Some Requirements in Equipment and Technics for Vectorcardiography

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To reduce the effects of extraneous potentials caused by muscle tremor, sweating, and interference from power circuits, it is desirable to restrict the frequency range of the cathode ray vectorcardiograph. Mathematical analysis of idealized waves and experiments with a photoelectric electrocardiographic generator indicate that a frequency range between the half-power frequency of 0.8 to 80 cycles per second is satisfactory for proper reproduction of most vectorcardiograms. Many investigators construct the vectorcardiogram graphically from the electrocardiogram. In this study it is shown that, unless simultaneous electrocardiograms recorded at greater than usual paper speed are used, such vectorcardiograms may be incorrect.

During the past six years the attention of cardiologists in increasing numbers has been directed toward vectorcardiography. This attention has been stimulated by the hope that this phase of electrocardiography may lead to new information of clinical importance in detecting and evaluating heart disease and of physical importance in determining the manner in which electric currents are generated by the living heart and propagated through the body.

Modern electrocardiography and vectorcardiography are intimately associated with vacuum tube amplifiers and oscillators, cathode ray oscilloscopes, and electronic timing circuits. Although the Einthoven string galvanometer is satisfactory for electrocardiography, modern automatic vectorcardiography would be impossible without the vacuum tube amplifier and the cathode ray oscilloscope. Theoretically the combination of vacuum tube amplifiers and cathode ray tubes should constitute the perfect vectorcardiograph. With this system the amplifier alone is the limiting factor in both low- and high-frequency reproduction. With a suitable direct-coupled amplifier all of the frequencies encountered in vectorcardiography may be reproduced properly. In practice, however, a drift-free, wide-band, direct-coupled amplifier having the required voltage gain of approximately 200,000 is difficult to construct and maintain. Moreover, the effects of extraneous voltages due to sweating at the electrode sites, both low- and high-frequency skeletal muscle activity, respiration, changes in the position of the subject, and inductive and electrostatic interference from adjacent power circuits and electrical equipment make it advisable to restrict as much as possible both the low- and high-frequency limits of the vectorcardiograph.

A theoretic study was made to determine the approximate frequency requirements for a satisfactory vectorcardiograph. In addition, a photoelectric generator was constructed which could produce voltages similar in waveform to those encountered in vectorcardiography. With the generator, it was possible to demonstrate some of the errors which may occur when the vectorcardiogram is constructed graphically from standard electrocardiograms, and to determine by means of frequency attenuating networks the influence of the frequency response of the vectorcardiograph.

Theoretic Analysis

In order to make a reasonably simple approach to a theoretic determination of the frequency requirements in vectorcardiography, assumptions were made regarding the duration and configuration of the waveforms likely to be encountered and the circuits used. The QRS complex is the shortest component with a minimum duration of about 0.04 second and the T wave is the longest with a maximum du-
ration of about 0.5 second. Intervals outside this range may be encountered in special circumstances but are unusual and were not considered in this analysis.

Usually, the duration of the QRS complex is about 0.08 second and of the T wave about 0.15 second. The QRS complex was considered to be a triangular pulse with equal rates of rise and fall, and the T wave either a triangular pulse or a half-wave sine pulse.

Since the voltage amplification required in vectorcardiography with the cathode ray tube is approximately 200,000 times, a maximum of three stages of amplification is necessary. Without serious difficulty due to drift, two of the stages can be direct-coupled so that only one R-C coupling network, which affects the low-frequency response, is necessary between stages. Therefore, only the single R-C coupling network shown in figure 1a was studied in detail to determine its effect on the relatively low-frequency T wave and loop.

Likewise, to restrict the high-frequency range, shunt capacitance would ordinarily be used in only one stage. The single R-C network shown in figure 1c was studied in detail to determine its effect on the relatively high-frequency wave and loop of the QRS complex. Because the ratio of the duration of the longest T wave to that of the shortest QRS complex likely to be encountered is over 12:1, it was assumed that in a practical vectorcardiograph the effect of the R-C coupling networks on the low-frequency response should be relatively unaffected by the shunt capacitance which limits the high-frequency response, and vice versa.

The pulses considered in this analysis are shown in figures 1e and 1f. The method of the Laplace transform was used to analyze the response of the various networks. Although the double networks of figures 1c and 1d were considered, they were not studied in detail. After the effect of the network on the time variation of the pulse was calculated, Lissajous patterns combining two of the input waves and two of the output waves could be drawn and compared for various phases between input components.

The Photoelectric Generator

A photoelectric generator for producing artificial electrocardiographic potential differences was built to evaluate both the possible errors in methods of graphically constructing the vectorcardiogram and the effect on the vectorcardiogram of the frequency characteristics of the recorder. With this unit, changes in the relative phase between “electrocardiographic” leads could be made readily and a study could be carried on without the difficulties involved in trying to obtain reproducible sequential records from a human subject. The basic circuit of the generator and its connections to a cathode-ray oscilloscope for these studies is shown in figure 2.

The generator consisted of a 6-watt fluorescent lamp as a light source, a lucite tube which was masked with tape to produce light variations resulting in patterns corresponding to desired electrocardiograms and driven by a phonograph motor at 78 revolutions per minute, two photoelectric cells, two cathode-follower amplifiers, and suitable rectifier and filter circuits. The output impedance of the cathode followers was approximately 2500 ohms. The cathode-ray oscilloscope employed direct-coupled amplifiers with essentially flat response to 100,000 cycles per second. Consequently, all of the important frequency modification could...
be obtained in the networks which were inserted between the cathode followers and the input terminals of the oscilloscope.

