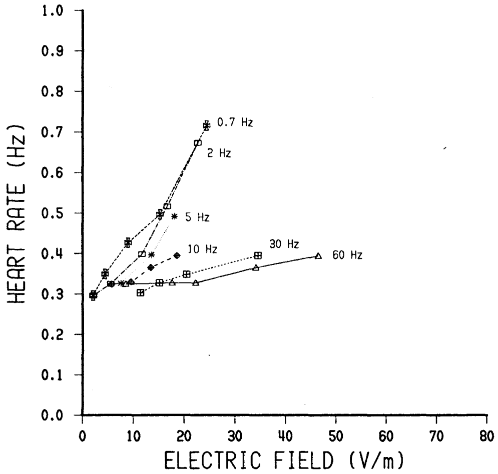

Fig. 2. Effects of ELF electric fields on the beating rate of a typical frog heart. Example 2.

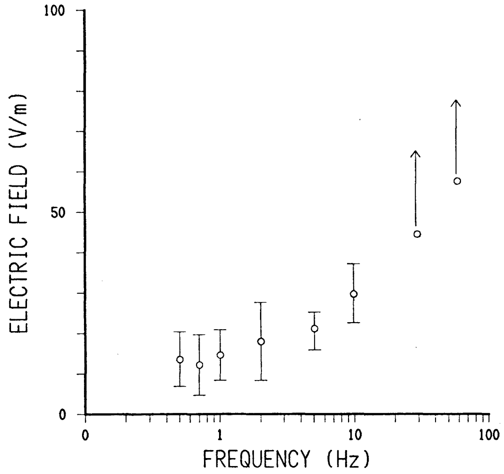

Fig. 3. Frequency dependence of the effect of ELF electric fields on the beating rate of isolated frog hearts. The electric field which causes a 30 percent increase in the rate is plotted as a function of frequency. Vertical bars show the standard deviations of the mean field values from ten different frog hearts. For 30 and 60 Hz, most of the hearts responded by less than a 30 percent change in rate even at the highest test fields used. The bases of the arrows in the figures indicate the mean fields of those hearts which gave the criterion response.

lustrated in Fig. 2, more than half of the heart preparations failed to respond at any field level for frequencies of 30 Hz and above. This phenomenon is indicated in Fig. 3 by arrows originating at the mean threshold for that fraction of the hearts which were affected in their firing rates by the applied fields.

The response depends, to some degree, upon the orientation of the heart relative to the direction of the electric field. However, the frequency dependence of the response at all angles is qualitatively the same as shown in Figs. 1-3 and thresholds are in the range of 20-30 V/m.

DISCUSSION

In a qualitative sense, the response of the frog heart pacemaker to electric fields is similar to *Aplysia* ganglion cells. Fields cause changes in the rate of beating and the frequencies which are most effective are those near the spontaneous rate of the pacemaker. Quantitatively, the two effects are dramatically different. The threshold effects on the heart, about 20-30 V/m, are two orders of magnitude greater than the 60 Hz threshold and approximately three orders of magnitude greater than the 1 Hz threshold for the *Aplysia* pacemaker neurons.

Frog heart pacemaker cell thresholds are comparable to those required to fire resting peripheral nerves, and, in fact, close to levels which in the mammal would cause ventricular fibrillation. The frequency dependence of the processes is qualitatively different, however. Localized fields of the order of 100 V/m are used for direct stimulation of heart muscle in artificial pacing. Thus, we cannot rule out direct stimulation of muscle cells as a factor in the observed response of the intact hearts, particularly at high frequencies.

From the magnitudes of the threshold fields, it is clear that this study gives no support to the hypothesis that pacemaker cells of the heart could be a site of action for electric fields induced in the body by exposure to transmission line fields.

ACKNOWLEDGMENT

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Spectrum Analysis of Human Pulse

CHUN T. LEE AND LING Y. WEI

Abstract—**Pulse spectral graphs (PSG) were obtained from pulses taken on the wrist by using electronics and computers. Energy ratio (ER) is defined as the ratio of the energy of PSG below 10 Hz to that above 10 Hz. We find that the ER for healthy persons is above 100 at all three-finger positions on both wrists, but those for sick persons are**

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below 100 at some specific positions of pulse-taking. The specific positions giving low ER values are related to the troubled organs, as would be expected from Chinese medicine. Potential application of this novel method in the health field is indicated.

