reasons, however, the wave propagation speed is not homogeneous and not invariant from one location to another. Thus, the periodicity of the heart rate is distorted at the ABP measuring point and the phase lag occurs. Although this stage is not perfect, the entire circulation system still partially functioned.

2.2 Data acquisition

In this study, the ECG signals were obtained from the three-lead ECG recording device. The ABP signals were conveyed from an invasive arterial-line system which involves an insertion of an arterial catheter connecting to a conducting tube filled with properly pressured fluid (see Fig.1). The mechanical signals were then transformed to the electrical ones with a midway pressure transducer. Both ECG and ABP data were transferred back to the Philips MP60 module which was the physiological signal monitoring system used in our study. The analog signals were output to the data acquisition card where they would be converted to the digital signals with a sampling rate of 500Hz and then forwarded to the portable computer for further analysis.

In order to achieve a stable sensitivity in response to the tiny wrist arterial pressure data, a commercial electret condenser microphone is employed, whose instructions are 20-20,000 Hz, 100mw, 32 Ω 105db sound pressure level sensitivity at 1kHz ± 2 %. The experimental facilities include a digital audio board (Onkyo Inc. SE-150 PCI, SN ratio 100dB, 0.3-44KHz, sampling rate 32-192KHz). Before the wrist artery with a sampling rate of 500Hz was acquired, the measuring point should be carefully located by human finger so as to make sure that the pulse signal is prominent. The schematic diagram is shown in Fig.2a where the front face with the actuating diaphragm of microphone (Figs.2b and 2c) was firmly attached to the measuring point.

The data of six different patients in the intensive care unit of a hospital in Taiwan were included in our study. The ECG, ABP, and microphone data were in all cases successfully and simultaneously recorded in the same sampling rate. During the period of acquiring

data, the ABP data was taken from the left wrist while the microphone data from the right wrist.

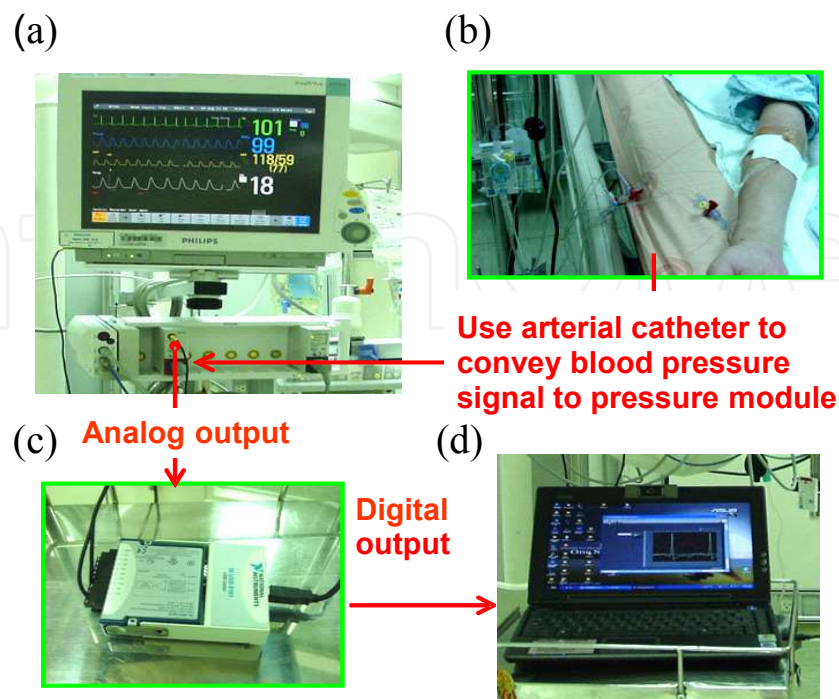


Fig. 1. Experimental instruments for the signal acquisition. (a) physiological signal monitoring system, Philips MP60, and pressure module; (b) invasive ABP monitoring system including an arterial catheter connecting to a conducting tube filled with fluid; (c) data acquisition card; (d) portable computer for displaying and storing the vital signs.

Although the direct invasive arterial-line system applied here provides the advantage of continuous and real-time monitoring, it may introduce additional signal damping, especially when the pressure conducting tube is long [Marino, 2007]. The inertia of the medium within the tube would inevitably remove most high frequency Fourier modes. Nevertheless, it is the currently available method to collect a continuous ABP signal during surgery.

Principally speaking, an electret condenser microphone uses the rate change of capacity to collect pressure signal so that it picks up the motion signal of the pulse. In other words, the microphone data reflect variations of pulse pressure rather than the pressure itself. In Ref.[Yu and Wang, 2006; Jeng & Lee, 2008], this signal had been successfully linked to the Wang pulse spectrum theory. However, in order to study the relation between ABP and microphone signal, the latter will be integrated once so that they have the same base.

3. Results and discussions

Consider the case of Fig. 7 of [Jeng & Lee, 2008] that the person had slight spleen disease as an example. Figure 3.1a plots the data before and after performing the integration once and their corresponding spectra are shown in Fig.3b. These figures indicate that the integration significantly smears the irregularity and rendering the fast attenuation of mode amplitude as the mode index increases. For the sake of clarity, their corresponding spectrograms of amplitudes are plotted in Fig.4a and 4b, respectively, in which the amplitude is transformed to be $\log_{10}(1 + \text{amp})$ to reveal the detailed information. According to the arterial wave theory [Wang et al. 1989; Young et al. 1989, 1992; Jan et al, 2003; Wang Lin et al, 2004; Kuo et

al, 2004; and Hsu et al. 2006] the fourth mode reflects the healthy condition of the spleen. The significant amplitude and frequency variations of the spleen mode of both figures provided by microphone system indicate that the person had better to see a doctor. In other words, the integration of the microphone arterial signal does not much alter its capability of resolving the detailed information.

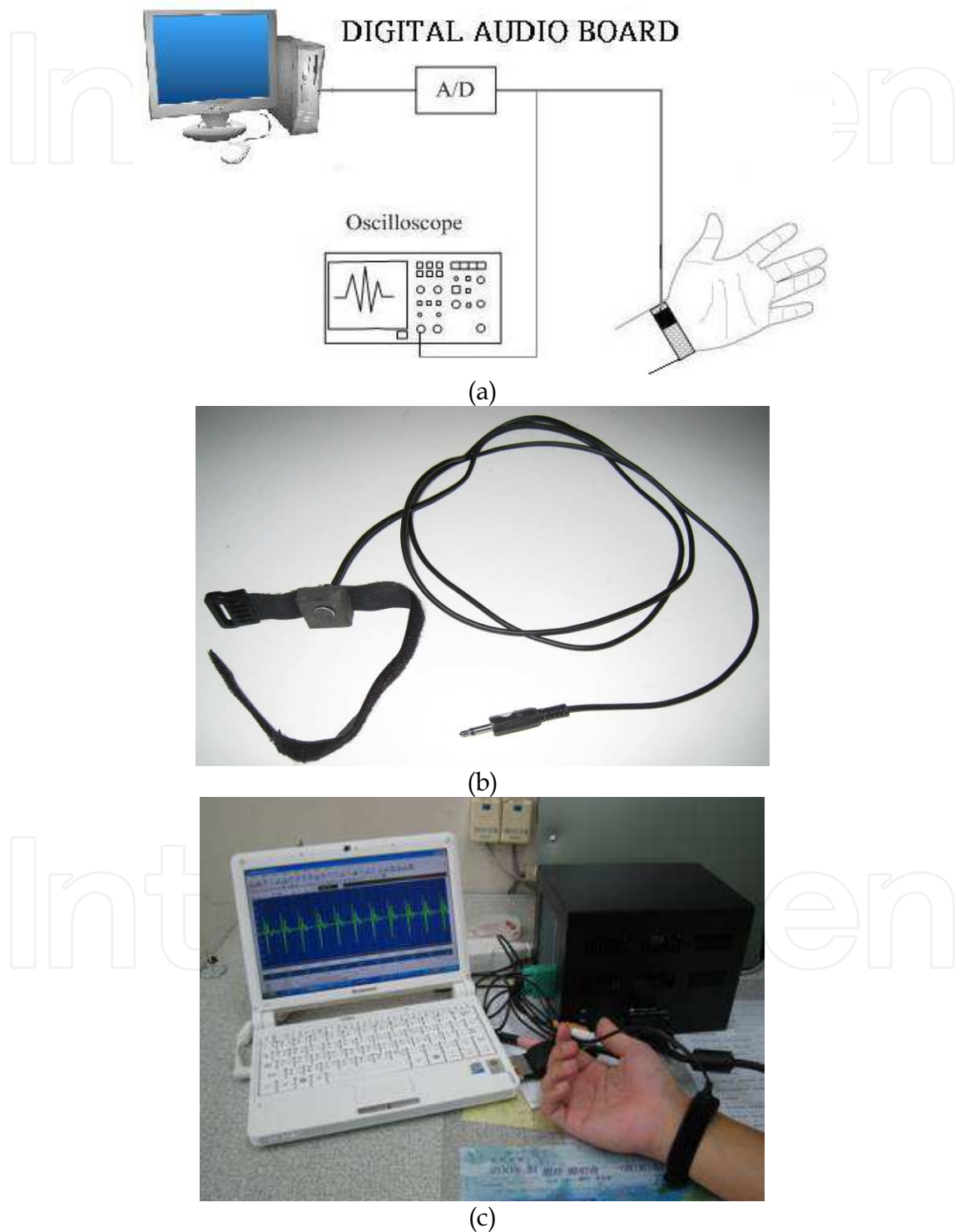


Fig. 2. An example of the sonocardiography system: (a) schematic diagram; (b) the microphone; and (c) an example of acquiring pulse data.

