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Improvement of the frequency responses in an ambulatory ECG system by the natural observation method

JUN-ICHI HORI,[1] YOSHIAKI SAITOH,[1] TOHRU KIRYU,[1] TETSUYA ASAKAWA,[2] KOHJI TAMURA[2] and TAIZO IIJIMA[3]

[1] *Faculty of Engineering, Niigata University, Niigata-shi, Niigata, 950-21, Japan*

[2] *Department of Second Internal Medicine, Yamanashi Medical School, Nakakoma-gun, Yamanashi, 409-38, Japan*

[3] *Faculty of Engineering, Tokyo Engineering University, Hachioji-shi, Tokyo, 192, Japan*

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Abstract—The ambulatory ECG system has been used not only in detecting arrhythmia but also in the diagnosis of myocardial ischemia. Therefore, it is necessary to reproduce ECG waveforms as accurately as possible. However, ambulatory ECG waveforms which are in clinical use are apt to be distorted because the frequency responses do not satisfy the AHA (American Heart Association) recommendation which is well accepted as the standard of the conventional ECG system. An improvement of frequency response is reported here using a compensation circuit, whose theory is based on the natural observation method. Since our system is adjusted with square waveforms and composed of a simple analog circuit, it can be compensated easily in real time. In this paper, our newly developed system and various improved ECG signals are presented and compared with conventional ECG signals. As a result, we could obtain less distorted waveforms than from commercially available devices. This new approach enables us to obtain diagnostic information of the distortion-free ST segment in ECG waveforms.

Key words: ambulatory ECG system; natural observation method; frequency response; ST segment distortion.

1. INTRODUCTION

The ambulatory ECG system is used continuously for 24 h to measure ECG signals and to detect arrhythmia. Recently, as it has been also used for diagnosis of myocardial ischemia, it has also been necessary to reproduce an accurate ECG waveform. However, the bandwidth of ambulatory ECG systems currently used in clinical study is narrow and its frequency does not satisfy the AHA (American Heart Association) recommendation which is well accepted as the standard of the conventional ECG system [1, 2]. Since ambulatory ECG signals are apt to be distorted, we have never satisfactorily analyzed and diagnosed the ST segment [3, 4].

We have paid attention to the frequency response of the ambulatory system and improved it with the natural observation method [5–8] which we proposed. Compensation methods were reported for the ambulatory ECG waveforms obtained using a phase compensation circuit [9] or first-order compensation circuits [10]. In the former case, however, the amplitude characteristics are insufficient, and in the latter case, it took a long time to obtain a proper frequency response because of the repeated measurement and compensation. Our compensation system is of simple composition and can be easily adjusted with square waves, we can improve responses of various ambulatory systems. As another application of the natural observation method, we have reported the correction method of distorted blood pressure waveforms in a catheter manometer system [11].

In this paper, we firstly measure the frequency response of an ambulatory ECG system and confirm that it does not satisfy the AHA standard. Secondly, we present our compensation method of frequency response using the natural observation method and the improvement of frequency response. In compensation, the circuit is adjusted to reproduce the signals using square waveforms approaching the original waveforms. Finally, we present various compensated ambulatory ECG signals and compare them with ECG signals measured with a conventional ECG system.

2. MEASUREMENT OF THE FREQUENCY RESPONSE

We measured the frequency response of an ambulatory ECG system, and we showed the response of the improved system together in order to confirm how the response has been improved. In this case, the ambulatory ECG system which we measured with is currently in clinical use (Fukuda SM-27, SCM-240). The method of measuring the frequency response is limited, not only because of the time difference between input and output signals but also the variety of replay rates (real time, 60 times and 120 times). Recently published papers have presented various measuring methods of ambulatory systems which utilize the sinusoidal wave response, white noise response, or harmonics of square or sawtooth waves [12].

In this study, we used the measuring method of the sinusoidal wave response, because this method is simpler and involves fewer errors. Figure 1 shows a block diagram to measure the frequency responses. Sinusoidal waves generated by a function generator were recorded by a Holter recorder (Fukuda SM-27). A recorded magnetic tape was replayed by a tape cardio-analyzer (Fukuda SCM-240) at 60 times speed. We measured the amplitudes of input and output waveforms, and determined an overall frequency characteristic of an ambulatory ECG system.