INTRODUCTION

At the turn of the third century, a Chinese medical scholar by the name of Wang Su Ho wrote the "Classic on Pulse." Since then pulse diagnosis has become a "must" skill in Chinese medicine. According to Wang and later workers, pulse can be taken at three close points called Tsun, Guan, and Chy, along the radical artery on the wrist, as shown in Fig. 1. By applying light and deep pressures, a physician is supposed to be able to detect at his finger tips the health conditions of the internal organs of the patient (see Fig. 1). In Chinese medical books, it is said that there are 29 variations of pulse patterns, each having a specific name. Without at least five years experience, no one could be expected to master the pulse diagnostic skills.

From the Westerner's view, the Chinese sphygmology seems to be inconceivable. However, the phenomena of the pulse are not as simple as people might think. The pulse, although driven by the heart, is transmitted by blood flow through arteries and goes a long way from the heart. Thus, it is affected not only by the condition of the heart, but also by the conditions of nerves, muscles, skin, arterial walls, blood parameters (volume, contents, viscosity, pressure, and velocity), etc. In fact, almost all body functions and activities interact with and are controlled by the autonomic nervous system (ANS). The actions of the ANS (say, slowing heartbeat, dilating blood vessel, juicing stomach, etc.) will find some way to manifest in the pulse. Hence, the pulse is better viewed as the music of the body symphony. This body music is not a monotone (say, 72 times per minute), but is rich in harmonics. It is the intensities and the frequency components in the harmonics of the pulse that should contain most, if not all, of the information on the body health. A scientific way of studying the pulse, then, should be to analyze its frequency spectrum and to correlate the spectral features with health conditions. This is likened to the modern approach used in physical chemistry. When one is to find the structure and function of an unknown macromolecule, he would put it through a series of spectroscopes (UV, infrared, visible light, Raman). The objective and the methodology of our study in human pulse follow exactly the same line. This is a serious attempt to test Chinese medical theory by Western science. In this paper, we shall present the results.

MEASUREMENTS AND COMPUTATIONS

Pulses were taken from healthy persons and from patients with known diseases (hepatitis, cardiac disease, and gastrointestinal troubles) at the Tri-Service Hospital in Taipei, Taiwan. A condenser microphone (Bruel & Kjar 4147) was used as a transducer to convert pulse on the wrist into electrical signals. The microphone ($\frac{1}{2}$ in diam) is highly sensitive and has rather flat frequency response in the range of 0.1-20 000 Hz. It was tightly sleeved into a Teflon tubing, whose opening was about 5 mm from the diaphragm of the microphone. The sleeve opening was put in direct contact with the skin of the wrist at the specific position. The pulse in the artery was transmitted through the tiny enclosed air space onto the diaphragm of the microphone and emerged as electrical signals therefrom. The analog waveforms were then digitized and stored in an audio tape.

The audio tapes were brought to the Computer Center at Chiao-Tung University (Hsinchu, Taiwan) for data processing. What the computer did was to convert digital signals into power spectrum, and plot pulse spectral graphs (PSG). The technique we used to write the program is the fast Fourier transform [1], [2] (FFT). Actually, we modified the program PMPSE [3] and named it BIOSPE, which allows two input sequences at one time to estimate spectra of different kinds simultaneously. The program BIOSPE has been tested by a test formula [3] and it gave the right result. We should say that our computer program is only one of several forms that could perform the same task and, hence, is neither unique nor necessarily the best.

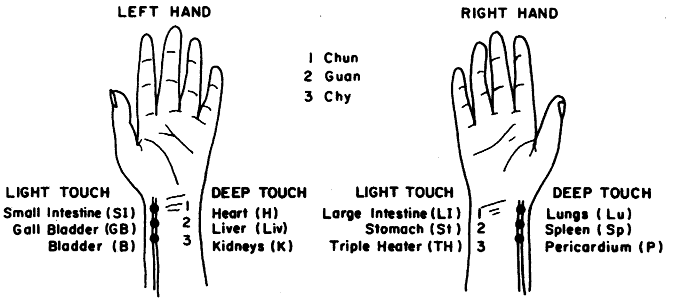

Fig. 1. Positions for pulse diagnosis used in traditional Chinese medicine. The relations of the positions with the organs are based on the "Classic on Pulse" written by Wang Su Ho (265-317 A.D.).