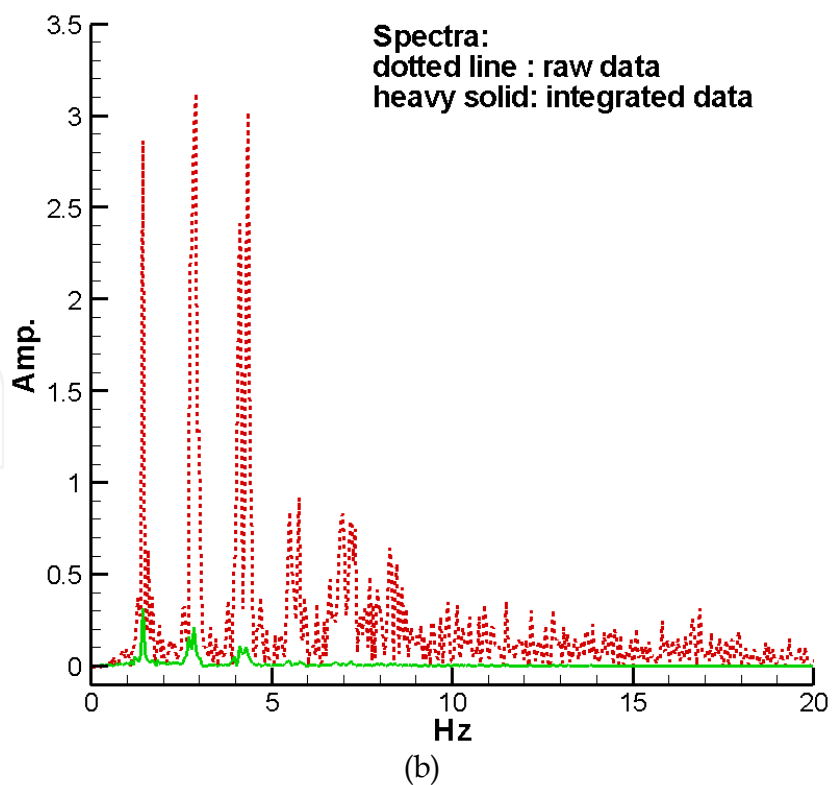
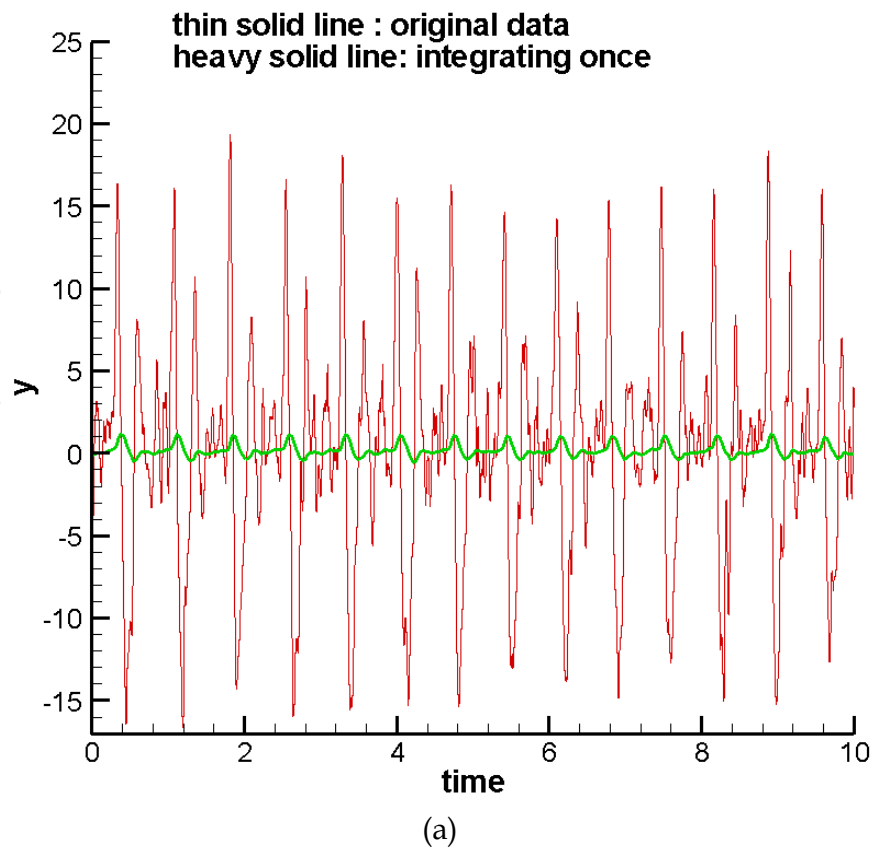
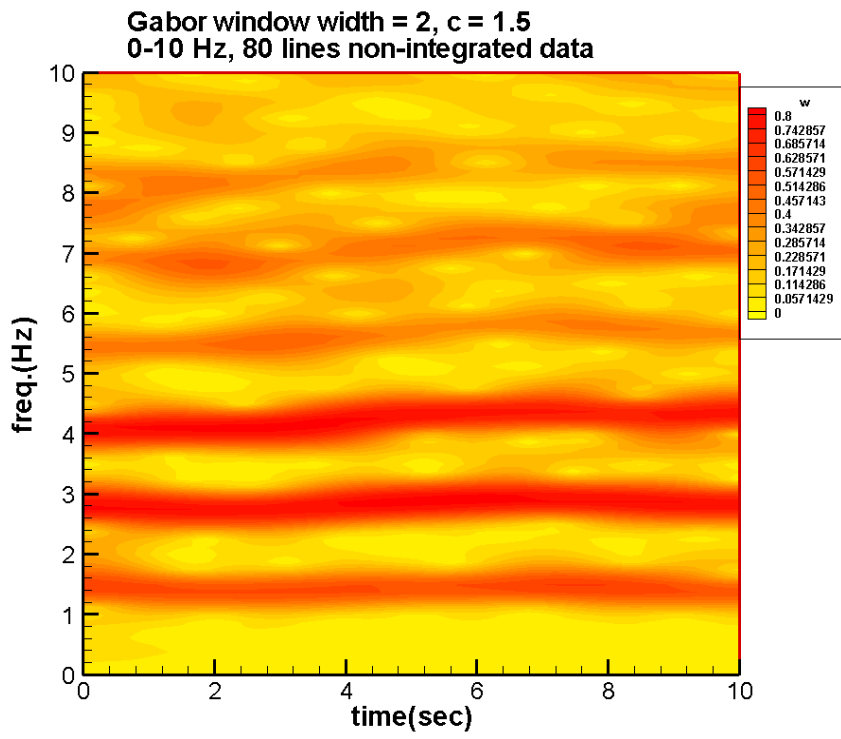
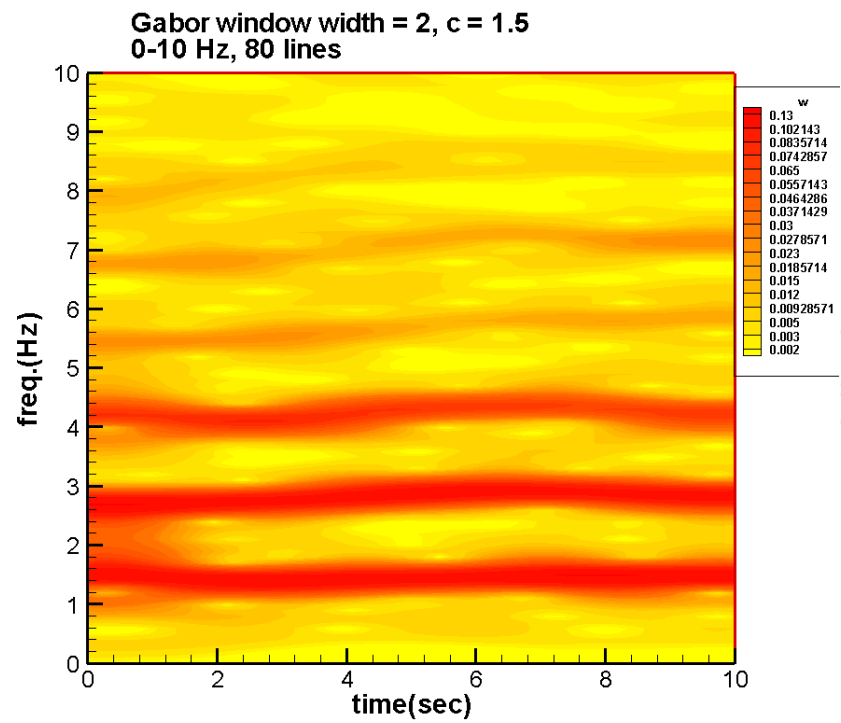


Fig. 3. Data and spectrum of a people with slight spleen disease: (a) raw (thin solid line) and integrated (heavy solid line) data; (b) spectrum of the raw and integrated data.



(a)



(b)

Fig. 4. Three-dimensional spectrograms: (a) raw data; and (b) integrated data.

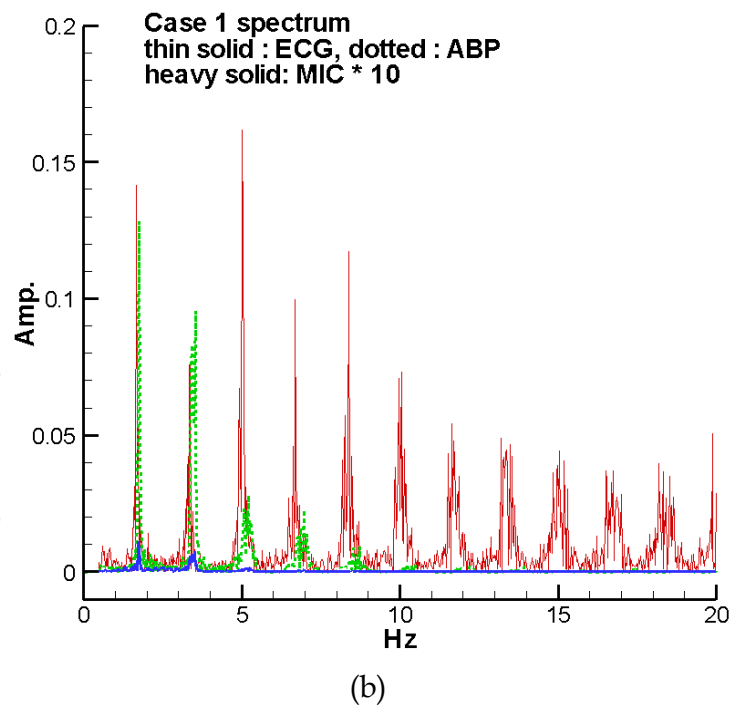
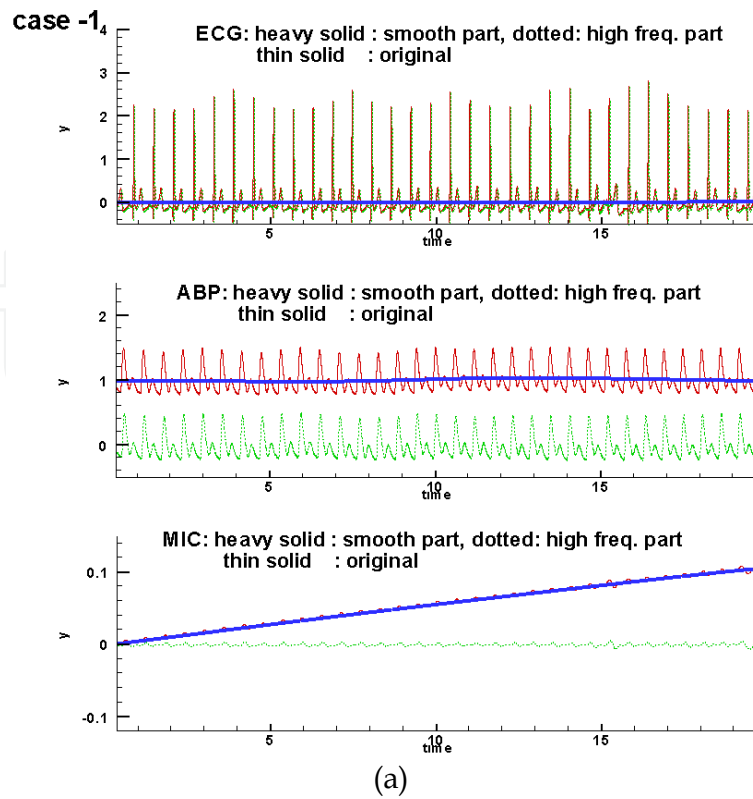


Fig. 5. The data and spectra of the first test case: (a) raw data; (b) spectrum in which the microphone's spectrum is enlarged 10 times.

In this study, data of six test cases are examined. All of them survived. However, the third case stayed in the hospital for one year after data collection. They are separately discussed below.

