Characteristics of the Frequency Spectrum in the Normal Electrocardiogram and in Subjects Following Myocardial Infarction

By PAUL H. LANGNER, JR., M.D., AND DAVID B. GESelowitz, PH.D.

With the technical assistance of Harry L. Fies

It has been demonstrated that there are high frequency components in the electrocardiogram not recorded by the conventional electrocardiographs in common use.\textsuperscript{1-4} It has been shown further that these high frequency components are more common in subjects with heart disease than in normal controls.\textsuperscript{5,6} The range of frequencies involved can be identified and quantified by means of an electronic filter of variable band width. In this paper, the results of such experiments will be reported.

The purpose is threefold: first, to determine the equipment requirements in terms of frequency response necessary to faithfully reproduce the electrocardiogram; second, to ascertain whether normal subjects have a frequency spectrum different from that of subjects with heart disease; and third, to determine the type of QRS complex which gives rise to high frequency components.

A word should be said about the use of the term "high frequency." This is a relative matter in that we are talking about frequencies much higher than those usually employed for recording the electrocardiogram. For instance, the average conventional apparatus in the past has had a very narrow frequency range, being practically unresponsive at 100 c.p.s., whereas equipment used in this study has a response flat to 1,000 c.p.s. and can record well beyond this range. The gross shape of the electrocardiogram can be revealed by an instrument with a frequency response that is flat only to 30 to 40 c.p.s. and unresponsive at 70 or 80 c.p.s. A rise time of .02 seconds requires a frequency response flat to 50 c.p.s. and a direct writer, which is flat to 50 c.p.s. and unresponsive at 100 c.p.s., can still show what appears to be a sharp peak. However, this is due not to responsiveness but rather to compression of the record by slow paper speed. To record a moderately sharp peak without distortion, using an expanded time scale, requires a response flat to at least 200 c.p.s. To record faithfully fast notches, however, a good frequency response to at least 500 c.p.s., and possibly 1,000 c.p.s., is required, as will be demonstrated.

Methods

One method of evaluating the high frequency components in a signal is to determine what remains when the low frequency components are removed. This can be accomplished by passing the signal through a high-pass filter. A high-pass filter is a device which transmits all frequencies above a specified point called the cut-off frequency and attenuates or eliminates frequencies below this point. Practical filters cannot be designed to reject completely all unwanted frequencies, but instead exhibit a response curve which falls off steadily in the region below the cut-off frequency. The cut-off frequency, or point where the response starts to decay, can be defined arbitrarily. Most commonly, the frequencies at which the output is either 70 per cent of the input (3 decibels down) or 50 per cent of the input (6 decibels down) are used. In the present paper, the 3 decibels point will be taken as the cut-off frequency.
Results of passing complexes from 3 different leads through a low-pass filter and successively decreasing the cut-off frequency. Lower amplitude of third complex, in bottom row, is due to respiratory variation. For further explanation, see text.

The ability of the filter to discriminate between frequencies below and above the cut-off point may be specified by the rate at which attenuation increases outside the pass band, and is commonly given in terms of decibels per octave. Thus, an attenuation rate of 24 decibels per octave indicates that every time the frequency is halved, the voltage response decreases by a factor of 16.

Alternatively, the high frequency components in a signal can be evaluated by determining the effect of removing them. For this purpose, a low-pass filter, which transmits all frequencies below a cut-off frequency and attenuates or eliminates higher frequencies, is necessary. (The same terminology applies for both low- and high-pass filters.) When a low-pass filter is used, the cut-off frequency can be made successively lower until a point is reached where a noticeable change occurs in the output waveform.

When the high-pass filter is used, the cut-off frequency is raised and the output amplitude is compared with input. Eventually, the point is reached where the output signal is completely masked by the noise. The most meaningful measure of input and output, when using the high-pass filter, would probably be the root mean square value which is directly related to the energy of the signal. However, to perform such measurements adequately requires comparatively involved and expensive equipment. A much simpler technique, yet one that provides valuable data, is a comparison of peak-to-peak amplitude. For reasons of simplicity, this measure was used in the present experiment.

Eighteen normal subjects, ages 32 to 68, with no signs, symptoms, electrocardiographic or x-ray evidence of heart disease, and 21 patients, ages 40 to 70, who had clinically proven myocardial infarction, were studied.

A Krohn-Hite variable electronic filter, in which the low and high cut-off frequencies could be varied independently, was employed. To achieve a high-pass filter, the upper frequency control dial was set at a maximum of 20,000 c.p.s. and the lower frequency was set consecutively at values between 10 and 1,000 c.p.s. Similarly, for low-pass filter tests, the low frequency control was set at the minimum of 0.2 c.p.s. and the upper frequency was successively adjusted to values between 100 and 1,000 c.p.s. The frequency response of the filter at both the upper and lower ends falls off at a rate of 24 decibels per octave. Scalar leads were used because the filter can pass only 1 waveform at a time.