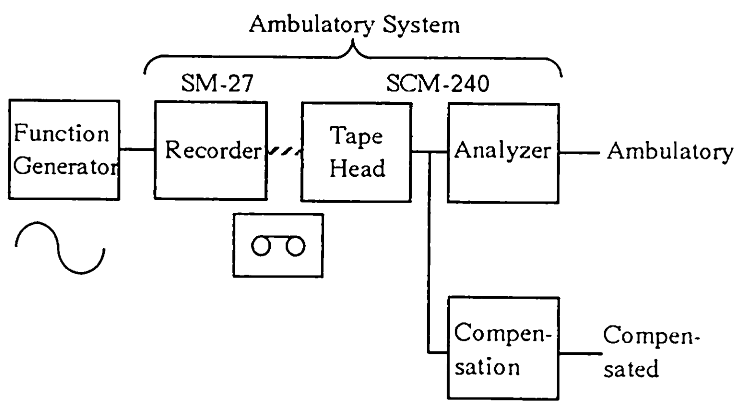

Figure 1. Measuring method of the frequency response with sinusoidal waves.

Figure 2 shows the results of measured frequency responses. Comparing them with the characteristics of the AHA standard, the response of the ambulatory ECG system (b) is limited in low and high frequency ranges, and has peaks at high (30 Hz) and low (0.6 Hz) frequency, showing that it does not satisfy the AHA standard. Since slopes of low and high frequency are about 12 dB per octave, we approximate each characteristic

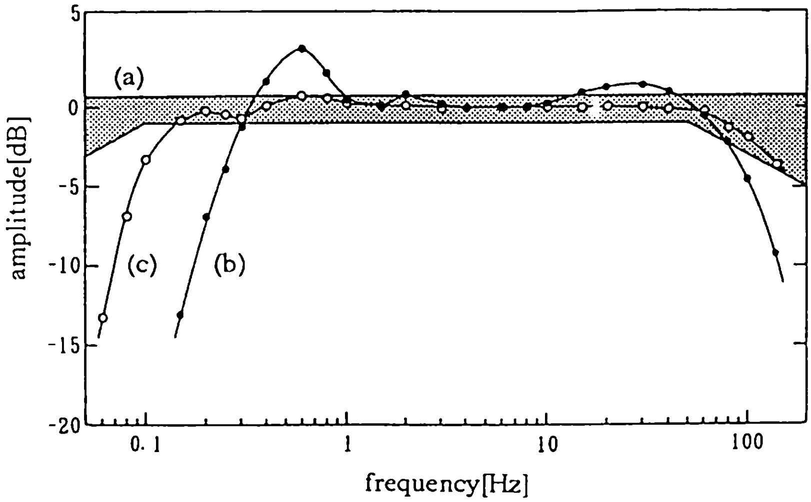

Figure 2. Frequency responses. (a) AHA recommendation for conventional ECG systems. (b) Response of an ambulatory system (Fukuda SCM-27, SM-240) measured by the method of Fig. 1. (c) Response after improvement with our system.

with the second-order high-pass filter (HPF) and low-pass filter (LPF). The transfer function of this ambulatory system is approximated as follows

$$H_a(s) = \frac{s^2}{(s^2+2\zeta_l\omega_{nl}s+\omega_{nl}^2)} \frac{1}{\left(\dfrac{s^2}{\omega_{nh}^2}+2\zeta_h\dfrac{s}{\omega_{nh}}+1\right)}, \tag{1}$$

where s is the Laplace operator, ω_{nl} and ω_{nh} are natural angular frequencies, and ζ_l and ζ_h and damping factors (subscript l denotes low, h denotes high).

Responses of other makers' ambulatory systems are similar to this.The ambulatory ECG signals which are distorted as denoted by equation (1) are compensated for by a compensation circuit described in the next section. Figure 2(c) shows the characteristic compensation by our method.

3. METHODS

3.1. Low-drift amplifier

Using a tape cardio-analyzer (SCM-240), we encounter such problems as noise, drift and baseline fluctuation. We accordingly picked up signals from the tape head coil and amplified them with the low-noise and low-drift operational amplifier (LT1028). The cut-off characteristic in the lower frequency range is compensated with the first-order LPF in this stage.