RESULT OF SPECTRUM ANALYSIS

Pulse signals were processed with a PDP-11 minicomputer that produced pulse spectral graphs (PSG). Because very small energy is contained above 50 Hz of PSG, we simply ignored that range. Information below 1 Hz can be discarded because of some uncontrollable movements of the patient's arm, giving rise to signals that often contain large nonperiodic components below 1 Hz. Such nonstationary effects can contaminate the signal spectrum interested above 1 Hz.

In the procedure of analysis, we divide each spectrum (1-50 Hz) into five bands: band 1 (1-10 Hz) and bands 2-5, each 10 Hz wide. For each band we calculate the mean value of spectral density and define the energy ratio (ER) by

$$\begin{aligned}\mathrm{ER} &= E_1/(E_2 + E_3 + E_4 + E_5)\\ &= E\text{ (below 10 Hz)}/E\text{ (above 10 Hz)}\end{aligned}$$

where E_i is either the spectrum band mean or the total energy in the ith band. Our results are expressed in two ways: ER values and PSG.

A. ER Values

In taking pulse, we pressed the transducer against the skin of the wrist at Tsun and Guan positions, first lightly and then heavily. Thus, from both wrists we obtained eight recordings of pulse for each person under test. We did not take pulse from the Chy positions (see Fig. 1) for two reasons: 1) we did not want a patient to become impatient in long recording, and 2) for the three kinds of patients (with acute hepatitis, cardiac disease, and gastrointestinal troubles), the pulse taken from the Chy position might not be very useful for comparison.

We tested four groups of people: 1) normal persons with no illness (N); 2) patients with acute hepatitis (AH); 3) patients with cardiac disease (C); and 4) patients with gastrointestinal troubles (G). The ER values of the pulses taken from eight positions (left and right, Tsun and Guan, light and deep) are shown in Table I. The names of the eight positions are referred to those given in Fig. 1. Let us first look at the ER values for ten normal persons (N-1-N-10). Among the 80 values, none is less than 100. This indicates that in healthy persons more than 99 percent of pulse energy is concentrated below 10 Hz. Let us then take a glance at the ER values for the 11 patients. We see that there are many values well below

TABLE I
"ENGERGY RATIO" VALUES OF PULSES TAKEN FROM TEN NORMAL PERSONS (N) AND FROM ELEVEN PATIENTS WITH ACUTE HEPATITIS (AH), CARDIAC DISEASE (C), AND GASTROINTESTINAL TROUBLES (G). THE TOP ROW INDICATES THE EIGHT PULSE-TAKING POSITIONS AS SPECIFIED IN FIG. 1.

	H	Lu	Liv	GB	Sp	St	SI	LI
N - 1	279	459	3024	1681	398	230	1113	1610
N - 2	312	202	526	468	316	154	120	363
N - 3	240	773	2074	3309	697	455	705	735
N - 4	1493	1916	1411	752	1874	791	907	1028
N - 5	526	1621	196	712	197	3227	777	1380
N - 6	860	505	196	516	551	390	469	785
N - 7	3446	3100	236	275	233	173	1440	1248
N - 8	201	689	887	521	621	248	560	1475
N - 9	436	1649	1414	714	197	128	130	714
N - 10	1670	3123	1087	855	3007	2621	837	1533
AH - 1	1180	1910	7	460	195	147	1430	1483
AH - 2	214	213	58	30	3505	1086	684	200
AH - 3	1073	190	24	46	154	165	1589	459
C - 1	81	121	121	33	6	53	69	33
C - 2	23	26	19	6	17	6	7	12
C - 3	68	700	55	24	572	544	77	517
G - 1	697	1388	402	144	55	24	67	94
G - 2	32	29	101	62	12	9	16	85
G - 3	962	1318	621	44	6	96	1041	101
G - 4	150	589	45	24	139	43	57	621
G - 5	45	17	21	15	13	16	57	16