The first one is a case of head injury with epidural hematoma resulted from a car accident. His raw data are shown in Fig.5a, in which the ECG, ABP and microphone data are plotted from top to bottom, respectively. He was in comatose state with ventilator use while the data was collected. As the governing center had some problems, the output command of the heart rate control system, say the envelope of his ECG, is obviously variable so as to keep a highly adaptive state as shown in Fig.5a. According to the wave theory [Wang et al. 1989; Young et al. 1989, 1992; Jan et al, 2003; Wang Lin et al, 2004; Kuo et al, 2004; and Hsu et al. 2006] and ancient Chinese medicine, the fourth (lung mode) and sixth harmonic (gall mode) are closely related to the circulatory homeostasis of lung and brain, respectively. The spectrograms of Figs.6b and 6c show that the amplitude and frequency of the sixth mode are variable. However, since the steady mechanical ventilator use under sedation provides a smooth breathing pattern, the fourth mode is slightly more stable than the sixth mode.

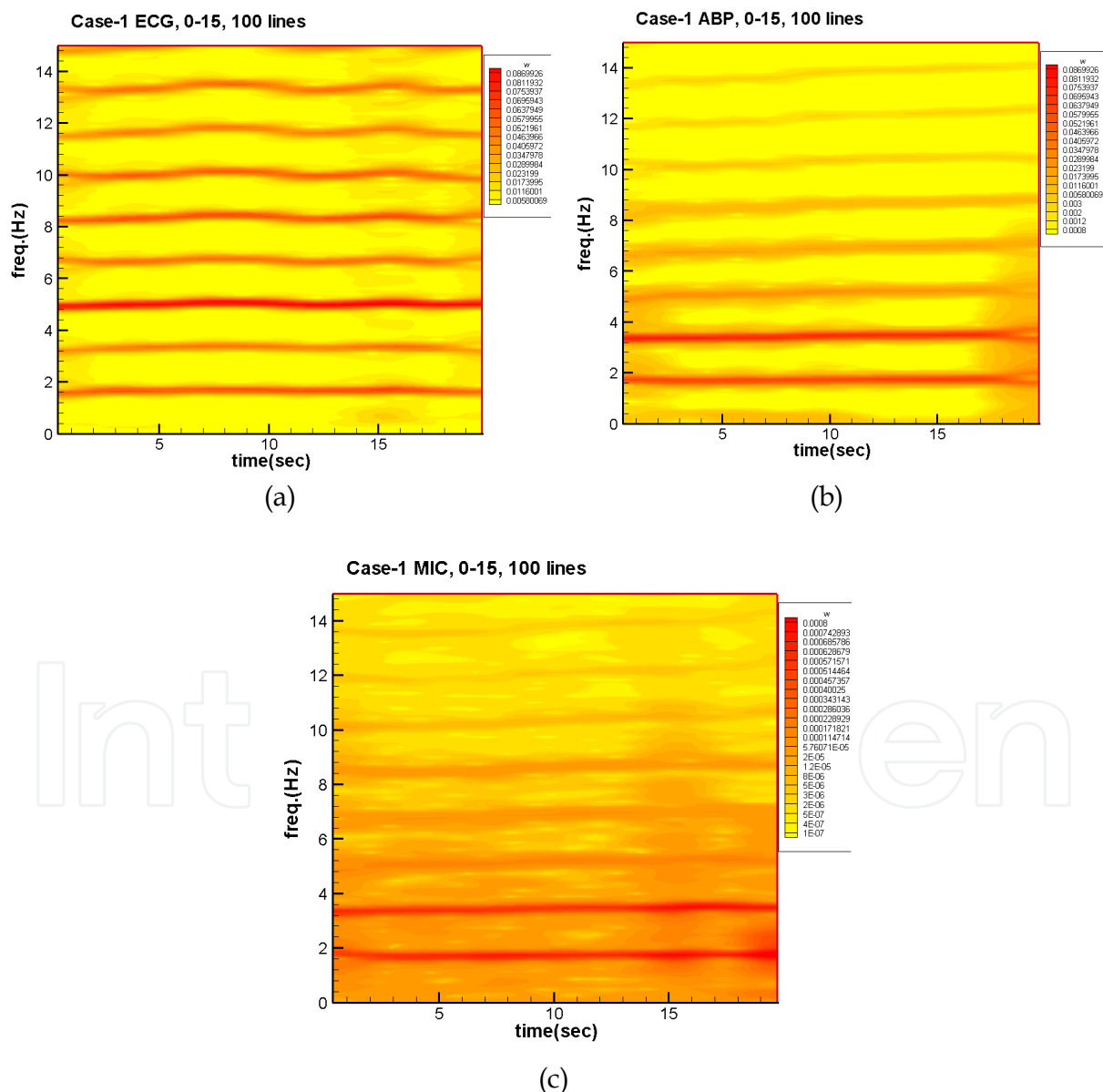


Fig. 6. The spectrograms of the first case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

The cross-correlations between three signals are plotted in Fig.7a through 7c, which are ECG, ABP, and microphone from top to bottom. Note that the time series of the three signals are measured at different points. Therefore, they should have certain phase differences between one another. Because the wave propagation speed distribution through the circulation system is not known, we shift the time scale of one of the wave components so as to attain a maximum absolute value of cross correlation coefficients. The shifted amounts are marked on the figures as shown. It seems that, around the heart rate mode of 1.7Hz, the ECG and ABP are almost totally correlated. In fact, the patient finally recovered after one month. It is interested to see that the correlations of both ECG and ABP with respect to the microphone signal are very high too.

It is interesting to see that the color distributions (represent the amplitude distribution) and wavy shapes (represent the frequency variation) of the fundamental and harmonics of Fig.7a are not similar to those of Fig.7b and 7c, respectively. Nevertheless, their differences of the heart beat wave component are not significant so that their cross-correlation coefficients are still very high and vital signs of the patient are stable.

A careful comparison between the sixth mode of Fig.6c and the fourth mode of Fig.5b reveals that the amplitude and frequency variations of the latter are obviously more complicated than those of the former. The former is corresponding to the signal of emergent case while the latter is not. This means that the behavior of the spectrum of the organ-meridian in emergency is much less sensitive than that does not in serious trouble. The reason is that, in critical situation, the adaptive capability of the blood circulation system concentrates on how to survive so that it takes care of the entire organ-meridians simultaneously. On the other hand, when only one organ is in trouble, the circulation system focuses on supporting this specific target. This difference occurs in all the rest test cases. In other words, both the wave theory of Wang et al. and ancient Chinese organ-meridian technology are suitable for most people before they face emergent health problems and are closely related to the preventive medicine.

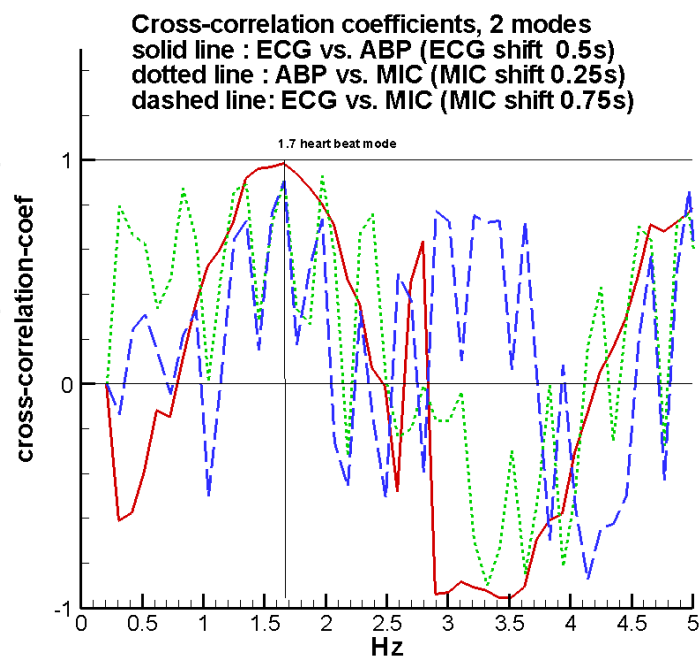


Fig. 7. The cross-correlation coefficients around the heart rate mode of the first test case.

The second one is a case of liver laceration resulted from a car accident. When the data was collected, the patient was in a stable hemodynamic state and non-operative management was applied. The corresponding raw data and spectra are shown in Figs.8a and 8b, respectively. It is seen that the spectral band around the fundamental (heart) and harmonics

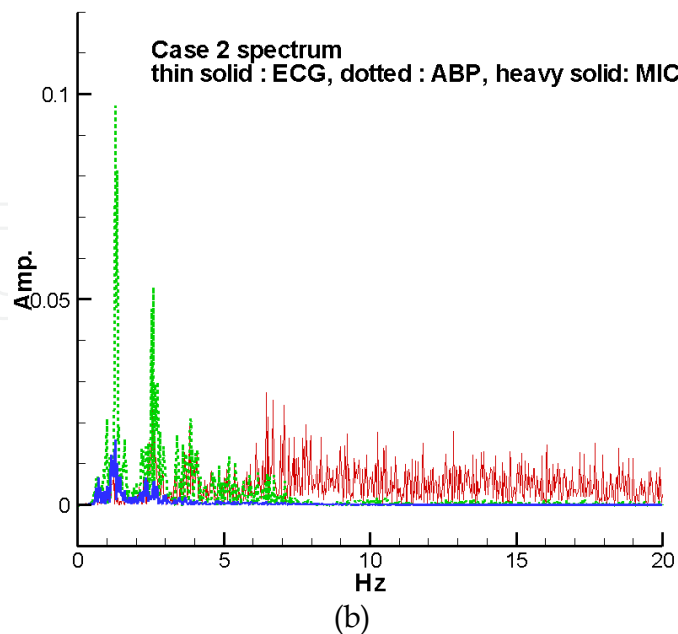
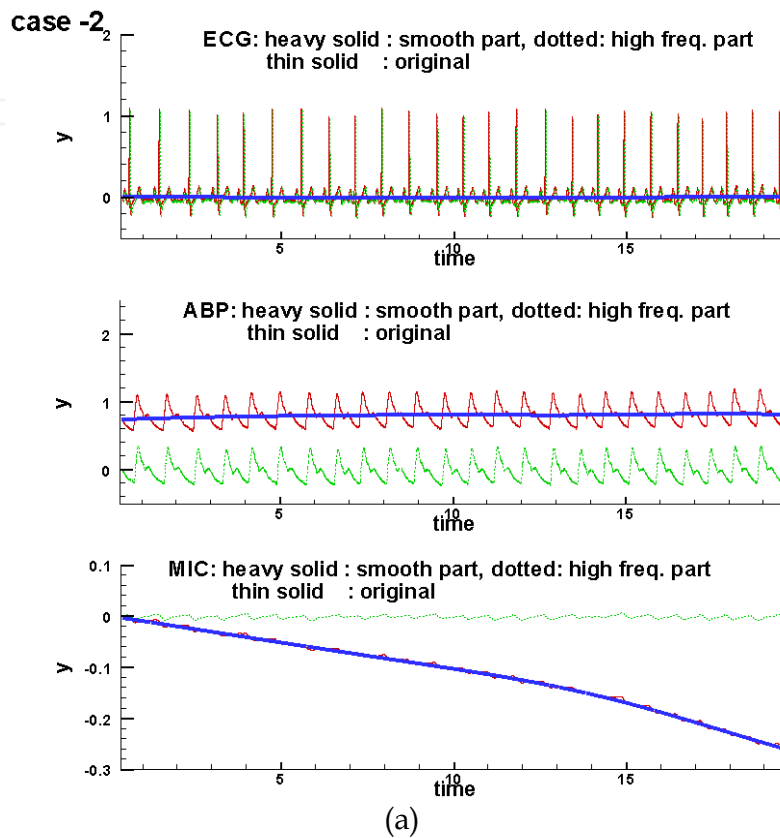


Fig. 8. The data and spectra of the second test case: (a) raw data; (b) spectrum in which the microphone's spectrum is enlarged 10 times.

seriously scattered. All the corresponding spectrograms of ECG, ABP and microphone signals exhibit significant variations of both amplitude and frequencies. It seems that the spectral scattering of a wave component is corresponding to the variation of one or two of the amplitude and frequency. The degrees of these dominant modes' variations are not less than the first harmonic (live mode). It seems that the injury of the major organ, liver, brought great impact on the operation of other systems, and the adaptation of the entire system was switched on. Fortunately, the situation is not serious enough to become chaos so that we can still trace every mode.