3.2. Improvement of frequency response

Figure 3 shows a block diagram of the compensation circuit by the natural observation method, which was proposed by one of our authors [5–8]. It was proposed as a new method of analyzing the waveform instead of Fourier analysis. This is composed of series of first-order LPFs or HPFs, and reconstructs the original waveforms by summing each stage's output series with appropriate weighting factors.

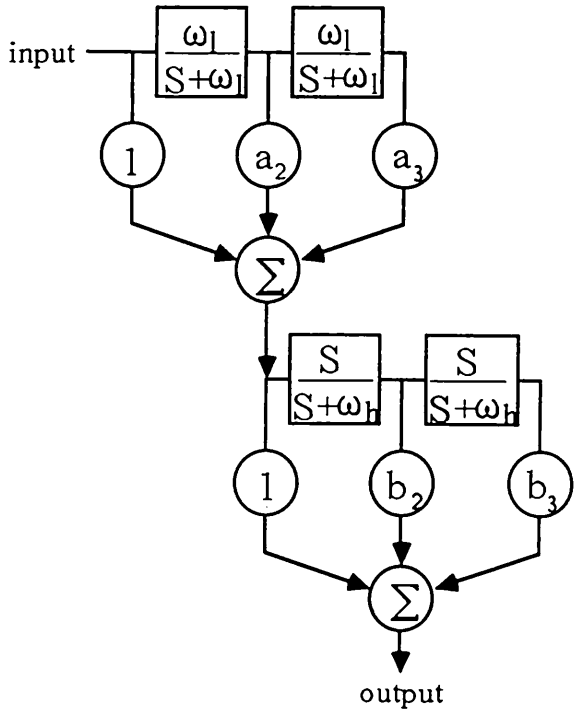

Figure 3. Block diagram of the compensation circuit by the natural observation method. Upper block is the compensation circuit for lower frequency and the lower block is for higher frequency.

In Fig. 3, the series of first-order LPFs and HPFs compensate for the lower and higher part of frequency response, respectively. The transfer function of these whole circuits is shown in equation (2)

$$\begin{aligned} H_c(s) &= \left[1 + a_2\frac{\omega_l}{s+\omega_l} + a_3\left(\frac{\omega_l}{s+\omega_l}\right)^2\right] \times \left[1 + b_2\frac{s}{s+\omega_h} + b_3\left(\frac{s}{s+\omega_h}\right)^2\right] \\ &= \left(\frac{1}{s+\omega_l}\right)^2\left[s^2 + \omega_l(2+a_2)s + \omega_l^2(1+a_2+a_3)\right] \\ &\times \left(\frac{\omega_h}{s+\omega_h}\right)^2\left(\frac{1+b_2+b_3}{\omega_h^2}s^2 + \frac{2+b_2}{\omega_h}s + 1\right), \end{aligned} \tag{2}$$

where ω_l and ω_h are the cut-off angular frequencies, and a_2, a_3, b_2 and b_3 are weighting factors.

In lower frequency compensation, we adjusted weighting factors a_2 and a_3 so as the second term in equation (2) coincides with a denominator of the first term in equation (1). The pole of equation (1) and the zero of the second term in equation (2) cancel each other. As a result, the first term of equation (2) forms the second order HPF with cut-off angular frequency ω_l. By setting this cut-off angular frequency to satisfy the AHA standard, we could improve the responses of the low frequency range. In higher frequency compensation, we similarly adjusted b_2 and b_3 so as the third term of equation (2) performs the second order LPF with cut-off angular frequency ω_h. We can adjust lower and higher weighting factors separately because each frequency is fairly separated. Each compensation section having only two weighting factors, we could easily compensate them. As a result of compensation, the higher cut-off frequency satisfies the AHA standard. Although the lower cut-off frequency still does not satisfy it, it fairly compensates in practice (see Fig. 2c). We present an actual compensation circuit composed of analog filters in Fig. 4.