100. This is our most important finding. The ER values could be used to quantify a health condition: healthy if ER is above 100 and unhealthy if ER is below 100. Next, let us examine the ER values for each class of patients. For patients with acute hepatitis (AH-1–AH-3), the ER values under the Liv column are all less than 100; for patients with cardiac disease (C-1–C-3), the ER values under the H column are all below 100; and for patients with gastrointestinal troubles (G-1–G-5), the ER values under the St column are all below 100. This indicates that the pulse-taking positions are indeed related to internal organs, as specified in the "Classic on Pulse." Although these relationships cannot be understood from present physiology, we should not easily ignore our finding, which agrees with the facts (the patient's disease) and with medical experience in China for more than 1600 years. This will be a good subject in science for future study.

Table I also shows that for patients with gastrointestinal troubles, the ER values are low under GB, Sp, and SI positions besides St. This is quite understandable because the gall bladder, the spleen, and the small intestine are all related or connected to the stomach. Here again our finding strengthens further the concept of definite relationships between the organs and the pulse-taking positions on the wrist.

B. PSG

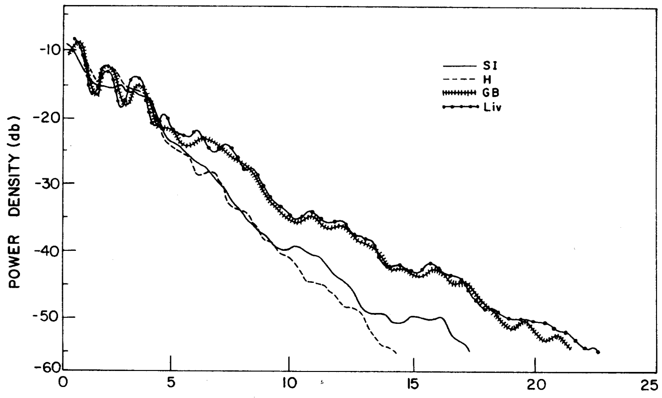

Fig. 2. Pulse spectral graphs (PSG) for the pulses taken from the left wrist of a healthy person, a typical case. The curves are labeled according to the positions where the pulse was taken.

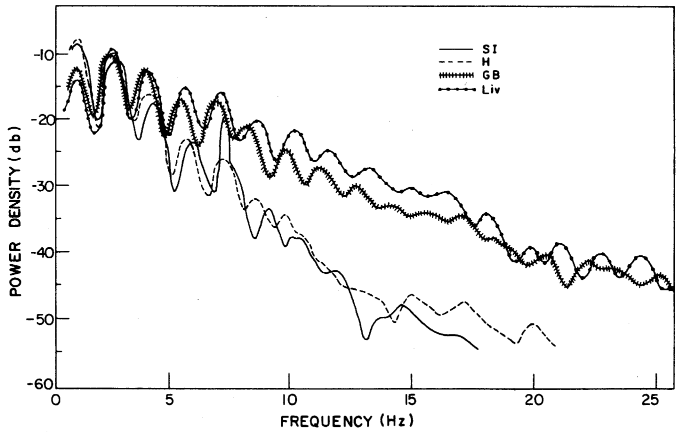

Fig. 3. PSG for the pulses taken from the left wrist of a representative patient with acute hepatitis.

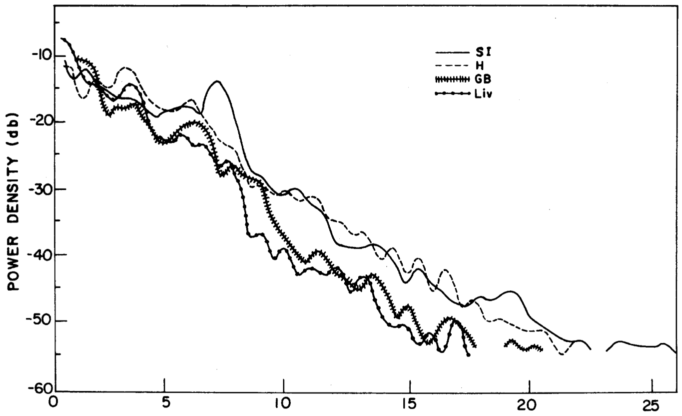

Fig. 4. PSG for the pulses taken from the left wrist of a representative patient with cardiac disease.