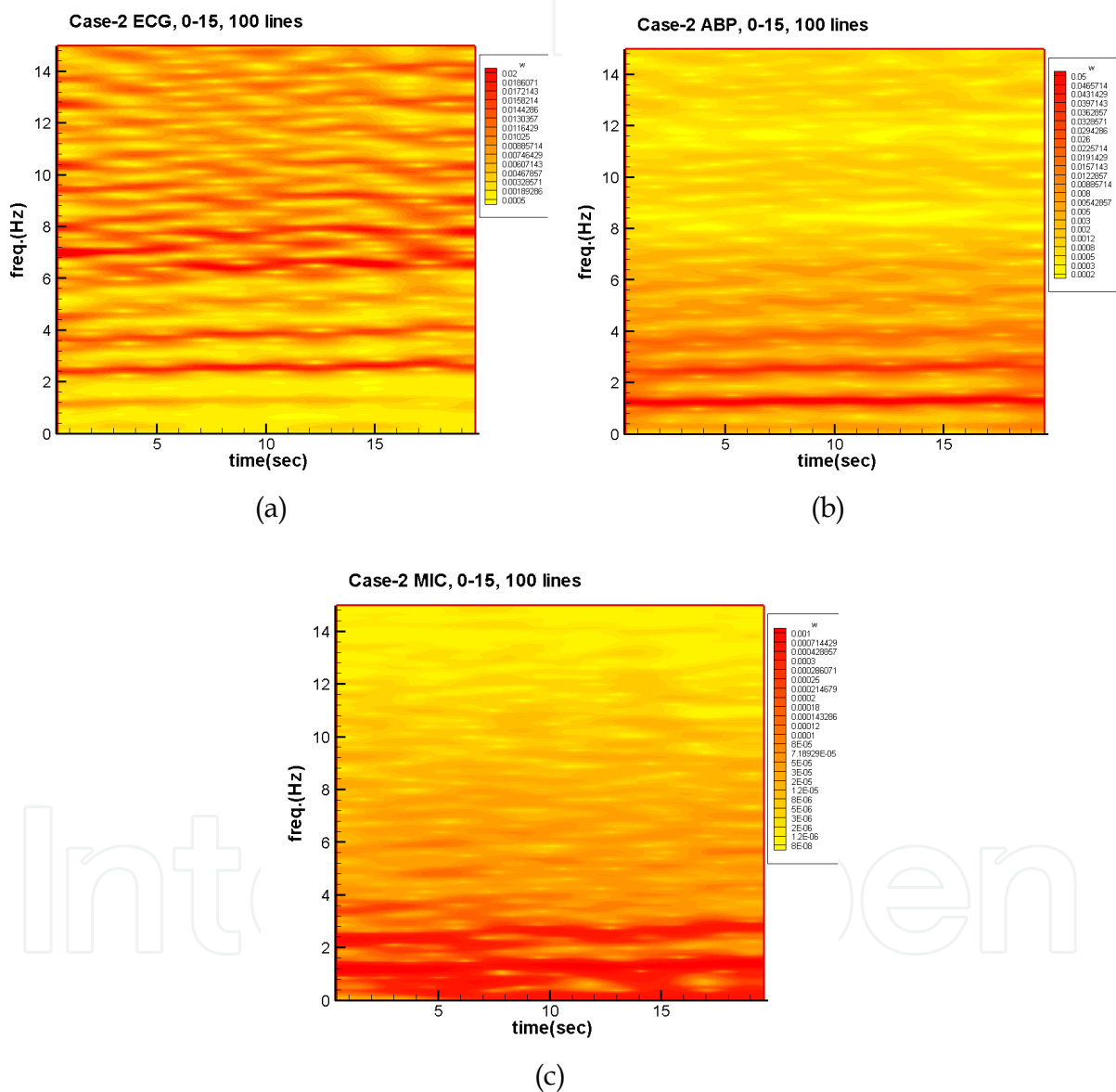


Fig. 9. The spectrograms of the second case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

The cross correlation coefficients are shown in Fig.10. The correlations of ECG-ABP and ABP-microphone are moderately high (about 0.7 and 0.6 respectively). The ECG and microphone signal is in highly negative correlation (-0.9). Now the color distributions and wavy shapes of most organ meridians shown in the three spectrograms are similar to each other such that they

are also partially correlated. Therefore, the patient's circulation system is healthy. This explanation was confirmed by the record that the patient had recovered after one month.

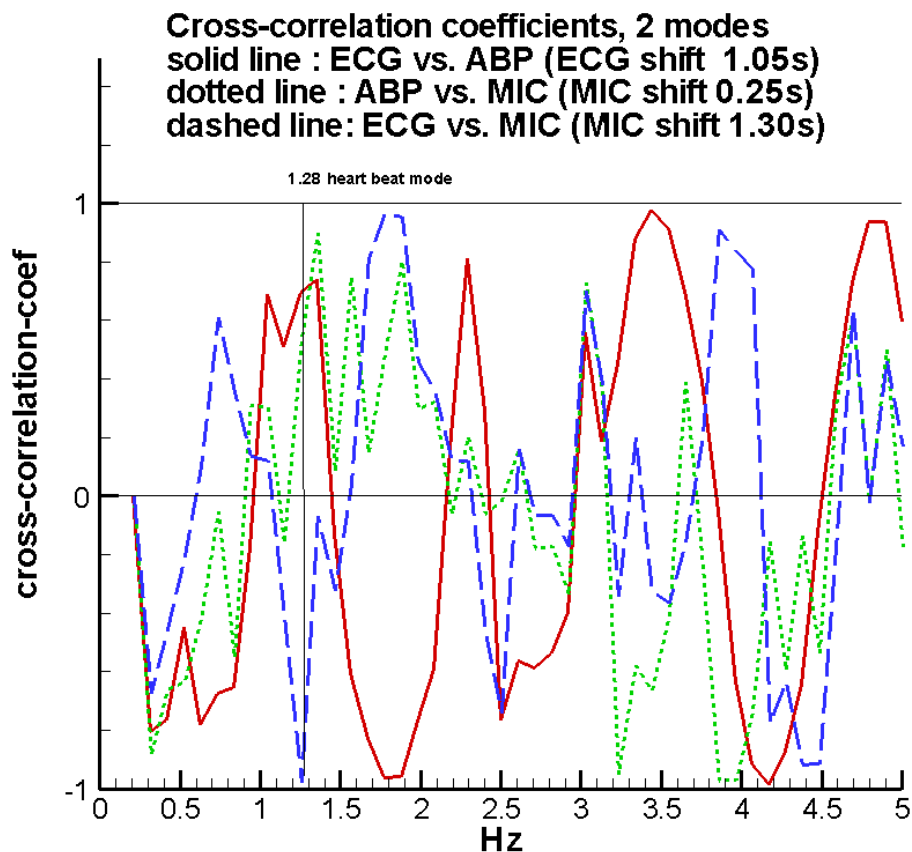


Fig. 10. The cross-correlation coefficients around the heart rate mode of the second test case.

The third test case suffered from serious electric shock and had cardiopulmonary resuscitation right before onto the ambulance. Though the vital signs resumed, he remained in comatose state with ventilator support while the data was collected. Unfortunately, the case had prolonged hospitalization for one year after that. The raw data and spectra are shown in Figs.11. Like the spectra shown in Fig.11b, spectrograms of Figs.12a through 12c are regular and do not have much amplitude variation. It seems that the coma had suppressed the system adaptation. Moreover, the similarity of color distribution and wavy shape of every organ meridian indicates that the three data are partially correlated too. Moreover, Fig.13 shows that all the correlation coefficients of the heart rate mode are very high as shown. In spite of the fact that the patient can not completely recover for a long time, the highly correlated state indicates that vital signs are stable.

The next case got right frontal parietal and temporal subdural hematoma after falling down. She also had the history of old stroke. The corresponding raw data and spectra are plotted in Figs.14a and 14b, respectively. From these signal we can not have much information. From the resulting spectrograms, it is obviously that the gall mode (related to brain organ-meridian) has obvious variations of both amplitude and frequency. Consequently, the second and still higher harmonics are all affected too.

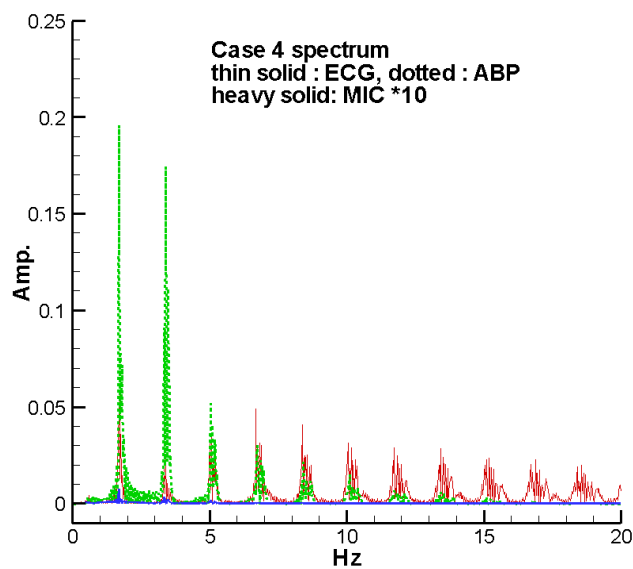
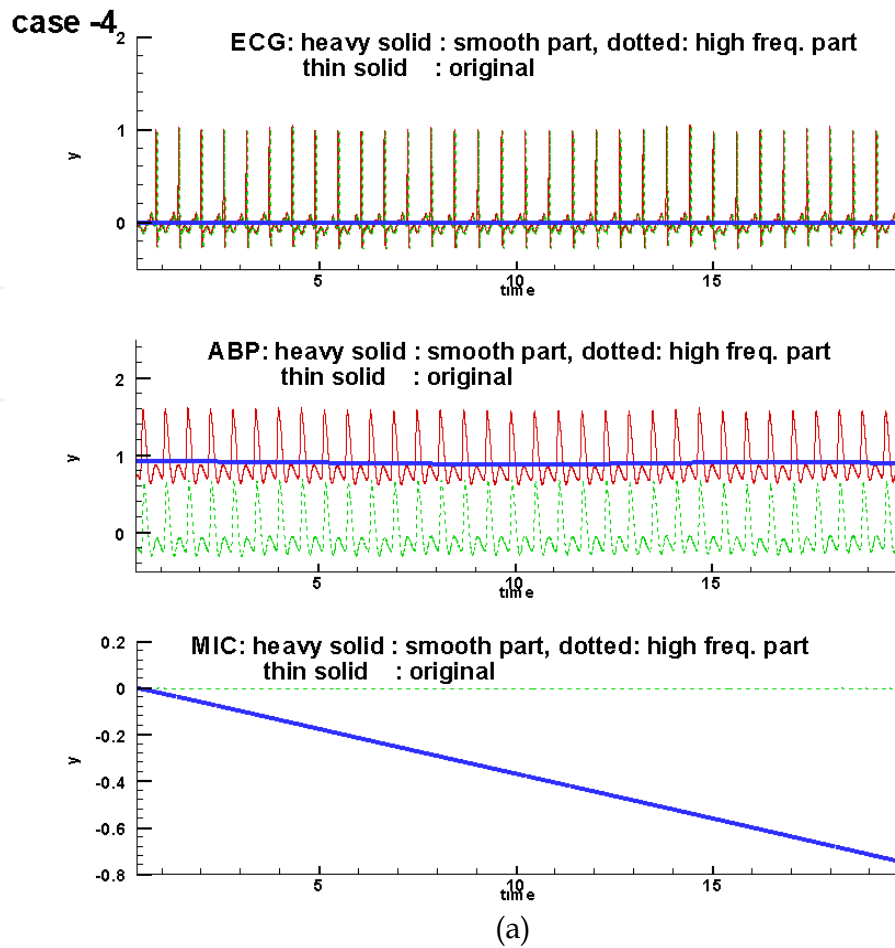