In both types of experiments, use was made of the repetitive characteristic of the electrocardiogram to extract the signal from the muscle potentials and other noises which are random in nature. Thus, in the high-pass filter experiments, a residual signal was clearly evident since it recurred regularly and its amplitude could be determined accurately by averaging over several beats. Similarly, in the case of low-pass filter experiments, notches and the like were readily distinguished from noise since they occurred regularly in successive complexes.

Results

Figure 1 reveals the results of an experiment with the low-pass filter. The first complex on the left in each series shows the low-pass filter with the high cut-off frequency control dial set at 1,000 c.p.s. There was no
Figure 2

Result of passing complex exhibiting single rapid deflection through high-pass filter and successively increasing the cut-off frequency. The percentages of the residual peak-to-peak signals are 24, 12, 4.0, 2.5, 0.6 and 0.4 for cut-off frequencies ranging from 50 c.p.s. to 1,000 c.p.s. See text for further explanation.

appreciable difference between this and the original signal. For the subsequent complexes in each series, the cut-off was set at 500, 250, and 100 c.p.s. Minor differences appear between 1,000 and 500, very appreciable differences between 500 and 250, and gross distortion occurs at 100. This experiment was conducted in 15 subjects with notching, beading, and slurring. On the basis of these experiments, it seems probable that an upper limit of responsiveness at 500 c.p.s. will prove adequate for visual diagnosis alone in a large majority of cases. However, in 6 subjects there is a noticeable change between 500 and 1,000 c.p.s. and the possible significance of this frequency range is further supported by residuals at 1,000 c.p.s. in high-pass filter studies.

Figure 2 reveals the result of a high-pass filter experiment. Signals were recorded, using a high-pass filter with the low cut-off frequency control dial set at successively higher stages from 50 to 1,000 c.p.s. Since the output decreased markedly as the cut-off frequency was raised, it was necessary to increase the gain of the equipment in order to record accurately the residual signal. The peak-to-peak amplitude of the signal was measured and expressed as a percentage of the original peak-to-peak deflection. The results are shown in table 1. The totals for any given lead do not add to 18 for normals and 21 abnormals because in some subjects several leads were omitted. In presenting these results, the background noise has been subtracted from the total signal under the assumption that signal and noise add as the sum of squares. The range at the 500 c.p.s. dial setting varied from zero to 6 per cent. The high-pass filter, using peak-to-peak amplitude as the criterion, did not provide a clear-cut separation between normal and abnormal subjects. High percentages of residuals at 500 and 700 c.p.s. occurred with greater incidence in abnormals in leads II, III, and V_2 through V_5, although there was considerable overlap.

However, inspection of the original signals revealed much more striking differences. As previously described, there was increased notching, slurring, or beading in the post-coronary subjects. In addition, there is a characteristic of the record which we have not previously emphasized, that is, the deflection
Table 1

<table>
<thead>
<tr>
<th>Percentage residual</th>
<th>Lead I 500</th>
<th>Lead I 700</th>
<th>Lead I 1,000</th>
<th>Lead II 500</th>
<th>Lead II 700</th>
<th>Lead II 1,000</th>
<th>Lead III 500</th>
<th>Lead III 700</th>
<th>Lead III 1,000</th>
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<td>6</td>
<td>10</td>
<td>13</td>
<td>15</td>
<td>16</td>
<td>1</td>
<td>6</td>
<td>4</td>
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<td>0.6 to 1.0</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>1.1 to 1.5</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1.6 to 2.0</td>
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<td>7</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>2</td>
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<td>1</td>
<td></td>
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<tr>
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<td>5.5 to 6.0</td>
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</table>

*N*= no. of normals; *A*= no. of abnormals; 500, 700, and 1,000 are cut-off frequencies in c.p.s.

Distribution of high-pass filter residual signals expressed as per cent of input peak-to-peak amplitude. For further explanation, see text.

Time of various portions of the tracing. Rapid deflections produced high frequency residuals. As may be expected from theoretical considerations, the amplitude of these residuals is related to the amplitude of the fast deflection in the original signal and varies in an inverse manner with its duration. In the case of a high-pass filter experiment, a large residual at high cut-off frequencies occurred when events of short duration and substantial amplitude were present. These rapid events may occur either as smooth fast deflections, or notchings, or both.