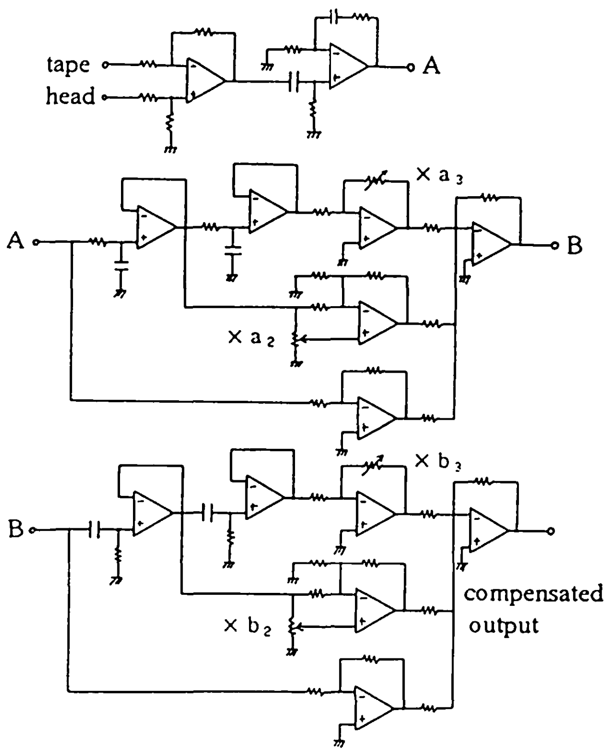

Figure 4. Actual compensation circuit composed of analog filters.

3.3. *Method of adjusting the compensation circuit*

Adjustment of weighting factors in the compensation circuit is achieved with square wave responses. Because if only a step response is reproduced to the original step form, every other waveform could be reproduced. As weighting factors denote gains of amplifiers in the analog circuit, proper adjustment is performed with each value of gain. That is, weighting factors a_2 and a_3 for the lower frequency region are adjusted as the sag of square wave response is similar to flat shape, and weighting factors b_2 and b_3 for the higher frequency region because of the short rise time and no overshoot. Square waves, both before and after compensation, are shown in Fig. 5. Figure 5(a) shows an input square waveform (1 mV_{p-p}, 1 Hz). As shown in the response waves of ambulatory ECG system in Fig. 5(b), baselines are sloped because of the lower cut-off characteristics and, moreover, overshoots are recognized due to the influence of a high frequency peak. From compensated results shown in Fig. 5(c) it is noticeable that the baseline slope has been decreased and rise up has been improved. Figure 5(d), being recorded by a conventional ECG system (Fukuda, LE-811), confirms that compensated waveforms are quite similar to the ones whose characteristics satisfy the AHA standard.

4. RESULTS

4.1. *Measurement and compensation of ambulatory ECG signals*

A block diagram of the measuring and compensating method of ECG signals is shown in Fig. 6. For compensation of various ECG waveforms, we obtain image ECG data from the recorded papers and convert them to time-series data for microcomputer (NEC PC-9801 VX and NEOS compact image scanner SC-109) processing. The sampling frequency is 400 Hz and the resolution of amplitude is 640 points per 4 cm. The time-series data are recorded on a Holter recorder (SM-27) through a D/A converter, the tape is then replayed at 60 times the normal speed with the tape cardiomonitor (SCM-240). In compensation, ECG signals are picked up at the tape head and amplified by the low-noise and low-drift amplifier. Because of the 60 times speed, compensated data are difficult to record on paper. They are accordingly time-converted to 1/60th speed (sampling frequency is from 50 kHz to 866.67 Hz) on a microcomputer. Other ambulatory systems currently in use can be applied without any change because we use only a part of the analog circuits in clinical care.

4.2. *The compensated results of ECG signals*

The compensation effects on various arrhythmia or ST variations are shown in Fig. 7. Every distorted waveform (Fig. 7b) recorded with the ambulatory ECG system is corrected as shown in Fig. 7(c) and is very similar to the conventional ECG waveforms (Fig. 7a).

5. DISCUSSION

5.1. *Frequency responses*

We confirmed that the frequency response of the ambulatory system (SM-27, SCM-240) did not satisfy the AHA standard. The responses of other maker's ambulatory ECG systems which are currently in use are similar to this [3, 4]. In this case, concerning the lower frequency responses, the AHA standard is -3 dB at 0.05 Hz but the ambulatory system is -3 dB at 0.27 Hz. Our trial compensation does not satisfy the AHA standard (-3 dB amplitude at 0.1 Hz). This response is inferior to the other makers' ambulatory systems [3, 4]. Other systems, whose characteristics are better than this, could be improved to satisfy the AHA standard.