Fig. 2 shows the PSG of a typical normal case. There are three salient features of the curves in Fig. 2. 1) The curves are smooth in the range over five cycles (from -5 dB to -55 dB). (Note: Every 10 dB change is equal to a change by ten times.) 2) At 10 Hz, the power drops by 30 dB or more (or to 10^{-3} or less). 3) The curves are very close to one another. The last feature indicates that the pulses taken from all positions are almost "indistinguishable" for a healthy person (that is also true for pulse taken on the right wrist, which is not shown here). This is what should be expected and is the prevailing view of everybody, be it layman or physician. That this is indeed substantiated by our analysis serves as a good indication for the correctness of our methodology.

Fig. 3 shows the PSG of a representative patient with acute hepatitis. Compared with Fig. 2, we see in Fig. 3 that: 1) the curves have many pronounced peaks and valleys; 2) the curves for pulses taken from the Liv and GB positions are much higher than those taken from H and SI in the higher frequency range (above 10 Hz), meaning very low ER values for the former.

Fig. 4 shows the spectra of a typical cardiac patient. The

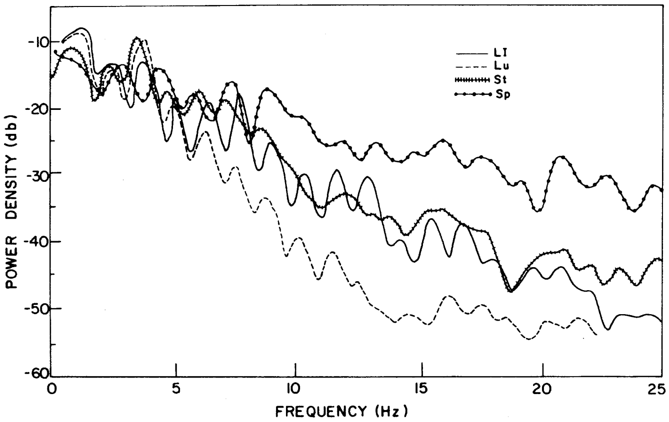

Fig. 5. PSG for the pulses taken from the right wrist of a representative patient with gastrointestinal troubles.

main difference between this figure and Figs. 2 and 3 is that here the H and SI curves sit atop Gb-Liv curves, while the reverse is true in the two previous figures. That the H-curve sits high means a low ER value for the pulse taken from the H-position of the left wrist. This indicates cardiac disease. In all other patients, the H-curves are always found to be lying low in the PSG.

In the spectra beyond 25 Hz (not shown here) there are pronounced peaks around 32 Hz found in all the cardiac patients we tested, but not seen for patients of other diseases. This effect requires further study.

Fig. 5 shows the spectra of a typical patient with gastrointestinal trouble. A special feature in this figure is that the St-LI curves follow closely. Since St and LI positions (see Fig. 1) do not fall on the same location in the right wrist, the pulse spectra from these positions usually do not go together, as evidenced from the patients with other disease. Here, in this patient with gastrointestinal trouble, the St-LI curves are threading through each other. The fact was that the patient's trouble did lie in the stomach and intestines. Here we have further evidence indicating the relation between the organs and the pulse-taking positions.

Based on the PSG's in Figs. 2-5, we find that a disease is indicated in a specific organ by two facts: 1) spectral curve sitting high in frequencies above 10 Hz (meaning low ER) and 2) large variations over the curve. The diseased organ is then inferred from the pulse-taking positions that yield the above facts.

Actually, there is much more information contained in PSG than we have described so far. This would require many years of careful study of vast data before its full potential can be realized.

DISCUSSION

In this paper, we have shown that human pulse is not as simple as it is felt at one's fingertips, contrary to the current medical practice. We employ PSG as a scientific method to extract information from the pulse and introduce a new concept of "energy ratio" (ER) for the ease of diagnosis. Here we shall elaborate on the meaning and usefulness of the ER.