It was found that at least 4 distinctly different types of QRS complexes resulted in high-amplitude, high frequency residuals. First is the single fast deflection of large amplitude (fig. 2); second is the small multiphasic deflection reflecting the end on view of a normal loop (fig. 3A). Both of these are normal variants. The third type is the markedly notched deflection with fast transients (fig. 4), and fourth is the relatively small multiphasic deflection, beginning with a Q wave found especially in the precordial leads (fig. 3B) after myocardial infarction. The last 2 are abnormal. Note from figure 2 that for a single rapid deflection the residual signal tended to be concentrated in a very brief time interval, while in figure 4, where considerable notching occurs, the residual is of much greater duration. It is quite possible, then, that even when the relative peak-to-peak amplitudes are comparable in residual signals, the relative energy content may be greater when notchings occur in the original QRS, as judged from the width as well as the amplitude of the residual signal. The energy can be quantified by using the root mean square value of the residual signals.

We shall limit our remarks with regard to the P and T waves to a simple statement, that using a high-pass filter there were no residual signals for the T wave at 20 c.p.s. The P wave frequently had residuals at 50 or 100 c.p.s., but only 3 cases revealed any residual signal at a setting as high as 200 c.p.s. Studies of auricular activity were made only from body surface electrodes. Esophageal electrocardiograms would probably reveal larger energy content of higher frequency.

Discussion

In a majority of normal individuals, the sequence of electrical activation of the ventricles produces a QRS loop in space which is usually elliptical and lies largely in a plane.7, 8 Scalar leads reflect the projection of this loop. The 3 scalar limb leads of largest amplitude and those recorded from the left precordium usually exhibit smooth R waves. In a majority of subjects, following myo-
Table 1—Continued

<table>
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<tr>
<th>Lead</th>
<th>V5</th>
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<th>V3</th>
<th>V2</th>
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<tr>
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<td>A</td>
<td>N</td>
<td>A</td>
<td>N</td>
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</tr>
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<td>1</td>
<td>5</td>
<td>3</td>
<td>11</td>
<td>10</td>
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<tr>
<td>1,000</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>8</td>
<td>18</td>
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Dial infarction, the loop is deformed, producing not only the usual Q waves in the scalar leads, but in some instances high frequency notching, slurring, and beading, the recording of which requires a wide-band recorder and an expanded time scale. There is evidence that these deformities, following myocardial infarction, are produced by patchy necrosis and subsequent fibrosis of the myocardium. Utilizing an electronic filter of variable band width, it was possible to analyze and identify the frequency ranges involved and to display this high frequency content in a quantitative manner. As shown under results, there was a measurable degree of energy as high as 1,000 c.p.s.

The high-pass filter is valuable as a means of studying the high frequency components of the electrocardiogram. For example, a single fast deflection produces residual signals, consisting of high peak-to-peak amplitude of short duration (fig. 2). These single fast deflections are a normal variant. Small fast multiphasic deflections also produce residuals of substantial amplitude; however, in this case the residual signal is wider. These fast multiphasic deflections may be a normal variant when they appear in leads of small amplitude, so oriented that they reflect the end on view of a long, narrow vectorcardiographic loop (fig. 3A), or may be abnormal, especially in midpapillary muscle leads (fig. 3B). Another type of QRS is the fast notched deflection (fig. 4). Marked notching with fast deflections is usually an abnormal finding. It results in residual signals of both high amplitude and greater than average width.

From these remarks, it is evident that peak-to-peak amplitude measurements alone do not give the best separation between normals and abnormals. We doubt that this method will develop into a useful tool for routine clinical diagnosis. There are 2 additional techniques—autocorrelation and measurement of the power spectrum. Franke and Braunstein found that with the latter method there was a difference in power spectra between normal controls and patients with heart disease. They concluded that the meaningful frequency range of the electrocardiogram extends to 500 c.p.s. Judging from the width of our high frequency residual signals, the findings of Franke and Braunstein would seem to be valid. However, further studies are required to determine whether the quantitative estimate of high frequency energy obtained with this more costly equipment, which is necessary to quantify energy content accurately, will add significant diagnostic information, or will serve principally to confirm the information already obtainable by a simple visual inspection of the high fidelity electrocardiogram made with an expanded time scale.
Figure 3

Results of passing 2 leads exhibiting small multiphasic deflections through high-pass filter with cut-off at 500 c.p.s. Left, normal lead III (3 per cent residual); Right, abnormal lead V₁ (5 per cent residual).

In high residuals at 500 and 700 c.p.s. Two of these are normal variants, so it may become necessary to identify these and separate them from the abnormal complexes before attempting to quantify high frequency energy content for diagnostic purposes.

