Characteristic parameters of electromagnetic signals from a human heart system*

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The electromagnetic field of a human heart system is a bioelectromagnetic field. Electrocardiography (ECG) and magnetocardiography (MCG) are both carriers of electromagnetic information about the cardiac system, and they are nonstationary signals. In this study, ECG and MCG data from healthy subjects are acquired; the MCG data are captured using a high-T_c radio frequency superconducting quantum interference device (HTc rf SQUIDs) and the QRS complexes in these data are analysed by the evolutionary spectrum analysis method. The results show that the quality factor Q and the central frequency f_z of the QRS complex evolutionary spectrum are the characteristic parameters (CHPs) of ECG and MCG in the time–frequency domain. The confidence intervals of the mean values of the CHPs are estimated by the Student t distribution method in mathematical statistics. We believe that there are threshold ranges of the mean values of Q and f_z for healthy subjects. We have postulated the following criterion: if the mean values of CHPs are in the proper ranges, the cardiac system is in a normal condition and it possesses the capability of homeostasis. In contrast, if the mean values of the CHPs do not lie in the proper ranges, the homeostasis of the cardiac system is lacking and some cardiac disease may follow. The results and procedure of MCG CHPs in the study afford a technological route for the application of HTc rf SQUIDs in cardiology.

Keywords: bioelectromagnetic field, magnetocardiography, electrocardiography, characteristic parameters, threshold ranges

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1. Introduction

The bioelectromagnetic field is the electromagnetic field that emanates from living matter. For example, the transmembrane potential of cells is a static field, the action potential and the magnetic fields of myocardial cells, and those of the brain system are all low-frequency fields. Currently, the mechanism, the function and the rules of the electromagnetic behaviour in living matter are not completely understood. Electrocardiography (ECG) and magnetocardiography (MCG) are both carriers of electromagnetic information about the entire cardiac system and they can be measured from the human body surface using noninvasive detection devices.[1−4] ECG and MCG signals have similar shapes in the normal sinus rhythm (see Fig. 1). They are mainly P-wave (atrial depolarization), QRS complex (ventricular depolarization) and T-wave (ventricular repolarization); the S–T wave segment reflects the repolarization status of myocardial cells. Transient information contained in the QRS complex is extremely important for identifying changes of the electromagnetic status in the cardiac system, and it can also provide clues about some cardiovascular diseases.[5] It is well known that ECG signals are related to the electrical potentials on the body surface, which are mainly dependent on the electrical strength and consequently only dependent on the conductivity of the volume current close to the body surface. However, MCG signals include more important details of electromagnetic source features of the cardiac system and, in particular, information about the whole current distribution and the high current density in the partial volume, from which one can observe a regionally focused magnetic flux. Moreover, MCG signals are more sensitive to the time-dependence feature and spatial distribution

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differences of the electromagnetic activities of the cardiac system.[6,7] For example, experiments in which physiologic states are simulated in early phase myocardial ischemia have been conducted by ligating the left anterior descending coronary artery in rabbits. The myocardial ischemia derived from left coronary artery stenosis is a symptom of coronary heart diseases such as acute myocardial infarction. The morphological variety of MCG signals of the QRS complex occurs about 30 min[8,9] earlier than that of ECG signals in response to a pathological change, and so this is an invaluable time for clinical diagnosis and treatment. Some chest pain patients with myocardial ischemia can be accurately diagnosed using resting magnetocardiography even when myocardial albumen enzyme detection and 12-lead ECG are normal.[10] According to the report from the 60th World Health Assembly in 2007, about 160 million people suffer from cardio-cerebral vascular diseases in China. Coronary heart disease is one of the leading diseases that threaten the health of human beings. If some of these diseases can be identified and predicted earlier, the possibility of cure will be greater. Researchers hope that MCG, as a basic clinical diagnosis method, can predict heart diseases such as myocardial ischemia earlier than ECG. That is why so much research on the clinical applications of MCGs using HTc rf SQUIDs has been performed in recent years.[11,12]

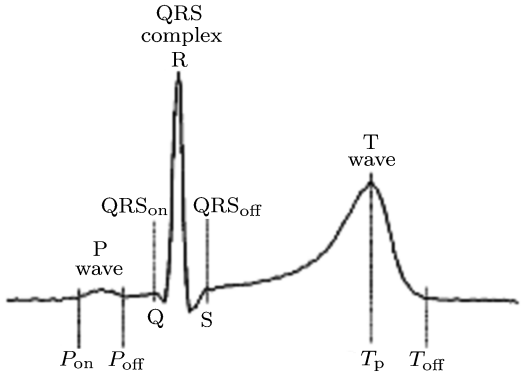


Fig. 1. Elementary waves of heart sinus rhythm and location points of one beat.