In the analysis of frequency spectrum of any complex wave, we used to focus our attention on where the energy (or power) is concentrated. Next, we like to see how the energy is distributed. In examining the PSG of all the ten healthy persons, we find that none of them has band 1 (below 10 Hz) energy lower than 99.1 percent (of total energy) from pulse taken at any of eight positions. The mean value is 99.79 percent and the variance is 0.36. For eleven patients, the corresponding values are 85.7 percent (minimum), 97 percent (mean), and 13.4 percent (variance). From our daily experience, 99.1 percent would mean "excellent" and 85.7 percent "very good." If applied to our case, these would cause confusion and misunderstanding because the band 1 energy (below 10 Hz) of the PSG is only a part of the whole story. The higher bands are where we should look for problems. Since the high-band energies are very small in percentage, their figures could be easily ignored as "insignificant." To correct the impression conveyed either by the high percentage of band 1 (below 10 Hz) energy or by the very low percentage of the higher band energy, we introduce the "energy ratio" as the ratio of the above two energies. Then 85.7 percent, 99.1 percent, and 99.79 percent of band 1 energy correspond to ER = 6, 100, and 475, respectively. Here one sees clearly that 6 is a very low number (unlike 85.7 percent) and 100 is not a large number (unlike 99.1 percent). If ER were used as a "health index," 500 would imply "very good health," 100, the *margin* of normal health, and less than 100, poor health. It is in this biomedical sense that the concept of the energy ratio is introduced and that it could serve a useful purpose.

The significance of the PSG, however, cannot be easily grasped by inexperienced personnel. Since it does not present real-time events as ECG does, it may not even appeal to practicing physicians. In our view, PSG can be appreciated best by using computer analysis with a large database of case histories. This viewpoint is derived particularly from the experience obtained in the field of speech recognition. There is every reason to believe that digital processing of human pulse signals will make an important contribution in the biomedical field, just as speech signals [4] have. Our work only took the initial step in this direction.

Although our data are not large enough to draw any firm conclusion, they do indicate a few interesting points. First, they tend to support both the beliefs held in Western medicine and in Chinese medicine. According to the former, there is little reason to expect pulses from adjacent points on the wrist to be felt differently. The PSG's below 5 Hz, as shown in Figs. 2-5, confirm this belief quite well. However, for the patients with pronounced illness, the PSG's above 5 Hz are clearly shown to differ appreciably (Figs. 3-5). Surely, this difference can only be felt by *trained* hands, just as music above 8 kHz can only be appreciated by trained ears. In fact, this is the very basis of pulse diagnosis that has been used by Chinese physicians for centuries.

Second, in physical sciences, the energy concept is very useful and is universally accepted. However, in modern medicine, the term "energy" is rarely used. For example, ill health is usually diagnosed on the basis of organic or functional disorder, but not on the basis of energy deficiency or distribution. Our methodology (PSG and ER) is a step that is moving towards the latter direction. Interestingly, it bridges the gap between the physical sciences and Chinese medicine, whose foundation is mainly laid on the conception of the Chi (energy) [5].

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The work was done during 1980-81 when the second author was on leave at Chiao-Tung University in Taiwan.

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Signal Distortion in the Electrocardiogram Due to Inadequate Phase Response

DAVID TAYLER AND RICHARD VINCENT

***Abstract*—Electrocardiographic monitoring is used for arrhythmia analysis and for the detection of myocardial pathology, especially ischaemia and infarction, when waveform distortion must be minimized if reliable results are to be obtained. ST segment distortion has been noted to occur with ambulatory recorders and some electrocardiographs.**

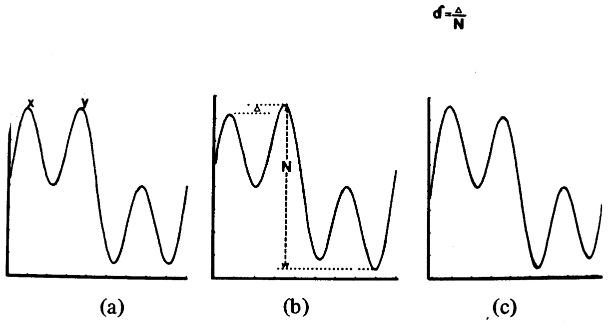
We analyzed the frequency spectrum of ECG waveforms and showed that even when the amplitude response of a recorder is flat down to the fundamental frequency, distortion of the ST segments can occur.