Fig. 11. The data and spectra of the third test case: (a) raw data; (b) spectrum in which the microphone's spectrum is enlarged 10 times.

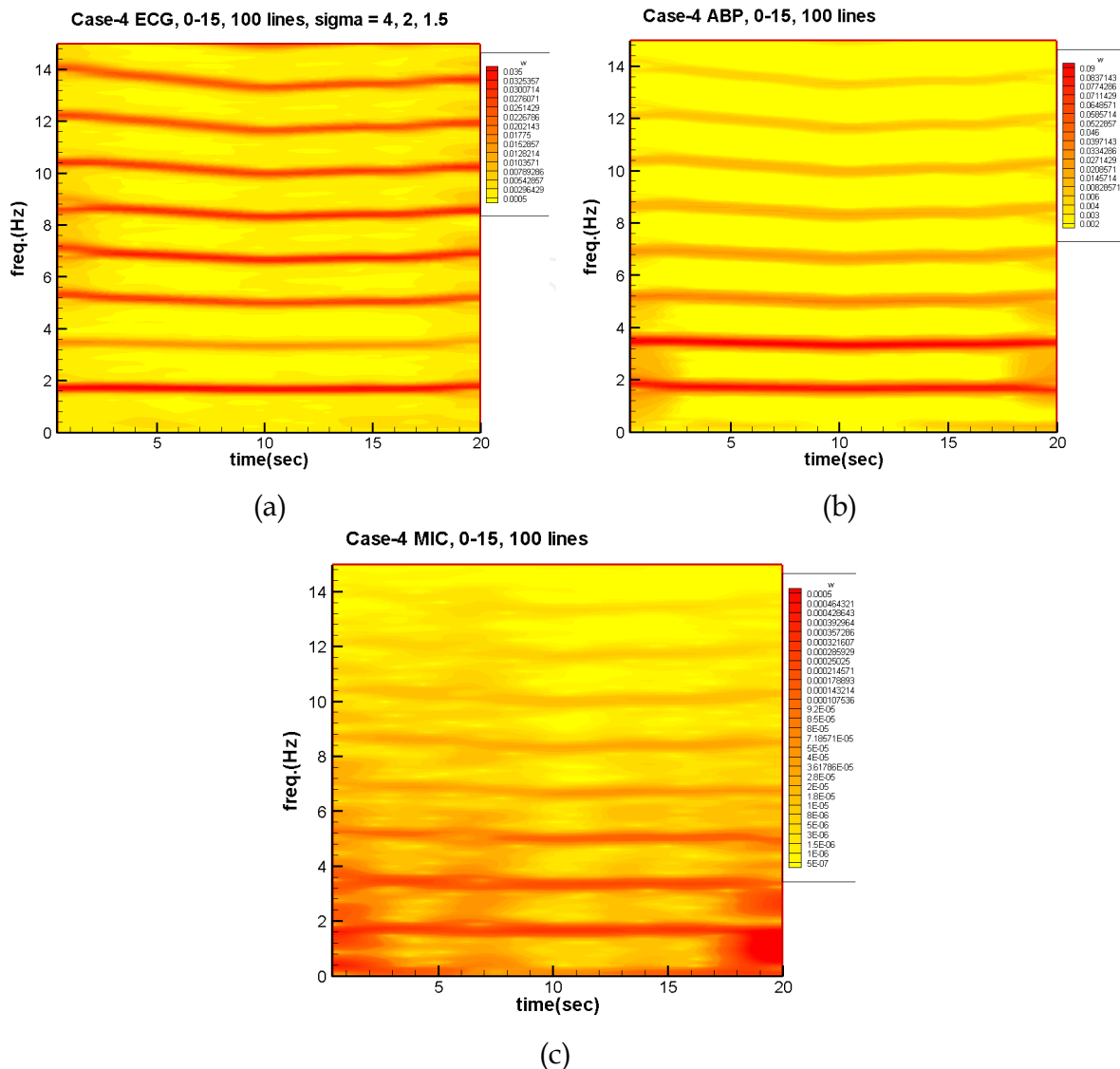


Fig. 12. The spectrograms of the third case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

The cross correlation between the ECG and ABP are very high (about 0.9 as shown in Fig.15). On the other hand, signals of ABP-microphone and ECG-microphone have negative correlations of about -0.6. The reason may be cause by the weak wrist pulse signal of the patient. Nevertheless, it seems that the system adaptation of the patient worked very well so that mode wave components gradually fluctuated as shown. These fluctuations are similarly existed in the three spectrograms of Figs.14a-14c which show that their energies are partially correlated. These correlations reflect the high possibility of recover which is verified by the fact that the patient had recovered after one month.

The fifth test case was suffered from a cervical vertebra injury after falling down and received the support of the endotracheal intubation. At the instant of measuring data, the patient lost consciousness and was quadriplegia. His raw data and spectra are shown in Figs.17a and 17b, respectively. The resulting spectrograms (Figs.18a-18c) show that both fundamental mode and harmonics have obvious amplitude and frequency fluctuations. His gall modes even have jumps at the instances of the tenth and fifteenth second as shown. It

indicates his self-protection system was in the adaptive state and tried to recover his health. In Fig.19, it is seen the ECG, ABP, and microphone signal have very high correlation between one another such that his circulation worked very well. The partial correlations among their energy are also reflected by the similarity between their organ meridians' amplitude and frequency distributions. These conclusions have the strong evident that he finally recovered after six months.

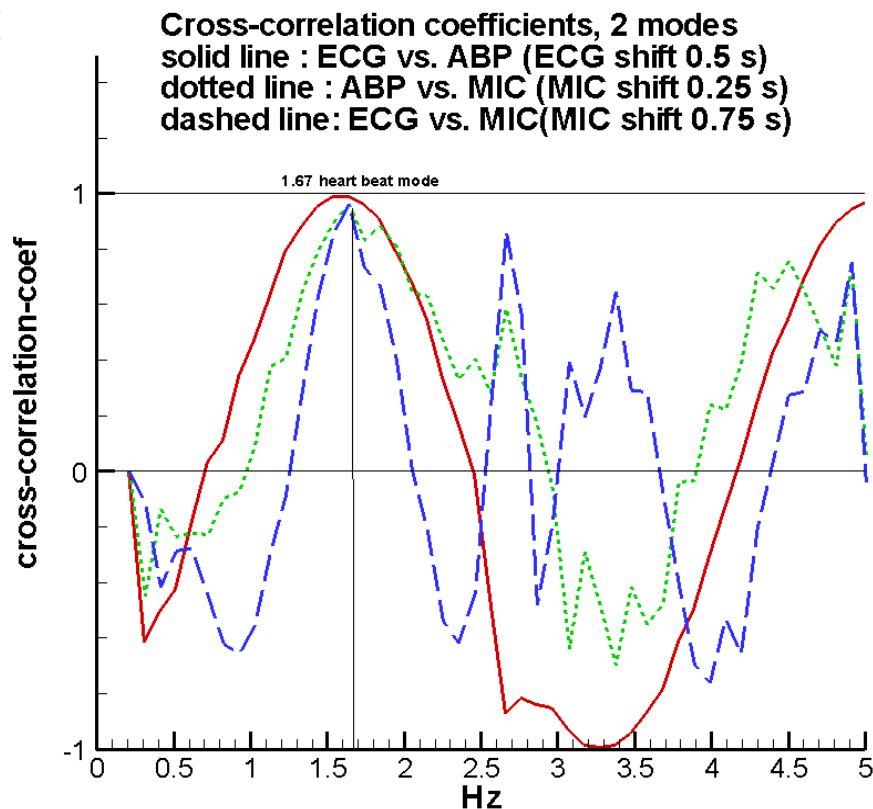


Fig. 13. The cross-correlation coefficients around the heart rate mode of the third test case.

The last test case got severe head injury with intracranial hemorrhage, subdural hematoma and subarachnoid hemorrhage. The raw data and spectra are shown in Figs.20a and 20b, respectively. Envelopes of the ECG and APP raw data have obvious oscillations as shown. The corresponding spectrograms of Figs.21a through 21b show his circulation system tried to adapt itself. The three gall modes has abnormal jump in the interval of 5-7 second as shown. In this case, the heart rate modes of ABP and microphone signal are highly correlated (correlation coefficient is about 0.9 in Fig.22). Figure 22 shows that his cross-correlation coefficients of ECG-ABP and ECG-microphone are about 0.3 and 0.1, respectively. Obviously, the phase lags are serious between these two signals. That indicates he was in a life-threatening situation at that time. Fortunately, the patient has partial correlation between three data because his amplitude and frequency fluctuations of all the organ meridian modes of three spectrograms are similar to one another. He recovered gradually and was transferred to the general ward within one month. Recently, he returned to the clinic for the treatment of epilepsy, a neurological sequel of the previous head injury. That means his neural control system is impaired. Although his circulation system has phase lag problems, the overall response is not too bad so that he finally recovered under

the proper supports and treatments in the intensive care unit. These messages indicate that he effectively struggled for his life during the period in the intensity care unit.