A healthy heart is an excitable complex nonlinear dynamical system and is capable of homeostasis.[13,14] Therefore, there is an inherent relation between the variation in the electromagnetic-field state and the homeostasis in the heart system. Like most data generated from life systems, ECG and MCG data are nonstationary signals (NSS). The essential and crucial features of NSS are the local time–frequency characteristics (LTFCH). Theoretically, the frequency spectrum of an NSS is time-dependent in the time–frequency domain (TFD), which means that temporal and spatial average methods, as well as the traditional Fourier transform and the conventional wavelet transform methods, are unsuitable for analysing the LTFCH of those signals.[15] Therefore evolutionary spectrum analysis and the corresponding algorithm are used for detecting time–frequency domain features of NSS.[8,16] In the present study, we analyse the features of the evolutionary spectra from the QRS complex of MCG and ECG signals in healthy subjects, and then obtain their characteristic parameters (CHPs). The CHPs are the quality factor Q and the central frequency f_z, which are biophysical parameters. The confidence intervals for the mean value of the CHPs are estimated based on the Student t distribution method in mathematical statistics. We believe that there are threshold ranges for the mean values of Q and f_z for healthy subjects. The meaning of the threshold range concept is as follows: if the sample mean values of the CHPs are in the proper ranges, the cardiac system is in normal condition and it possesses the capability of homeostasis. In contrast, if the sample mean values of the CHPs do not lie in the proper ranges, the homeostasis of the cardiac system is lacking and some early cardiac diseases may follow. In this study we analysed ECG data from four subjects with heart failure at the time of sudden cardiac death, which are cited from the MIT–BIH (Boston's Beth Israel Hospital) database. The results demonstrate that the threshold range concept is reasonable. The threshold range concept affords a new and promising criterion for ECG clinical diagnosis and a new technological route for the application of MCGs by HTc rf SQUIDs in cardiology.

2. MCG and ECG data acquirement

ECG data are low-frequency electric signals and their frequencies are time-dependent, with a range from 10^{-5} Hz to 0.5 Hz. Both in physiological research and in clinical research, however, most attention has been paid to higher frequencies. MCG data are of weak magnetic signals. The peak intensity of an MCG signal is usually around 50 pT–100 pT, while in an ordinary laboratory or in downtown areas, the low-frequency magnetic noise is about several nT (10^{-9} T), which is about 100 times larger than the human cardiac signal. Moreover, 50-Hz AC and

its harmonics can bring larger noises up to 10^{-8} T or even 10^{-7} T, which is 10^3–10^4 times larger than the human cardiac signal. Therefore, all MCG data are recorded in a magnetically shielded room (MSR). The typical system noise in the high-quality MSR is 2.7 pT/Hz$^{1/2}$ within the white-noise region, the average noise spectral densities are 10 fT/Hz$^{1/2}$ at 1 Hz and 5 fT/Hz$^{1/2}$ at 100 Hz. In addition, changes of ECG data frequency are related to effects from the respiratory system and the nerve system, for example, respiratory-related fluctuations (around 0.20 Hz–0.35 Hz), which may reflect parasympathetic activity; a "10-s rhythm" band (between 0.07 Hz–0.15 Hz), which may reflect sympathetic activity; and the frequencies around 0.04 Hz (between 0.02 Hz–0.07 Hz), which may be of variable origin. Therefore, original MCG and ECG data should be pre-processed with noise-reduction,[6] baseline elimination and 50-Hz elimination before performing evolutionary spectrum analysis. The detailed pre-process procedures are not included in this paper.

The MCG data and the ECG data from healthy subjects used in this study were obtained from the State Key Laboratory for Artificial Microstructure and Mesoscopic Physics, Physics School of Peking University. A high-T_c radio-frequency (RF) cardiac magnetic measurement system (HTc rf SQUIDs) developed by Peking University with proprietary intellectual property rights for China was used. The HTc rf SQUIDs was used to acquire data from healthy subjects within the MSR. MCG signals were recorded from 36 positions over the surface of the chest. Constrained by the SQUID system, ECG data were recorded simultaneously as MCG from a fixed lead II. The measurement 36-position array divides the overchest surface into a–f(Row)×1–6 (Column) positions (see Fig. 2), and the positions are labeled as a–1, a–2, ..., a–6; b–1, b–2, ..., b–6; ...; f–1, f–2, ..., f–6.

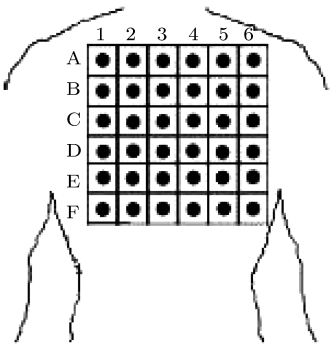


Fig. 2. Measurement 36-position sketch of the chest surface, where black dots denote measurement positions.

This division approach is recommended by the International Biomagnetics Symposium as an international standard for MCG measurement.

3. Evolutionary spectrum and characteristic parameters of MCG and ECG data from healthy subjects

3.1. Brief introduction of the evolutionary spectrum

The evolutionary spectrum is a time-dependent spectrum analysis method in the TFD based on the wavelet transform theory.[17] The original signal is frequency modulated and a Gaussian function is used as a filter because it exhibits both good local field definition in the time domain and smoothness in the frequency domain. When the uncertainty principle in the TFD is satisfied, the three-dimensional (3D) evolutionary spectrum that is the local time–frequency power density distribution of an NSS in the neighbourhood for an instant in time, will be obtained.[18] Detailed evolutionary spectrum analysis methods (ESAM) and corresponding algorithms can be found in Refs. [9] and [16]. The evolutionary spectrum, which contains two parameters of time and frequency, has the same physical interpretation as the conventional spectrum of a stationary process, in that it can describe the distribution characteristics of the power spectrum density of the signals over frequency.[9,16] Therefore, the ESAM is suitable to demonstrate the time–frequency domain features of NSS. Currently, in clinical diagnosis technology, ECG data acquired from clinical and research ECG recorders (including portable Holters), are usually classified by the QRS complex. Accordingly, in this study we use the characteristic parameters of the QRS complex evolutionary spectrum of MCG and ECG data as the basic indicators to detect the electromagnetic behaviours of the cardiac system.