In this paper we described the case compensated only in 60 times speed, but even in other conditions such as real time or 120 times speed, we could adjust the compensation circuit. We confirmed through computer simulation that the phase characteristic as well as amplitude characteristic (freqency response) can be improved with the compensation of the natural observation method.

5.2. *Drift reduction*

In order to improve the lower frequency characteristics to meet the AHA standard, the drift must be reduced. The drift is probably caused by the tape head amplifier because it

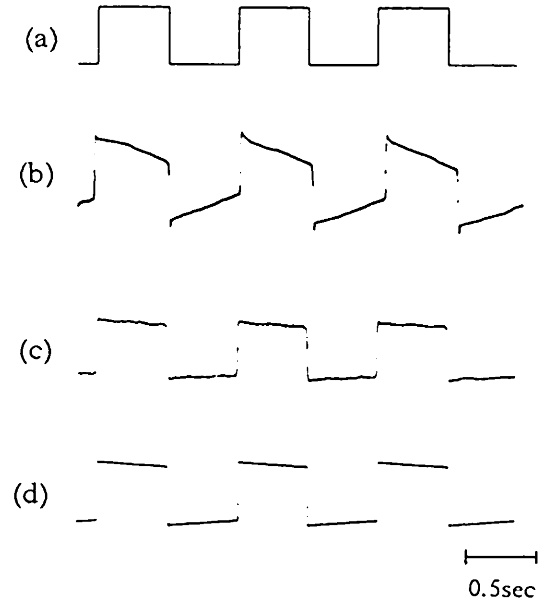

Figure 5. Comparison of reference signals. (a) Input waveform (square wave, 1 mV_{p-p}, 1 Hz). (b) Output of an ambulatory ECG system. (c) Compensated output of (b) with the natural observation method. (d) Output of the conventional ECG system.

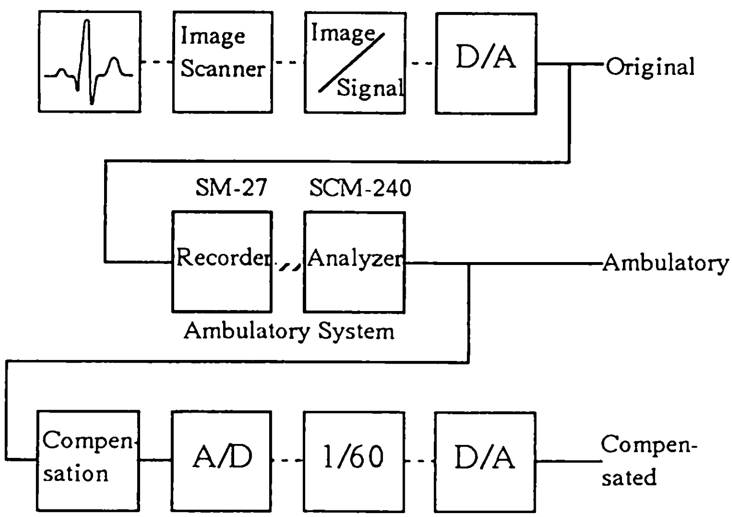

Figure 6. Meausring and compensating methods of the ambulatory ECG system. —— ; analog signals, - - - - ; digital signals.

occurs in the input-short condition with the amplitude compensated, and the amplitude of drift does not change when replaying the tape through the tape head.

