[2] P. D. Welch, "The use of fast Fourier transform for the estimation of power spectra," *IEEE Trans. Audio Electroacoust.*, vol. AU-15, pp. 70–73, June 1970.
[3] Digital Signal Processing Committee, Ed., *Programs for Digital Signal Processing.* New York: IEEE Press, 1979, ch. 2.1.
[4] J. L. Flanagan, "Talking with computers: Synthesis and recognition of speech by machines," *IEEE Trans. Biomed. Eng.*, vol. BME-29, pp. 223–232, Apr. 1982.
[5] I. Veith, *The Yellow Emperor's Classic of Internal Medicine.* Berkeley, CA: Univ. California Press, 1973.

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

Manuscript received September 2, 1982; revised January 28, 1983.
D. Tayler was a Registrar in the Cardiac Department, Brighton, England. He is now with Northern General Hospital, Sheffield S5 7AU, England.
R. Vincent is with the Department of Cardiology, Royal Sussex

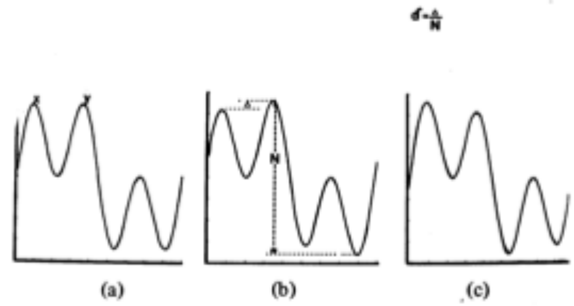

Fig. 1. A phase sensitive waveform for the measurement of relative phase response. (a) $f(t) = \sin wt + \sin 3wt$, the input waveform. (b) $f(t) = \sin wt + \sin (3w + \theta)$, the third harmonic delayed relative to the fundamental. (c) $f(t) = \sin wt + \sin (3wt - \theta)$, the fundamental delayed 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.

phase characteristics, and conversely, could reduce the distortion by correcting the phase responses.

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