A segment waveform of the QRS complex of MCG data sampled from a healthy subject and the corresponding evolutionary spectra are shown in Fig. 3. Figure 3(b) is the 3D evolutionary spectrum (3DES), which has only one peak,[9] computed from the QRS complex sample data (Fig. 3(a)). The internal relationships among the time, frequency and power density distributions of the QRS complex in a cardiac cycle (a beat) are revealed by Fig. 3(b), which contains

instantaneous electromagnetic information about the cardiac system in the neighbourhood of a time instant corresponding to the R-wave. The projected image of the 3DES in Fig. 3(b) onto the time–frequency (t–f) plane can be seen in Fig. 3(c). We select the frequency/power density spectrum distributions of the half-power points in Fig. 3(b) and it is projected to the t–f plane in Fig. 3(d), which is termed the half-power frequency distribution (HPFD). To further demonstrate the basic features of the QRS complex evolutionary spectrum, we find the frequency f_z of the peak in Fig. 3(b) and call it the central (peak) frequency. The highest frequency ($f_{\rm H}$) and the lowest frequency ($f_{\rm L}$) corresponding to the half-power points in Fig. 3(d) are obtained. The half-power bandwidth is defined as $W_{\rm b} = (f_{\rm H}–f_{\rm L})$. The quality factor of the evolutionary spectrum is defined by

$$Q = f_z/W_{\rm b}, \tag{1}$$

where Q and f_z are the characteristic parameters (CHPs) of the QRS complex evolutionary spectrum in the TFD, which are the biophysical parameters of an MCG or ECG.

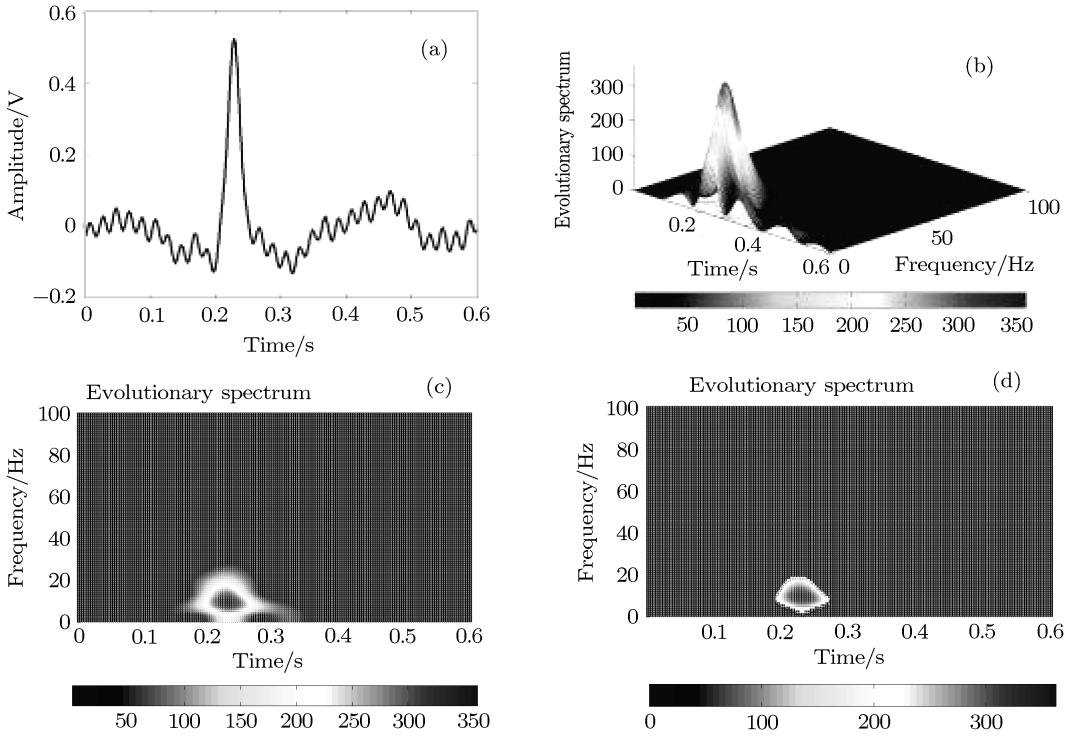


Fig. 3. A segment waveform of QRS complex of MCG data sampled randomly from a healthy subject and the evolutionary spectra. (a) The QRS complex data. (b) The 3DES of QRS complex data. The coordinate time, frequency and power are denoted as t-axis, f-axis and p-axis, respectively. (c) The projected image of 3DES in Fig. 3(b) on the t–f plane. (d) The HPFD of the QRS complex data.