Although we use an ultra low-noise operational amplifier (LT1028), the drift cannot be eliminated. As described in Section 5.1, if the response of the ambulatory ECG

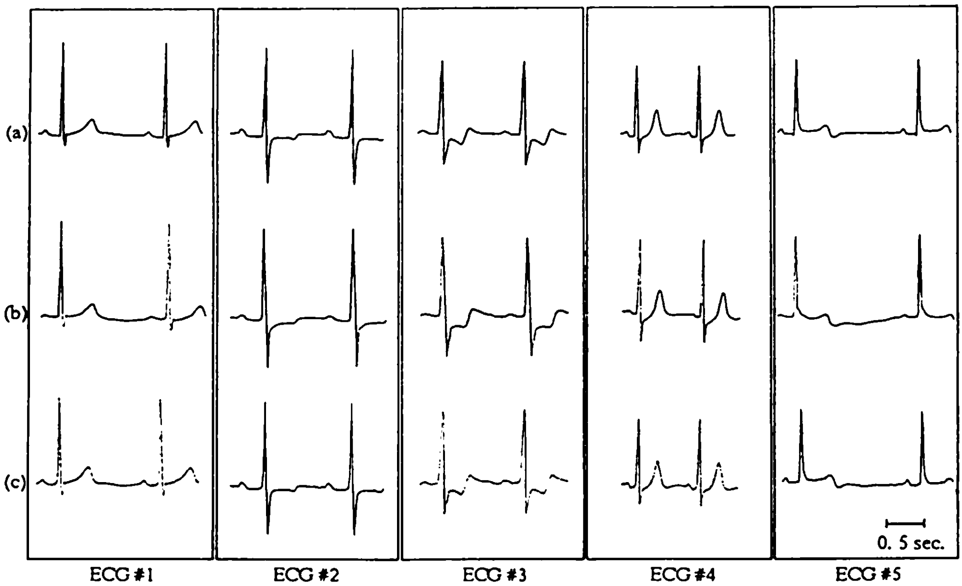

Figure 7. Comparison of ECG signals. (a) Original ECG signals measured by a conventional ECG system. (b) Outputs of the ambulatory ECG system. (c) Compensated ECG signals.

system is as good as other makers' ambulatory ECG systems, we will be able to improve the frequency response to satisfy the AHA standard.

5.3. The waveforms used for the compensation adjustment

It is desirable that the weighting factors of the compensation circuit can be easily adjusted. In this paper, we use the square wave as the input signal and adjust the weighting factors to reproduce the original square wave. This method is already established in the field of electronics and control systems. The square waves can be substituted with the waves generated by a calibration switch or an event switch are built in the ambulatory ECG system. This method is very useful because optimum frequency characteristics are achieved through adjusting compensation circuits to obtain proper square waveforms. Even when frequency characteristics are unknown, the adjusting technique is still applicable. As in Fig. 5(b), the square wave response of the ambulatory ECG system shows a sloped baseline and overshoots. The former affects ECG signals whose heart rate is lower, and the latter has an effect on the QRS complex.

5.4. The results of compensation

We consider each ECG waveform in Fig. 7.

ECG No. 1. Normal ECG waveform. In the compensated ECG waveforms, the P wave and the baseline (T–U) are improved.

ECG No. 2. Horizontal ST depression is shown in the original ECG waveform. However, the waveform derived from the ambulatory system is distorted to the junctional ST depression. From the compensated output the horizontal part is recognized to be similar to the original.

ECG No. 3. Downsloping ST depression is observed in the original ECG waveform.

In the ambulatory ECG waveforms, however it is distorted to the horizontal depression. The R and S waves are enhanced. After compensation, the waveform is corrected to represent the downsloping depression.

ECG No. 4. The ST depression of the ambulatory ECG waveform is larger than that of the original ECG waveform, and the S wave is emphasized. They are improved after compensation.

ECG No. 5. In the original waveform, the ST segment is higher than the baseline level. However, the waveform obtained by the ambulatory ECG system is depressed to the baseline in the concave form and fluctuation of the baseline (T–U) is observed. Every distorted part is improved after compensation.

In this paper, we have studied the electrical characteristics of an ambulatory ECG system and reported the new method to improve them. This method, we believe, will be of great use for long-term ECG monitoring and further research will be pursued.

6. CONCLUSION

The frequency response of the ambulatory ECG system has been improved with the natural observation method and, as a result, we have obtained less distorted ECG waveforms than from commercially available devices. Therefore, this new approach would enable us to obtain precise diagnostic information of the ST segment in ECGs. Our compensation system, i.e. the square waveform adjusting method, makes it easy, with fewer adjusting points, to compensate the frequency response of the ambulatory ECG system.

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