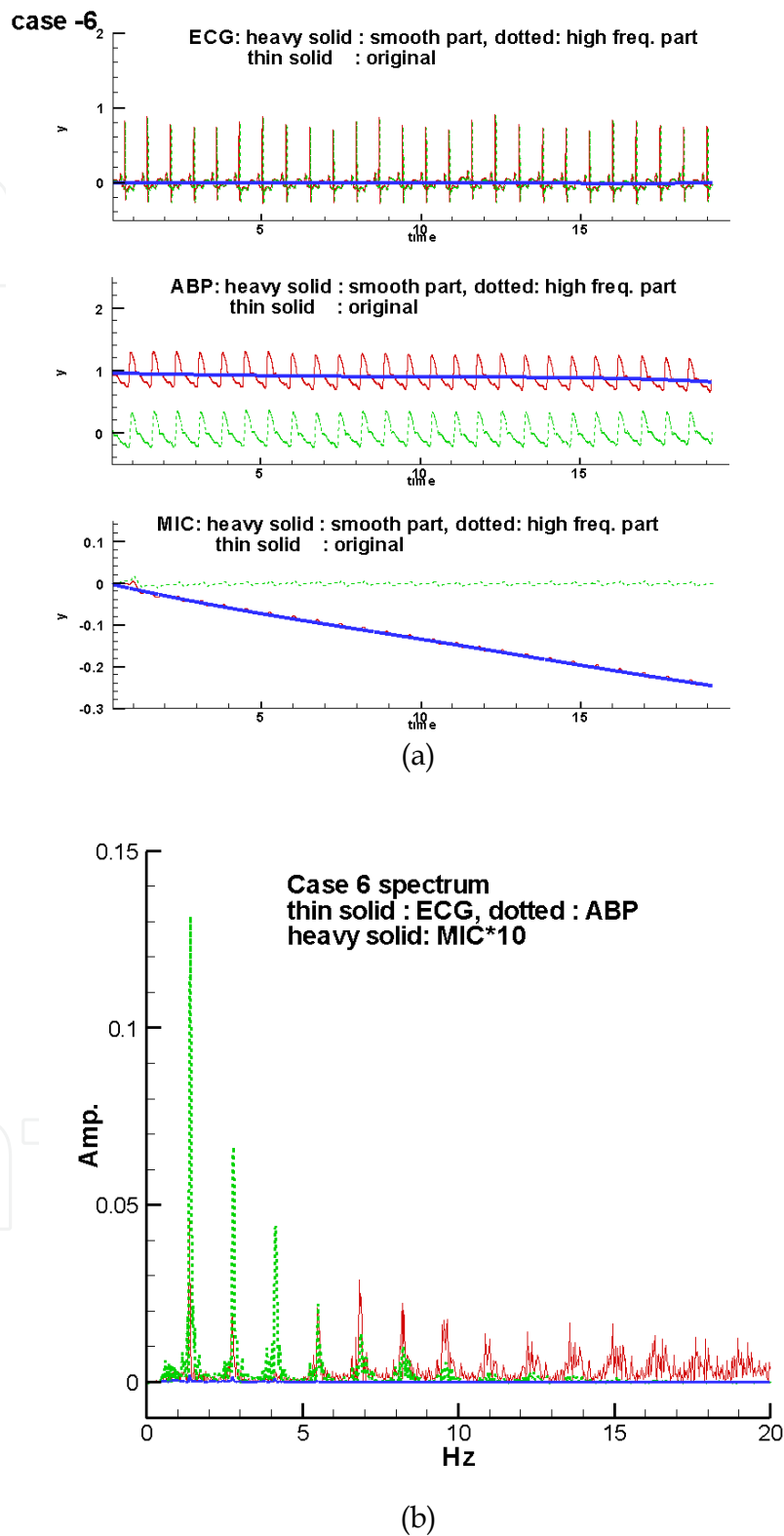


Fig. 14. The data and spectra of the fourth test case: (a) raw data; (b) spectrum in which the microphone’s spectrum is enlarged 10 times.

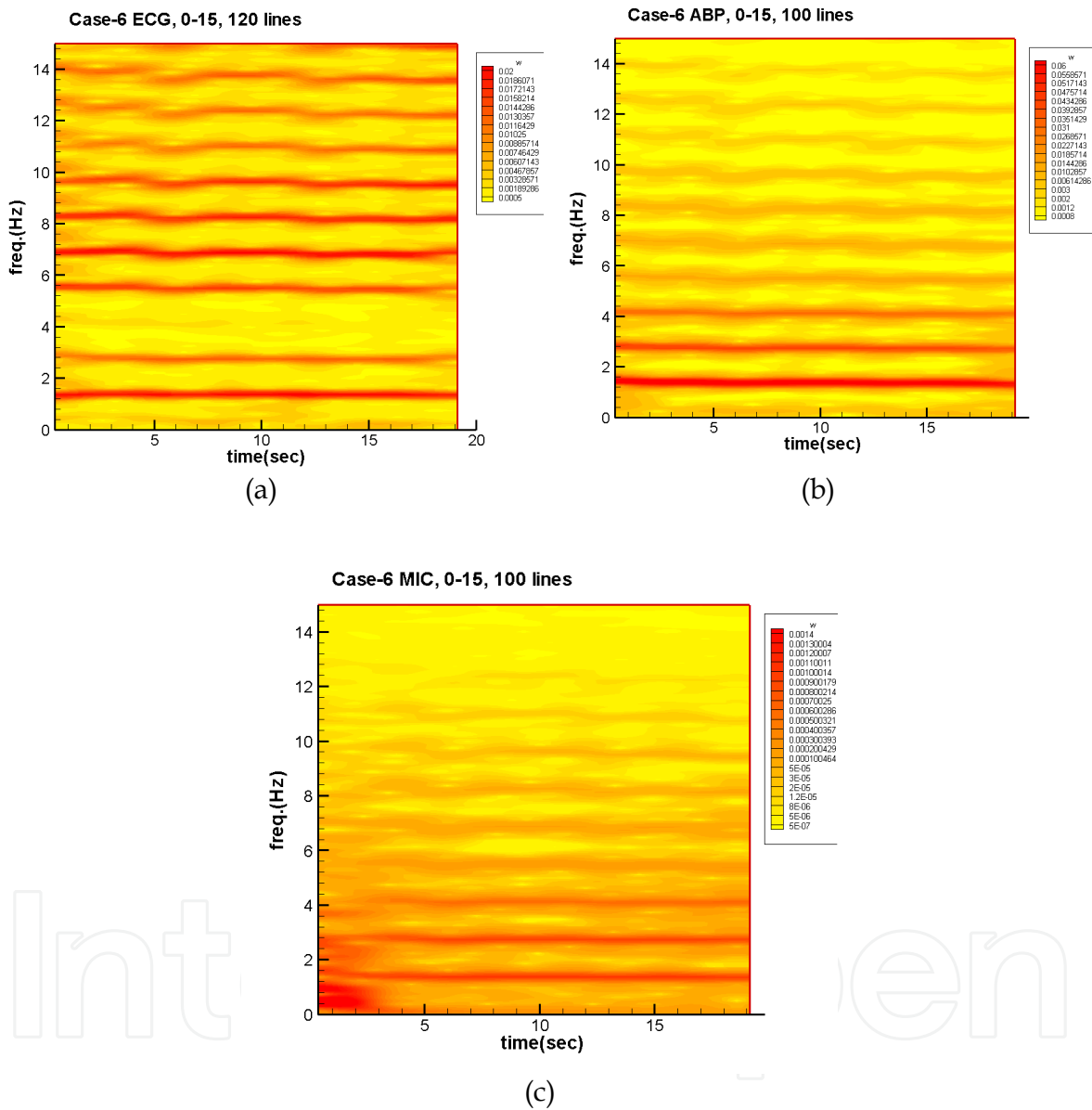
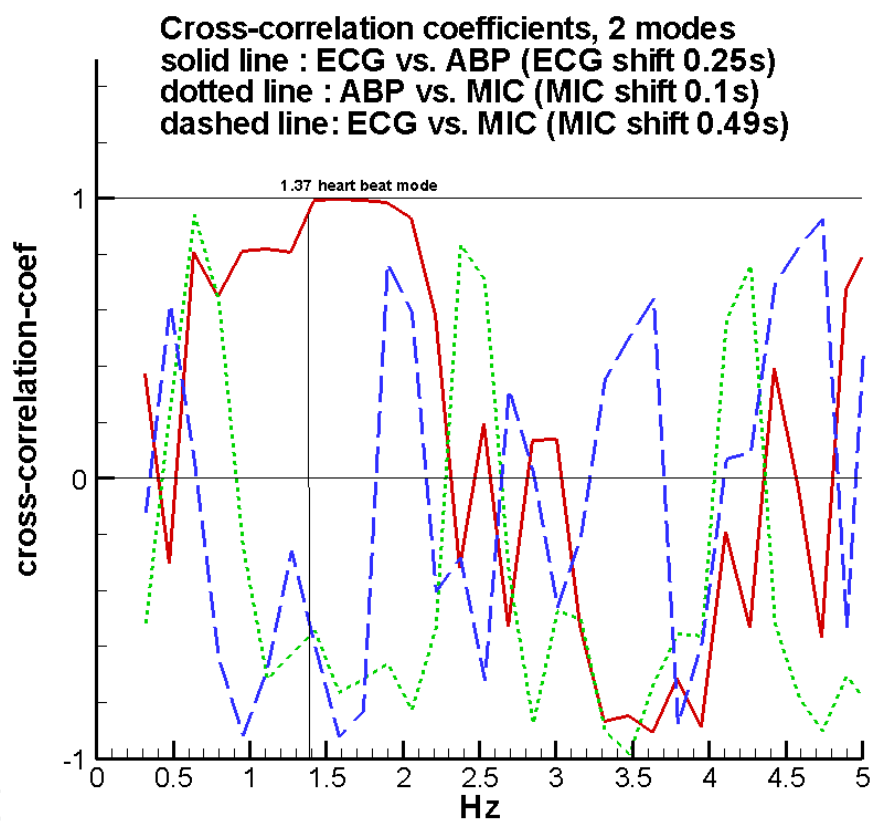


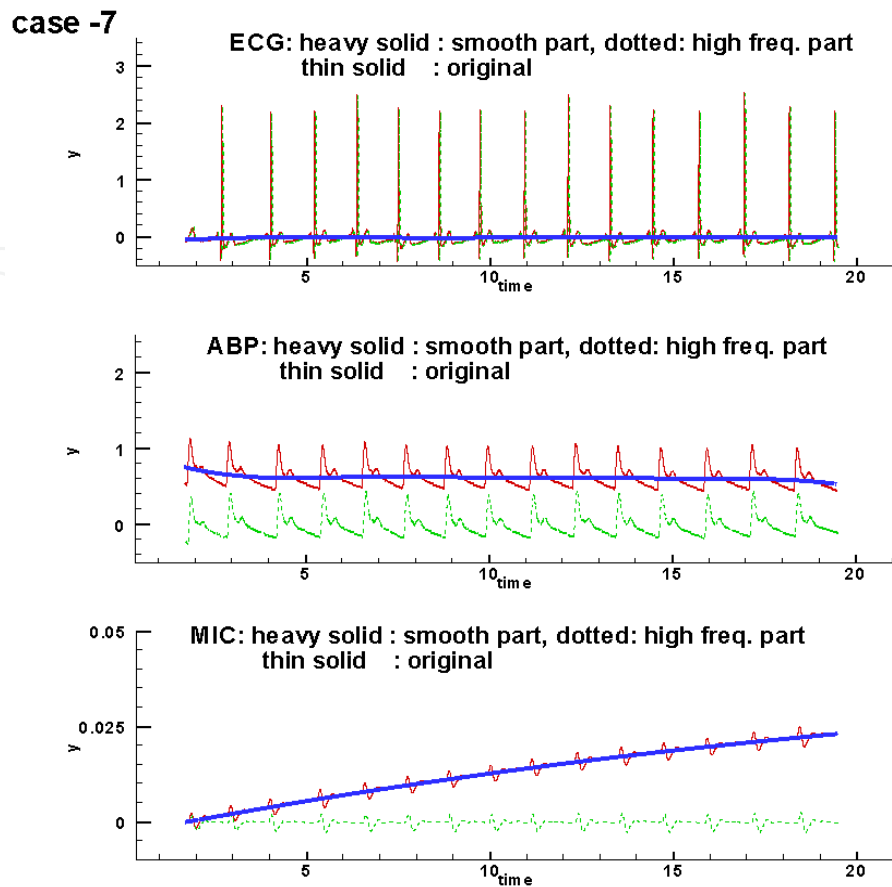
Fig. 15. The spectrograms of the fourth case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