3.2. Characteristic parameters of the QRS complex of MCG and ECG data from the same array position in different healthy subjects

We calculate the characteristic parameters Q and f_z of QRS complex evolutionary spectra of MCG data from the same position e–3 from different healthy subjects, and those of ECG data, which are simultaneously recorded as MCG data but from lead II. The sample mean and the standard deviations of Q and f_z are obtained from the sample data from 19 healthy subjects, each of which samples lasting 36 s for every subject. The results are presented in Table 1, where Q_m and f_{z-m} are the sample mean values of the characteristic parameters (CHPs) for MCG, Q_e and f_{z-e} are those of ECG; σ_m, σ_{z-m}, σ_e and σ_{z-e} are the standard deviations of them respectively; $\Delta Q = (Q_m - Q_e)$ and $\Delta f_z = (f_{z-m} - f_{z-e})$ are defined respectively as the differences in value between the CHPs of MCG (Q_m , f_{z-m}) and ECG (Q_e, f_{z-e}).

By analysing the sample mean values of the CHPs

of the QRS complex evolutionary spectra from the MCG and ECG data for individual healthy subjects in Table 1, we find that their features are as follows. For MCG, the average values (AVRs) of the quality factor Q_m are in a range of 0.6150–0.9284 and the AVRs of Q_m over 19 subjects are in a range of 0.7590±0.099; the AVRs of the central frequency f_{z-m} are in a range of 8.86 Hz–16.80 Hz and the AVRs of f_{z-m} over 19 subjects are in a range of (12.32±2.559) Hz. For ECG, the AVRs of the quality factor Q_e are in a range of 0.5692–0.8128 and the AVRs of Q_e over 19 subjects are in a range of 0.6720±0.067; the AVRs of the central frequency f_{z-e} are in a range of 8.03 Hz–13.96 Hz, and the AVRs of f_{z-e} over 19 subjects are in a range of (10.39±1.652) Hz. As a whole, the sample mean values of the CHPs of ECG data are smaller than those of MCG data from the same subject; for example, the difference between values of the quality factors is $\Delta Q = (Q_m - Q_e)$=0.0078–0.2361 and that between values of the central frequencies is $\Delta f_z = (f_{z-m} - f_{z-e})$=0.78 Hz–6.38 Hz. Moreover, the standard deviation ranges are σ_m=0.0183–0.0931, σ_{z-m}=0.1318 Hz–2.0851 Hz for MCG, and σ_e=1.178×e^{-16}–0.0352, σ_{z-e}=0.0000 Hz–0.3239 Hz for ECG. The standard deviation of σ_m or σ_{z-m} for MCG data is more than that of σ_e or σ_{z-e} for ECG data from the corresponding parameter of the same subject. This means that the sample mean values of the CHPs of QRS complexes of MCG data are more sensitive to change in the electromagnetic field states of the cardiac system than those of ECG data, and it indicates that the electromagnetic field in the human myocardial tissue is time-dependent.[7]

Table 1. Sample mean values and standard deviations of Q and f_z of QRS complex of MCG and ECG data from 19 healthy subjects.

healthy subjects	MCG/e–3				ECG				parameter difference	
	Q_m	σ_m	f_{z-m}/Hz	σ_{z-m}	Q_e	σ_e	f_{z-e}/Hz	σ_{z-e}	ΔQ	Δf_z
volunt-1	0.6150	0.0259	8.86	0.2429	0.5897	0.0108	8.03	0.0833	0.0253	0.83
volunt-2	0.6913	0.0183	10.11	0.1318	0.6429	1.178×10^{-16}	9.00	0.0000	0.0484	1.11
volunt-3	0.6417	0.0236	9.75	0.2165	0.6703	0.0171	11.78	0.2635	–0.0286	–2.03
volunt-4	0.6156	0.0216	9.89	0.1816	0.6078	0.0071	9.03	0.0833	0.0078	0.86
volunt-5	0.8410	0.0698	14.69	0.7046	0.6156	0.0101	11.78	0.2329	0.2254	2.91
volunt-6	0.7028	0.0681	11.22	0.6667	0.6327	0.0095	10.00	0.1667	0.0701	1.22
volunt-7	0.7127	0.0239	13.41	0.3239	0.6449	0.0065	10.96	0.1111	0.0678	2.45
volunt-8	0.7615	0.0518	13.22	0.5221	0.7811	0.0144	11.06	0.1667	–0.0196	2.16
volunt-9	0.6591	0.0714	9.93	0.5472	0.7211	0.0256	12.59	0.3239	–0.0620	–2.66
volunt-10	0.6719	0.0516	9.22	0.4409	0.7548	0.0178	13.96	0.1111	–0.0829	–4.74
volunt-11	0.8447	0.0631	11.58	0.5449	0.7125	0.0114	9.97	0.0833	0.1322	1.61
volunt-12	0.8872	0.0299	16.80	0.3559	0.7280	0.0099	11.21	0.0929	0.1592	5.59
volunt-13	0.8812	0.0749	16.29	1.2744	0.8128	0.0063	13.01	0.0489	0.0684	3.28
volunt-14	0.8351	0.0843	16.36	0.7796	0.6053	0.0352	9.98	0.2906	0.2298	6.38
volunt-15	0.9284	0.0625	14.04	1.1235	0.6923	1.178×10^{-16}	9.00	0.0000	0.2361	5.04
volunt-16	0.7110	0.0849	9.78	0.6200	0.6923	1.178×10^{-16}	9.00	0.0000	0.0187	0.78
volunt-17	0.8568	0.0735	13.24	0.7505	0.6596	0.0075	9.06	0.0833	0.1972	4.18
volunt-18	0.7919	0.0799	12.33	1.1792	0.6429	1.178×10^{-16}	9.00	0.0000	0.1490	3.33
volunt-19	0.7814	0.0931	13.36	2.0851	0.5692	0.0095	9.00	0.0000	0.2122	4.36
total	0.7590	0.0990	12.32	2.5590	0.6720	0.0670	10.39	1.6520	0.0870	1.93