The low-pass filter is a valuable tool for establishing equipment requirements. Using the low-pass filter, it appears, on inspection, that obvious changes occurred about the 500 c.p.s. dial setting. In other words, above this figure it was difficult in our records to be sure of any significant influence of high frequency components; certainly above 1,000 c.p.s., there is no change upon direct visual inspection. Major changes occur when the cut-off frequency is lowered from 500 to 250 c.p.s. From theoretical considerations, greatest distortion would be expected when two rapid deflections occur consecutively, i.e., when there is a notch of short duration. As the frequency range of the equipment is lowered, the ability to follow fast deflections diminishes, and the instrument is unable to respond to a rapid notch. One would get the impression that if visual inspection were adequate as a means of judging requirements for frequency response, an instrument with a response flat to 500 c.p.s. would be adequate in a majority of cases and that a response below 300 c.p.s. would be definitely inadequate. On the other hand, in measuring high-pass filter residuals, substantial signals at 1,000 c.p.s. are often observed, and for this purpose higher frequency response is necessary. There is no inconsistency here, however, because the residual signals at 1,000 c.p.s. are invariably less than 1.5 per cent. Thus, when we are looking at the time function, a response to 500 c.p.s. seems adequate. However, when one performs a frequency analysis not involving time but rather amplitude versus frequency, detectable signals can be observed at 1,000 c.p.s., and beyond.

Scher and Young have reported the results of a frequency analysis on 17 normal subjects and 8 patients. They found that the high frequency components of 100 c.p.s., or higher, are less than 10 per cent of the amplitude of the fundamental of the QRS. As a result, they concluded that there are no significant contributions in the electrocardiogram at frequencies of 100 c.p.s., or higher. Even if their findings are valid for their small group of subjects, their conclusions are at variance with the results reported in this paper and elsewhere in a larger series of subjects with coronary heart disease. As shown above, high frequency components markedly affect the waveform and may be of diagnostic significance even though they are considerably less than 10 per cent of the amplitude of the original waveform.

Just as there is a diagnostic value for low-frequency Q waves, there is diagnostic value for low frequency notches. Best revealed by equipment with somewhat better performance than the conventional machines, for instance, the new Viso 100. It has been shown that there is additional information to be gained from high-frequency characteristics as revealed by the cathode ray oscillograph and an expanded time scale. Such high frequency characteristics can also be seen in vectorcardiographic loops, provided the amplifiers have adequate high frequency response; however, nondipole components may be sup-

*SSee footnote, p. 577.
pressed in vectoreardiographic systems.\textsuperscript{14, 15} The interrupted light beam for measuring time in the vectoreardiographic loop will also obscure high frequency components.

There is evidence that the mechanism for the production of notching and other high frequency deformities following myocardial infarction is the result of patchy myocardial necrosis with subsequent fibrosis.\textsuperscript{9-11} We found notching more common in angina pectoris a disease in which Zoll, Wessler, and Blumgart frequently found multiple infarctions.\textsuperscript{16} These cause interspersed patches of living and dead myocardium. However, patchy necrosis or fibrosis due to coronary disease is not the only cause of notching and other similar deformities in the electrocardiograms. These are also seen in presumably healthy, young individuals, but the degree is much less, and it occurs less frequently than in people with coronary heart disease.\textsuperscript{5} In these normal subjects, the mechanism of the notching is still a matter of speculation, but it could be due to small scars in the myocardium following rheumatic fever, diphtheria, viral myocarditis, and other infections.

\textbf{Summary}

The results of a study of the scalar electrocardiogram, utilizing a wide-band recorder, expanded time scale and a low-pass filter, indicate that a recorder flat to at least 500 c.p.s. is required for faithful reproduction. With a high-pass filter, measurable residual signals are present at a cut-off frequency of 1,000 c.p.s., or higher. Therefore, to record these, an adequate response at 1,000 c.p.s. or more is required. The high frequency energy of the electrocardiographic spectrum arises from the fast deflections contained in the original waveform. These may occur in a single fast deflection, notching, or both. Whereas, in the normal individual, high frequency energy usually arises from a relatively smooth, fast deflection, in abnormals the fast events may occur in conjunction with notching, and other deformities. Judging from the technic used in this experiment, a variable band-pass filter is valuable as an aid for studying the high fre-
quency components of the electrocardiogram and establishing equipment requirements. Measurement of peak-to-peak voltage of residual signals gives partial but not clear-cut separation of normal and abnormal subjects and would not seem to add to the value of high-fidelity electrocardiography per se in routine clinical diagnosis. It is possible that root mean square readings, reflecting the total energy content, might give a better separation between normal and abnormal subjects than peak-to-peak amplitude alone.

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References


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