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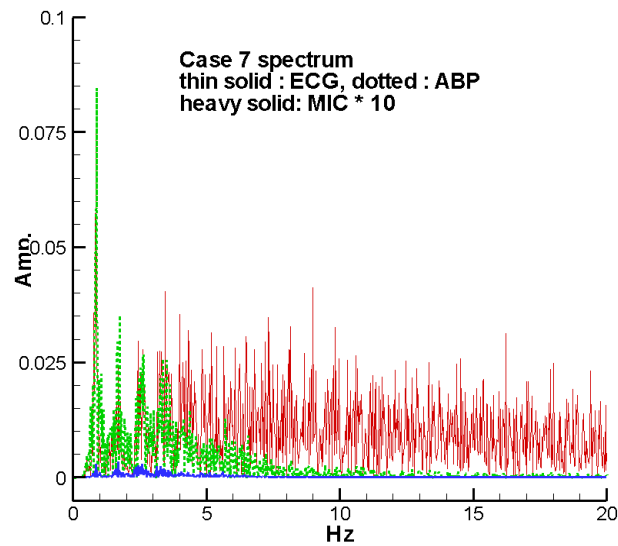


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Fig. 16. The cross-correlation coefficients around the heart rate mode of the fourth test case.



(a)



(b)

Fig. 17. The data and spectra of the fifth test case: (a) raw data; (b) spectrum in which the microphone's spectrum is enlarged 10 times.

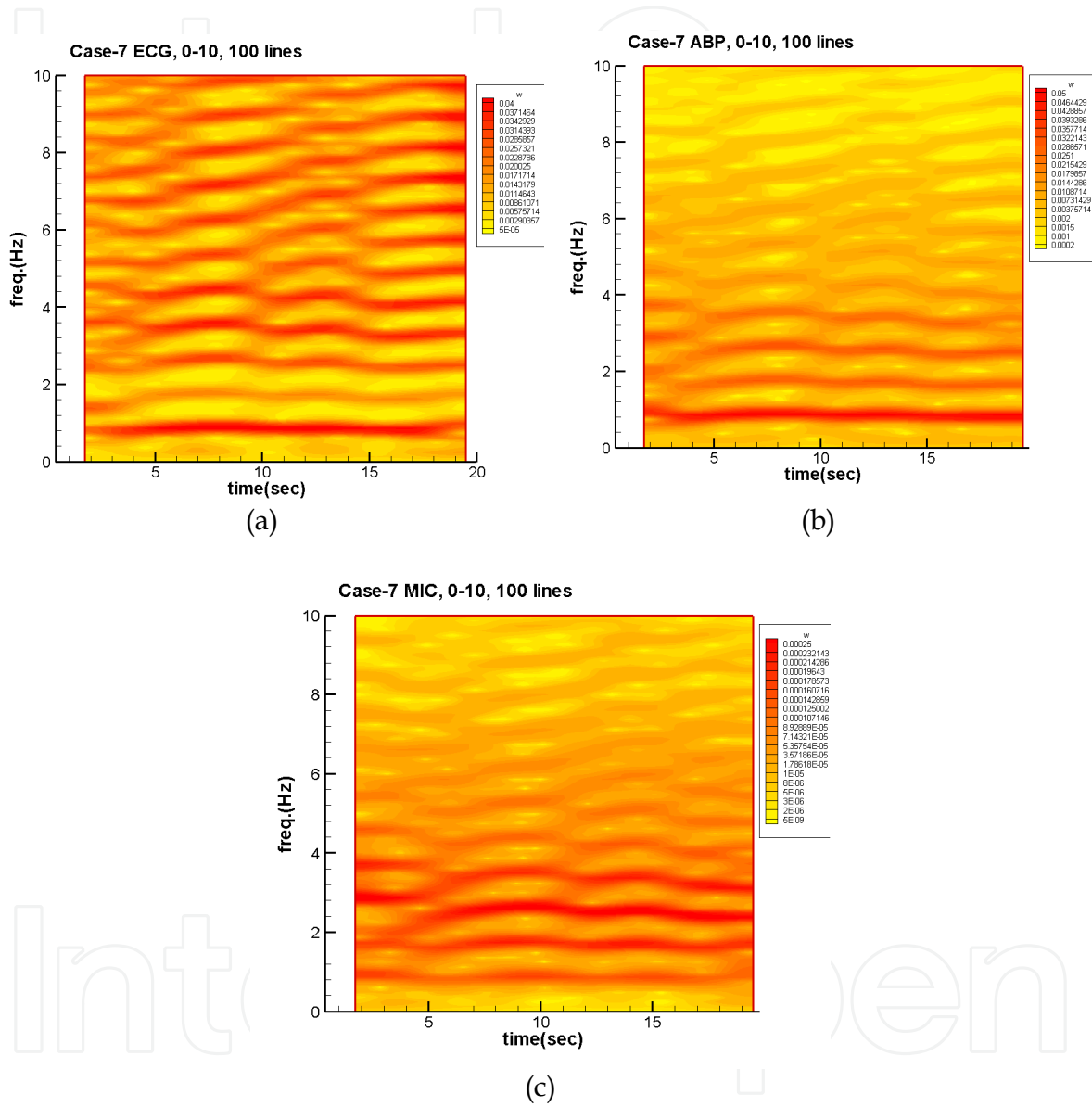


Fig. 18. The spectrograms of the fifth case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

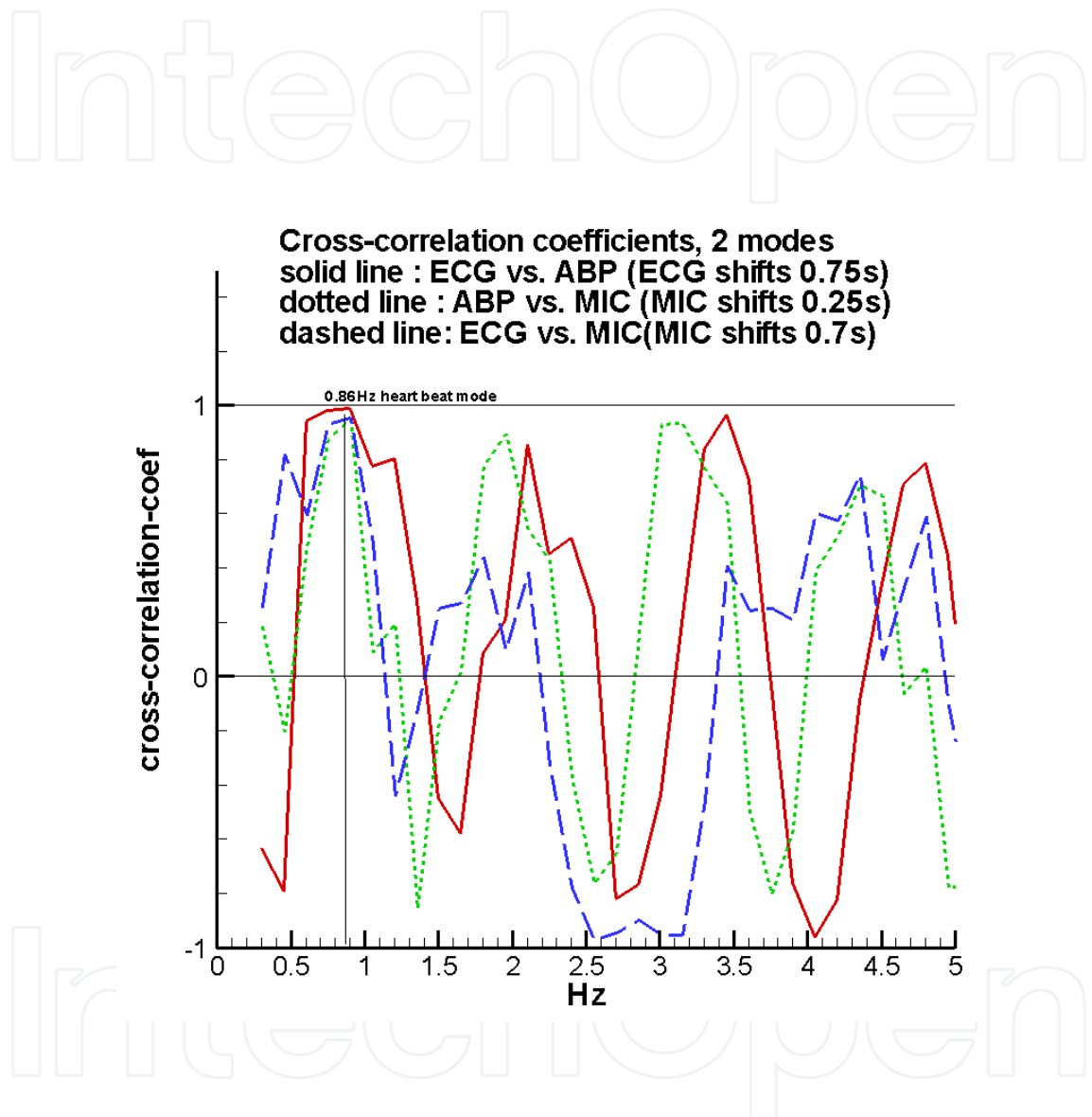


Fig. 19. The cross-correlation coefficients around the heart rate mode of the fifth test case.