In Table 1, volunt= volunteer; Q_m, f_{z-m} and Q_e, f_{z-e} are the sample mean values; σ_m, σ_{z-m}, σ_e and σ_{z-e} are standard deviations; $\Delta Q = (Q_m - Q_e)$ and $\Delta f_z = (f_{z-m} - f_{z-e})$ are parameter differences between the CHPs of MCG and ECG.

However, magnetocardiography by means of HTc rf SQUIDs has not yet been a successful diagnostic instrument due to the lack of strong clinical evidence. So far in clinical diagnosis technology, ECG data acquired from clinical and research ECG recorders are usually classified by the QRS complex. Accordingly, in this study we mainly use the CHPs of the QRS complex of ECG data as basic indicators to detect the electromagnetic behaviour for the cardiac system.

3.3. Confidence intervals of the characteristic parameters and the threshold ranges

In this subsection, the confidence intervals for the mean values of the CHPs are estimated based on the Student t distribution method in mathematical statistics. Suppose the probability $p = \alpha$, the $\beta = 1 - \alpha$ confidence interval for parameter A is defined as $(A_L < A < A_h) = (A_L, A_h)$, where A_L is the lower cutoff value and A_h is the upper cutoff value. If the standard deviation of parameter A is σ, then the measurable value range of A (MVRs/A) is defined by $(A_h - \sigma,\ A_L + \sigma)$ or $(A_L + \sigma,\ A_h - \sigma)$. Take $p = 0.05$ (the level of significance), the 95% confidence intervals for the sample mean values of the CHPs of MCG and ECG data from the 19 healthy subjects are obtained and the results are presented in Table 2. We can ascertain the features of the mean values of CHPs for the 19 healthy subjects from the results in Table 2.

For MCG, the confidence intervals (CIRs/Q_m) of the quality factor Q_m range from (0.594, 0.636) (No. 1) to (0.877, 0.979) (No. 15) and the standard deviations of Q_m are in a range of 0.0250 (No. 1)–0.0625 (No. 15), their MVRs/Q_m values range from (0.611, 0.619) to (0.916, 0.939), where the lower cutoff value range is (0.611, 0.916)≈(0.60, 0.90) and the upper cutoff value range is (0.619, 0.939)≈(0.60, 0.90). The confidence intervals (CIRs/f_{z-m}) of the central frequency f_{z-m} range from (8.608, 9.004) (No. 1) Hz to (16.509, 17.090) (No. 12) Hz and the standard deviations of f_{z-m} are in a range of 0.2429 (No. 1) Hz–0.3559 (No. 12) Hz; their MVRs/f_{z-m} values range from (8.761, 8.850) Hz to (16.734, 16.864) Hz, where the lower cutoff value range is (8.761, 16.734) Hz≈(9.00, 17.00) Hz and the upper cutoff value range is (8.850, 16.864) Hz≈(9.00, 17.00) Hz.

Table 2. Sample mean values and 95% confidence intervals of Q and f_z of QRS complex of MCG and ECG data from the 19 healthy subjects.