We then measured the phase response of several commercially available ambulatory recorders and electrocardiographs using a waveform sensitive to phase distortion, and demonstrated nonlinearities occurring at frequencies contained within a normal ECG. Correction of these nonlinearities reduced the signal distortion. Conversely, distortion of ECG waveforms could be caused by introducing phase shifts while maintaining a flat amplitude response.

We conclude that a flat amplitude response alone is not sufficient to ensure faithful reproduction of an ECG. Phase response must also be linear down to the fundamental frequency of the ECG waveform. Phase linearity can easily be measured with a phase-sensitive signal, and should be included as a parameter in machine specification.

INTRODUCTION

The electrocardiogram is used for arrhythmia analysis, when the detection of P and QRS waves is important, and to evaluate myocardial disease, especially ischaemia and infarction when ST segments and T waves become prime considerations. Elevation or depression of ST segments frequently indicates myocardial ischaemia and can be measured objectively to assess both its severity and its response to therapy [1]. Thus, it is mandatory that ECG waveforms and ST segments in particular are reproduced without distortion or artefact. False ST segment shifts have been noted to occur with ambulatory recorders currently available, in particular the Medilog 1 direct recording system (Oxford Instrument Company Ltd.) [2], [3], but little analysis has been published as to why this distortion occurs. We have measured the amplitude response of several ambulatory recorders and electrocardiographs and shown this to be satisfactory. The phase response of two machines, however, was markedly nonlinear and these machines produced distortion of ECG waveforms. We could produce similar distortion with an all-pass network having nonlinear phase characteristics, and conversely, could reduce the distortion by correcting the phase responses.



(a) (b) (c)

Fig. 1. A phase sensitive waveform for the measurement of relative phase response. (a) $f(t) = \sin wt + \sin 3wt$, the input waveform. (b) $f(t) = \sin wt + \sin (3w + \theta)$, the third harmonic delayed relative to the fundamental. (c) $f(t) = \sin wt + \sin (3wt - \theta)$, the fundamental delayed relative to the third harmonic. N is the peak-to-peak amplitude of the output waveform, A is the distance between two consecutive peaks of equal polarity, δ is the normalized distance between peaks, i.e., corrected for output amplitude. δ is related to the degree of phase nonlinearity of the system.

METHOD AND RESULTS

The investigation consisted of four sections.

1) Evaluation of the amplitude and phase responses of three commercial ambulatory recorders and three electrocardiographs.

2) Demonstration of the distortion produced by these machines on a simulated ECG and on patients' records.

3) Distortion of an ECG waveform by an all-pass filter.

4) Correction of the distortion produced by the machine with the poorest phase response.

Method and results will be presented for each section in turn.

Measurement of Amplitude and Phase Response in Selected Machines

We investigated three ambulatory monitors, the Medilog 1, the Medilog 2 (Oxford Instrument Company Ltd.), and the Tracker (Reynolds Medical Electronics), and three electrocardiographs, the Mingograf Minor (Siemens Elema), the VS4 (Cambridge Instrument Company), and the DMS 600 monitor (Simonsen and Weel), modified to perform a 12 lead ECG. Amplitude response was measured from 0.13 Hz to 5.4 Hz using a microcomputer to generate a sine wave of variable frequency and of accurately defined amplitude (1 or 2 mV pk-pk). The pen recorders integral with either the electrocardiographs or playback units provided the output tracings. Phase response was measured using a phase-sensitive waveform as proposed by Wagner [4]: the test waveform [Fig. 1(a)] was defined by

$$f(t) = \sin (wt) + \sin (3wt).$$

If the third harmonic ($3w$) is delayed relative to the fundamental (w), the waveform becomes as in Fig. 1(b). If the fundamental is delayed relative to the third harmonic, the resultant waveform becomes as in Fig. 1(c). The normalized difference in amplitude between the two peaks X and $Y (\delta)$ was calculated for relative phase angle (θ) from 0° to 172° using a minicomputer.

The relative phase angle (θ) is $\phi(3w) - 3\phi(w)$, where $\phi(w)$ is the phase shift at frequency w, and $\phi(3w)$ is the phase shift at frequency $3w$. This technique does not measure phase response directly, as usually defined in Bode plots, but rather shows the displacement between the fundamental and its third harmonic.

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