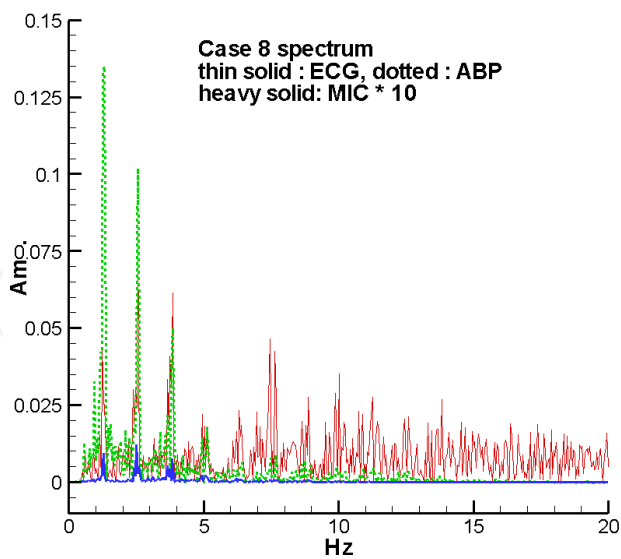
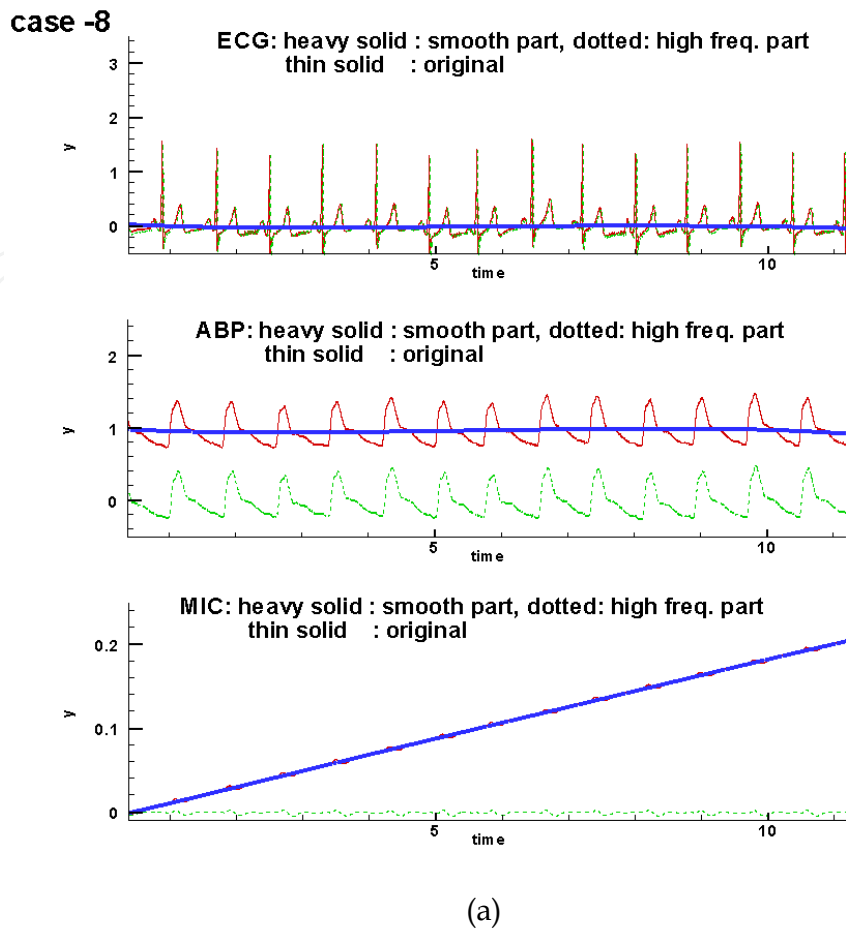


Fig. 20. The data of the sixth test case, fell down, bilateral temporal bone fractures extends into the right middle ear cavity: (a) raw data; (b) spectrum in which the microphone's spectrum is enlarged 10 times.

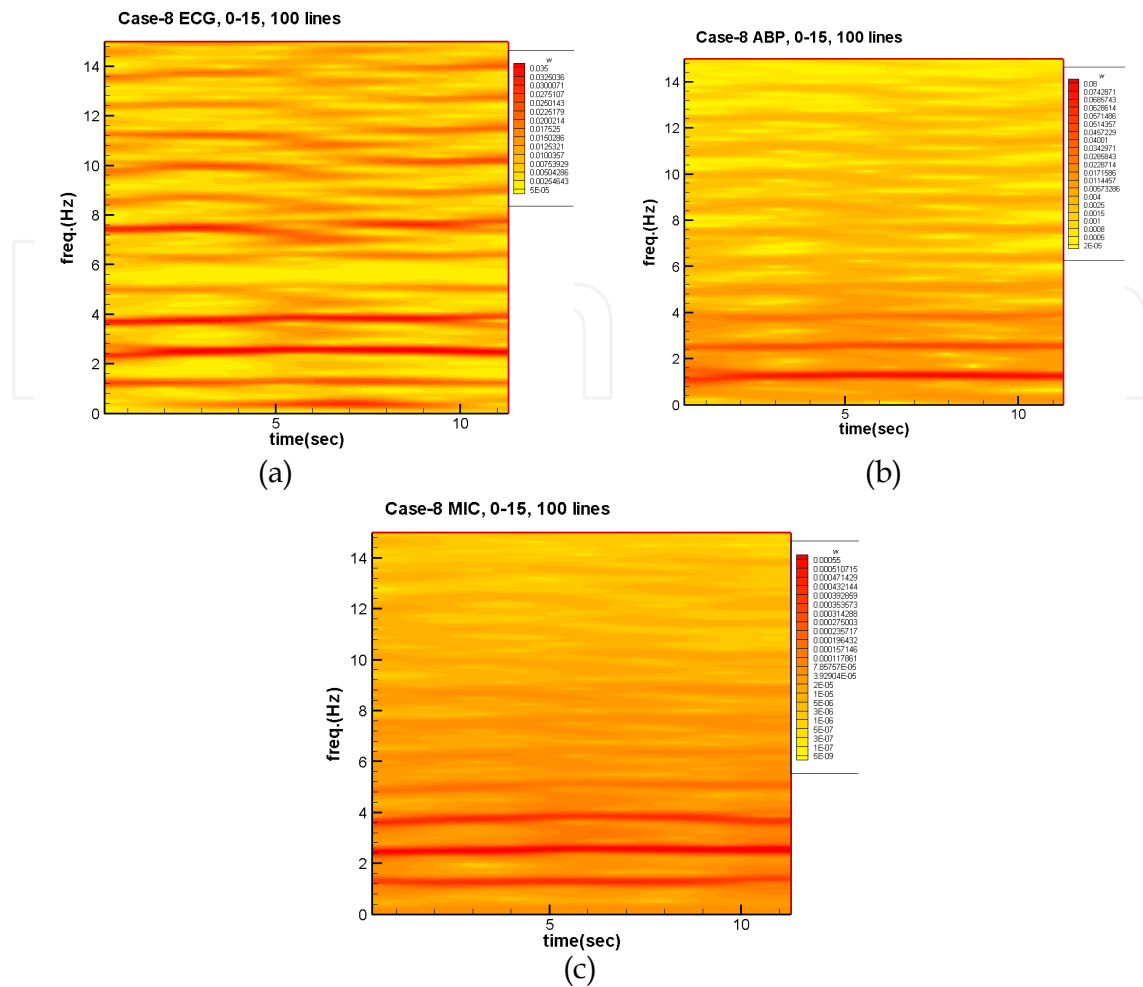


Fig. 21. The spectrograms of the sixth case: (a) ECG; (b) ABP; and (c) microphone wrist arterial signal.

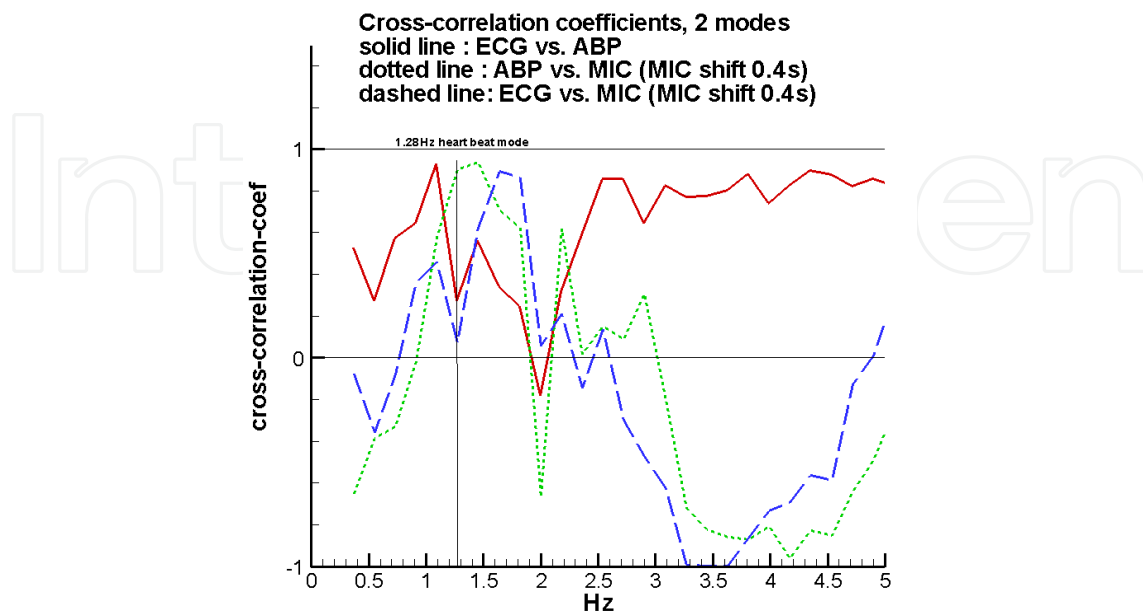


Fig. 22. The cross-correlation coefficients around the heart rate mode of the sixth test case.

In summary, several consistent points of the above discussions are listed below.

1. The heart modes of microphone signal and ABP are correlated. It indicates the possibility that the electret condenser microphone system is a potential tool to be an alternative of ABP system. Since the microphone is a non-invasive sensor and closely related to the ancient Chinese medicine, it can be equipped with simple ECG system to become a valuable tool of clinic and preventive medicine.
2. The cross-correlations between ECG, ABP and microphone can be examined either by the directly calculating the coefficient among time domain heart rate components or by checking the similarity of every organ meridian's shape and color variations with respect to time in their spectrograms. All the test cases show that the heart rate modes of ECG and ABP are correlated. The followed up records show that all these patients remain alive under the effective treatments of the intensive care unit.
3. In critical cases, the wave theory of Wang et al. about single organ meridian still works but is not prominent as in the less emergent situations.
4. When the state is not critical, all the organ-meridians fluctuate which reflect the adaptation of the blood circulation system to struggle for survive.

Since the sample size is too small to achieve a statistical level, further studies will be done to enrich the data base so as to make these facts become useful.

4. Conclusions

The precise post processing algorithm combining the trend removal, Fourier transform and modified Gabor transform provides a tool to look into details of ECG, ABP, and microphone data of wrist arterial signal. The heart modes of all the microphone signals are correlated with ABP. In other words, the non-invasive acoustic sensor can also be a potential tool to monitor human healthy state. The cross correlation coefficient between heart beat modes of ECG and ABP seems to be a possible index of human vital sign. In summary, the microphone system is a potential tool to effectively construct a bridge among ancient and modern medicine and modern technologies.

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During the recent years, traditional Chinese medicine (TCM) has attracted the attention of researchers all over the world. It is looked upon not only as a bright pearl, but also a treasure house of ancient Chinese culture. Nowadays, TCM has become a subject area with high potential and the possibility for original innovation. This book titled *Recent Advances in Theories and Practice of Chinese Medicine* provides an authoritative and cutting-edge insight into TCM research, including its basic theories, diagnostic approach, current clinical applications, latest advances, and more. It discusses many often neglected important issues, such as the theory of TCM property, and how to carry out TCM research in the direction of TCM property theory using modern scientific technology. The authors of this book comprise an international group of recognized researchers who possess abundant clinical knowledge and research background due to their years of practicing TCM. Hopefully, this book will help our readers gain a deeper understanding of the unique characteristics of Chinese medicine.

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