healthy	MCG/e–3				ECG			
subjects	Q_m	CI/Q_m	f_{z-m}/Hz	CI/f_{z-m}	Q_e	CI/Q_e	f_{z-e}/Hz	CI/f_{z-e}
No. 1	0.6150	(0.5940, 0.6361)	8.86	(8.6075, 9.0036)	0.5897	(0.5808, 0.5985)	8.03	(7.9598, 8.0957)
No. 2	0.6913	(0.6764, 0.7062)	10.11	(10.0037, 10.2185)	0.6429	(0.6429, 0.6429)	9.00	(9.0000, 9.0000)
No. 3	0.6417	(0.6224, 0.6609)	9.75	(9.5735, 9.9265)	0.6703	(0.6563, 0.6843)	11.78	(11.5629, 11.9926)
No. 4	0.6156	(0.5980, 0.6332)	9.89	(9.7408, 10.0369)	0.6078	(0.6020, 0.6136)	9.03	(8.9598, 9.0957)
No. 5	0.8410	(0.7841, 0.8979)	14.69	(14.1199, 15.2689)	0.6156	(0.6073, 0.6238)	11.78	(11.5886, 11.9669)
No. 6	0.7028	(0.6472, 0.7583)	11.22	(10.6787, 11.7657)	0.6327	(0.6250, 0.6404)	10.00	(9.8641, 10.1359)
No. 7	0.7127	(0.6932, 0.7322)	13.41	(13.1433, 13.6715)	0.6449	(0.6396, 0.6502)	10.96	(10.8724, 11.0535)
No. 8	0.7615	(0.7192, 0.8037)	13.22	(12.7966, 13.6478)	0.7811	(0.7694, 0.7928)	11.06	(10.9197, 11.1914)
No. 9	0.6591	(0.6009, 0.7174)	9.93	(9.4798, 10.3720)	0.7211	(0.7007, 0.7419)	12.59	(12.3285, 12.8567)
No. 10	0.6719	(0.6298, 0.7140)	9.22	(8.8627, 9.5817)	0.7548	(0.7403, 0.7694)	13.96	(13.8724, 14.0535)
No. 11	0.8447	(0.7933, 0.8961)	11.58	(11.1391, 12.0276)	0.7125	(0.7032, 0.7218)	9.97	(9.9043, 10.0402)
No. 12	0.8872	(0.8628, 0.9116)	16.80	(16.5098, 17.0902)	0.7280	(0.7199, 0.7362)	11.21	(11.1390, 11.2906)
No. 13	0.8812	(0.8201, 0.9423)	16.29	(15.2527, 17.3307)	0.8128	(0.8076, 0.8179)	13.01	(12.9671, 13.0468)
No. 14	0.8351	(0.7663, 0.9038)	16.36	(15.7199, 16.9912)	0.6053	(0.5766, 0.6340)	9.98	(9.7409, 10.2147)
No. 15	0.9284	(0.8774, 0.9794)	14.04	(13.1210, 14.9531)	0.6923	(0.6923, 0.6923)	9.00	(9.0000, 9.0000)
No. 16	0.7110	(0.6418, 0.7802)	9.78	(9.2723, 10.2833)	0.6923	(0.6923, 0.6923)	9.00	(9.0000, 9.0000)
No. 17	0.8568	(0.7969, 0.9167)	13.24	(12.6288, 13.8526)	0.6596	(0.6535, 0.6658)	9.06	(8.9876, 9.1235)
No. 18	0.7919	(0.7267, 0.8571)	12.33	(11.3719, 13.2948)	0.6429	(0.6429, 0.6429)	9.00	(9.0000, 9.0000)
No. 19	0.7814	(0.7055, 0.8573)	13.36	(11.6556, 15.0555)	0.5692	(0.5614, 0.5769)	9.00	(9.0000, 9.0000)
total	0.7590	(0.5520, 0.9670)	12.32	(6.9400, 17.6940)	0.6720	(0.5330, 0.8120)	10.39	(6.9190, 13.8620)

In Table 2, No. n=volunteer number n, $n = 1, 2, \ldots, 19$; Q_m, f_{z-m}, Q_e and f_{z-e} are the sample mean values; CI: the confidence interval.

Similarly, for ECG, the CIRs/Q_e values of the quality factor Q_e range from (0.577, 0.634) (No. 14) to (0.808, 0.818) (No. 13) and the standard deviations of Q_e are in a range of 0.0095 (No. 14)–0.0063 (No. 13), their MVRs/Q_e values range from (0.586, 0.624) to (0.811, 0.814), where the lower cutoff value is in a range of (0.586, 0.811)≈(0.60, 0.80) and the upper cutoff value is in a range of

(0.624, 0.814)≈(0.60, 0.80). The CIRs/f_{z-e} values of the central frequency f_{z-e} range from (7.960, 8.096) (No. 1) Hz to (13.872, 14.053) (No. 10) Hz and the standard deviations of f_{z-e} are in a range of 0.0833 (No. 1) Hz–0.1111 (No. 10) Hz, their MVRs/f_{z-e} values range from (8.012, 8.043) Hz to (13.941, 13.983) Hz, where the lower cutoff value is in a range of (8.012, 13.941) Hz≈(8.00, 14.00) Hz; and the upper cutoff value is in a range of (8.043, 13.983) Hz≈(8.00, 14.00) Hz.

From the above results, we believe that there are threshold ranges of the CHP Q and f_z of QRS complex evolutionary spectra of MCG and ECG data from healthy subjects. The threshold ranges of the CHPs should be $Q_m = (0.60, 0.90)$, $f_{z-m} = (9.00, 17.00)$ Hz for MCG; and $Q_e = (0.60, 0.80)$, $f_{z-e} = (8.00, 14.00)$ Hz for ECG, respectively. The meaning of the threshold range concept is as follows, if the sample mean values of the CHPs lie outside the threshold ranges, then the data indicates morbidity.

4. Characteristic parameters of ECG data in time of sudden cardiac death

Sudden cardiac death provides extreme examples of how the electromagnetic behaviour of the heart system can vary in a short time.[19] In order to analyse the changing process and the features of the CHPs of ECG data through the last stages in sudden cardiac death, we select a part of the ECG data of patient No. 52 (female, 82 years old) from the Sudden Cardiac Death Holter Database in the MIT-BIH database. The trace-exchanging survey of ECG signals recorded from patient No. 52 with heart failure just before her death is shown in Fig. 4, and it shows a variety of different rhythms. The data were recorded from the chan-1 lead, start time at 12:00, duration 7 h and 15 min. At 15:42:49, the rhythm consisted of beats originating from the normal sinus node pacemaker (N), with two isolated premature ventricular ectopic beats arising from an abnormal site in the ventricles (V). The trace at 16:05:55 showed an alternation of normal sinus beats with ventricular ectopic beats and three sequences of three consecutive ventricular ectopic beats, non-sustained ventricular tachycardia (NSVT). At 19:13:53, the record was initially similar to the record at 16:05:55, but there was a more prolonged non-sustained ventricular tachycardia (NSVT), followed by a sinus beat, and then a sustained ventricular tachycardia (VT) that led to sudden death. This is a nonreversible process. The sample mean values of Q and f_z of ECG data at different time intervals are presented in Fig. 5, where time intervals each with 1 min long and 15 min apart were used.

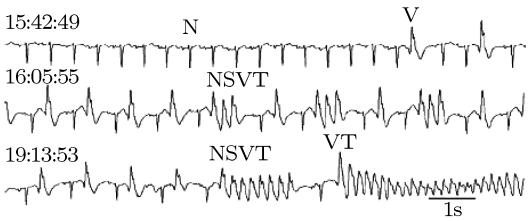


Fig. 4. Trace exchanging survey of ECG signals recorded from a patient with heart failure at the time before death and it includes a variety of different rhythms measured from the continuous electrocardiogram using a portable monitor (Holter tape).

It is demonstrated from Fig. 5 that 100% of the sample mean value of f_z is less than 8.00 Hz, which reflects the trend of pathological changes in the cardiac system. However, the sample mean value of Q_e shows fluctuations: two values of Q_e are more than 1.00, and 80.65% of the sample mean value of Q_e are less than 0.60, and so these indicate the attenuation of the homeostasis capability in the cardiac system. Similarly, patients No. 34 (male, 34 years old), No. 44 (male, age unknown) and No. 46 (female, age unknown) also suffered from heart failure and sudden cardiac death. ECG data of all the four subjects have been obtained from the MIT–BIH database. Segments of the four subjects' ECG data containing 40–50 heartbeats, during the time when the beats originated from the normal sinus node pacemaker, (as in the first trace in Fig. 4), were captured randomly, and the measurable value ranges (MVRs) of the 95% confidence intervals for the sample mean values of the CHPs of the QRS complexes of these data were estimated. The results are presented in Table 3. The major feature of these results is that all of the upper cutoff values of the MVRs have $Q_e < 0.60$ and $f_{z-e} < 8.00$ Hz. All of the results in Fig. 5 and Table 3 demonstrate that the threshold range concept of characteristic parameters of ECG data may be valid.

Table 3. Sample mean values and the measurable value ranges of the 95% confidence intervals for Q and f_z of QRS complex of ECG data from the 4 subjects with heart failure.

subjects	Q_e	σ_e	MVRs/Q_e	f_{z-e}/Hz	σ_{z-e}	MVRs/f_{z-e}
No. 34	0.4501	0.0658	(0.4380, 0.4622)	4.2444	0.3127	(4.1867, 4.3022)
No. 44	0.4062	0.0492	(0.3971, 0.4153)	3.5111	0.2028	(3.4736, 3.5486)
No. 46	0.4878	0.0639	(0.4761, 0.4996)	4.7111	0.7491	(4.5727, 4.8495)
No. 52	0.4779	0.0463	(0.4693, 0.4865)	5.5111	0.4807	(5.4223, 5.5999)

In Table 3, Q_e and f_{z-e} are the sample mean values; σ_e and σ_{z-e} are the standard deviations; and MVRs: the measurable value ranges.

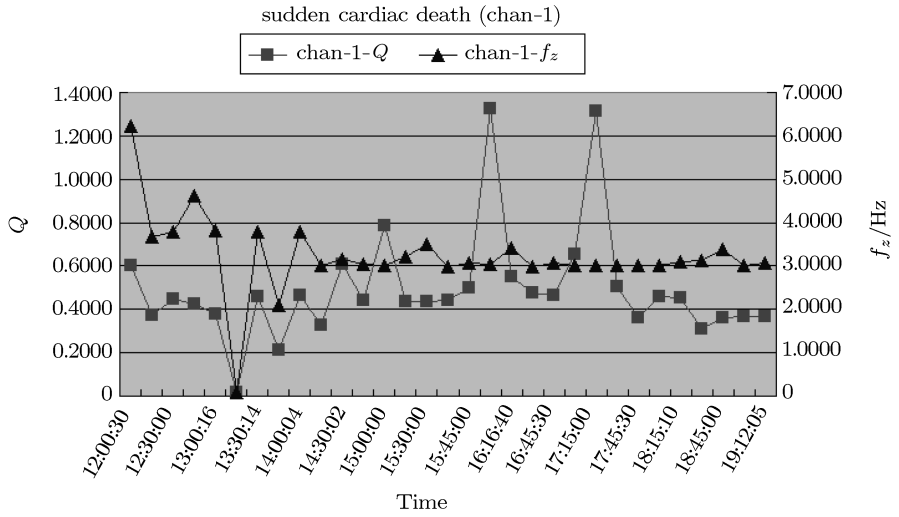


Fig. 5. Sample mean values of Q and f_z of ECG data at different time intervals of chan-1 lead of patient No. 52.

5. Conclusion

A healthy heart is an excitable complex nonlinear dynamical system. The electromagnetic field of the human heart system is a bioelectromagnetic field and is a basic biophysics property of the living matter. Both electrocardiography (ECG) and magnetocardiography (MCG) are carriers of electromagnetic information about the cardiac system. Both ECG and MCG data are of nonstationary signals (NSS). The local time–frequency domain characteristics of the NSS can be depicted by the evolutionary spectrum analysis method. The features of QRS complex evolutionary spectra of MCG and ECG data from healthy subjects are analysed in this study, and the results demonstrate that the quality factor Q and the central frequency f_z are characteristic parameters (CHPs) of MCG and ECG data in the time–frequency domain.

The present study proposes that, in cardiac dynamics, the characteristic parameters Q and f_z of QRS complex evolutionary spectra of MCG and ECG data from healthy subjects have the threshold ranges in the time–frequency domain. When the sample mean values of the CHPs are within the threshold ranges, the cardiac system is probably in a healthy condition and it can maintain homeostasis. In contrast, when the sample mean values of the CHPs are outside the threshold ranges, the data indicate morbidity and the cardiac system is probably unable to maintain homeostasis; serious myocardial ischemia or other early heart diseases are likely to ensue. The confidence intervals for the mean values of the CHPs of the healthy subjects are estimated by the Student t distribution method. For healthy subjects, the threshold ranges of the CHPs are $Q_m = (0.60, 0.90)$, $f_{z-m} = (9.00, 17.00)$ Hz for MCG; and $Q_e = (0.60, 0.80)$, $f_{z-e} = (8.00, 14.00)$ Hz for ECG. If the lower values of the CHPs are $Q_{m,L} < 0.60$, $f_{z-m,L} < 9.00$ Hz and $Q_{e,L} < 0.60$, $f_{z-e,L} < 8.00$ Hz; or the upper values of CHPs are $Q_{m,h} > 1.00$, $f_{z-m,h} > 18.00$ Hz and $Q_{e,h} > 0.90$, $f_{z-e,h} > 15.00$ Hz, then all of these data

are probably of the morbidity status. For example, the sample mean values of the CHPs of ECG data from all the four subjects with heart failure were outside the threshold ranges.

The threshold range concept affords a promising criterion for detecting the normal or abnormal status of the electromagnetic fields of the cardiac system, and provides a technological route for the application of MCG by HTc rf SQUIDs in cardiology. Of course, this is an empirical conclusion from experiment results, whose physiological meaning is not clear. The reliability of the threshold ranges proposed above should be further verified or modified using the evolutionary spectrum method to analyse more experimental and clinical data, especially a large number of clinical MCG and ECG data. Only when doctors' clinical experience is combined with the threshold range concept may some technical parameters helpful for clinical medicine be achieved.

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References

[1] Holter N J 1961 *Science* **134** 1214
[2] Baule G M and McFee R 1963 *Am. Heart J.* **66** 95
[3] Cohen D, Edelsack E A and Zimmerman J E 1970 *Appl. Phys. Lett.* **16** 278
[4] Sternickel K and Braginski A I 2006 *Supercond. Sci. Technol.* **19** S160
[5] Li Y J, Yan H, Wang Z L and Yang X L 2009 *Sci. Chin.* Ser. C **39** 1181
[6] Liu X Y, Xie B Q, Dai Y D, Wang F R, Li Z Z, Ma P, Xie F X, Yang T and Nie R J 2005 *Acta Phys. Sin.* **54** 1937 (in Chinese)
[7] Kosch O, Meindl P, Steinhoff U and Trahms L 2000 *The 12th International Conference on Biomagnetism*, Biomag 2000, Helsinki, Finland, August 13–17, 2000
[8] Gao J, Yang T, Ma P and Dai Y D 2010 *Chin. Phys.* B **19** 067402
[9] Liu X Y, He D W, Pei L Q and Zhang S M 2009 *Progress in Natural Science* **19** 1317
[10] Tolstrup K, Riuz J A, Greenwood S and Flores S 2004 *Circulation* **110** PIII-743
[11] Park J W, Hill P M, Chung N, Hugenholtz P G and Jung F 2005 *Ann. Noninv. Electrocardiol.* **10** 312
[12] Goernig M, Liehr M, Tute C, Schlosser M, Haueisen J, Figulla H R and Leder U 2009 *Int. J. Bioelectromagnetism* **11** 107
[13] Pei L Q, Dai X L and Li B D 1998 *Sci. Chin.* Ser. E **28** 83
[14] Ivanov P Ch, Amaral L A N, Goldberger A L, Havlin S, Rosenblum M G, Struzik Z R and Stanley H E 1999 *Nature* **399** 631
[15] Pola A, Macerata A and Emdin M 1996 *IEEE Trans. Biomed. Eng.* **43** 46
[16] Priestley M B 1996 *Time Series Analysis* **17** 85
[17] Daubbechies I 1992 *Ten Lectures on Wavelets* (Philadelphia Society for Industrial and Applied Mathematics)
[18] Liu X Y, Pei L Q, Zhang S M, Wang Y and Dai Y D 2010 *Chin. Sci. Bull.* **55** doi: 10.1007/s11434-010-4066-7
[19] Glass L 2005 *PNAS* **102** 10409