The fluorescent lamp was inserted along the axis of the lucite tube and was supplied with rectified and filtered current to avoid variations in light intensity which would result from operation with alternating current. To start it, one of its filaments was heated through a series resistor and the lamp was short-circuited. The inductive surge from the filter inductor on removal of the short-circuit started the lamp satisfactorily, and then the filament-heating circuit was opened. The photocells could be moved forward or backward in the direction of rotation to advance or delay one "electrocardiogram" with respect to the other. It was also possible to record simultaneously the "electrocardiograms" with two string galvanometers of the type employed in electrocardiography connected, as shown in the diagram, from the terminals ECG to ground.

**RESULTS**

Some of the results of the theoretic analysis and of the experimental tests with the photoelectric generator are shown in figures 3 through 10. The analysis shows that the important effects of limiting the low-frequency response are reduction of peak amplitude of the reproduced wave, overshoot on the return to zero, and premature return to zero. As shown in figure 3 when the time constant of the network

\[ CR = 4 \text{ seconds and } 2\tau/CR = 0.125, \]

there is for the 0.5-second triangular wave a 3 per cent reduction of peak amplitude and 6 per cent overshoot on return to zero, and a premature return to zero of 0.025 second. Reduction of CR causes proportional increases of all of these effects. Inspection of the T wave of the experimentally obtained electrocardiograms of figures 4 and 5 shows how these distortions increased as CR was reduced. However, for a given ratio \( 2\tau/CR \), the experimental distortion was about one-half of that predicted by the analysis. The effect of low-frequency attenuation on the reproduction of the T and P loops of the vectorcardiogram is shown in figure 6. The overshoot artefact

**Fig. 2.** Basic circuit of photoelectric generator showing connections to frequency-attenuating networks, oscilloscope, and string galvanometer electrocardiographs.

**Fig. 3.** Theoretic response of single low-frequency attenuating networks to triangular pulse representative of the T wave.
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when \( CR = 0.4 \) second is evident and is predicted by space-quadrature combination of the modified triangular pulses of the theoretic analysis. Analysis with the sine pulse agreed closely with that for the triangular pulse.

Fig. 4. Experimental response of single low-frequency attenuating network to generated electrocardiogram. Duration of T wave \( 2\tau = 0.14 \) second. Upper trace with direct-coupled circuit \((CR = \infty; 2\tau/CR = 0\) for the T wave). Lower trace with R-C coupling network \((CR = 2\) seconds, \(2\tau/CR = 0.07\)).

Fig. 5. Experimental response of single low-frequency attenuating network to generated electrocardiogram. Upper trace with direct-coupled circuit. Lower trace with R-C coupling network \((CR = 0.4\) second; \(2\tau/CR = 0.35\) for the T wave).

Limitation of the high-frequency response is most evident in reproduction of the QRS complex. Analytically the effects were delay and reduction of the peak amplitude of the reproduced pulse. As shown in figure 7, the network with \( CR = 0.002 \) second reduced the peak of the 0.04-second triangular pulse by 6 per cent and delayed the pulse by 0.002 second. In this case \( 2\tau/CR = 20 \). The peak reduction is approximately proportional to \( CR \) and constant for a given ratio \( 2\tau/CR \). The delay, essentially independent of the pulse duration, is equal to the time constant of the network. The peak reduction of the steep component of

Fig. 6. Experimental effect of single low-frequency attenuating networks on the generated vectorecardiogram. Circuit conditions reading from left to right were as follows for horizontal and vertical circuits of the oscilloscope: direct-coupled; R-C coupled, \( CR = 2 \) seconds; R-C coupled, \( CR = 0.4 \) second; R-C coupled, \( CR = 2 \) seconds for vertical circuit, \( CR = 0.2 \) second for horizontal circuit. Only part of QRS loop shown. Dissimilar waves in horizontal and vertical circuits.

Fig. 7. Theoretic response of single high frequency attenuating network to triangular pulse representative of the QRS complex.

the experimentally produced electrocardiogram is shown in figure 8. Satisfactory agreement between theory and experiment was indicated by an experimental peak reduction of about 5 per cent when \( 2\tau/CR = 27 \). The shortening of
the major axis of the QRS loop as a consequence of high-frequency attenuation, with little change in its direction or in the configuration of the loop, is shown in figure 9.

![Fig. 8. Experimental response of single high-frequency attenuating network to generated electrocardiogram. Duration of steepest segment of QRS complex 2τ = 0.08 second. Top trace with R-C network (CR = 0.003 second; 2τ/CR = 27 for segment of QRS complex). Middle trace with direct-coupled circuit (CR = 0; 2τ/CR = ∞). Bottom trace with R-C network (CR = 0.005 second; 2τ/CR = 16).](image)

![Fig. 9. Experimental effect of high-frequency attenuating networks on the generated vectorcardiogram. Circuit conditions, reading from left to right, were as follows: direct-coupled; R-C networks, CR = 0.003 second; R-C networks, CR = 0.001 second in vertical circuit; CR = 0.0005 second in horizontal circuit. The effect of different time constants in the circuits to the vertical and horizontal amplifiers is shown in the right-hand vectorcardiograms of figures 6 and 9. This narrowing or widening of the loops is to be expected because of the difference in phase shift of the vertical and horizontal electrocardiographic waves as a result of the difference in time constants. Of importance to many experimenters who graphically construct the vectorcardiogram are the effects produced by changes in the relative time-phase of the horizontal (I) and vertical components (VF) of the vectorcardiogram. These effects are shown in figure 10. The three vectorcardiograms are obviously different, yet they were produced by the same electrocardiographic patterns which, in their correct relative time-phases, are shown below the corresponding vectorcardiogram. The differences in the vectorcardiograms are the result of almost imperceptible differences in the relative time-phases of the electrocardiograms. If we consider the middle group as the reference with the vectorcardiograms traced clockwise, that on the left with the vectorcardiogram traced clockwise was obtained by advancing lead I by 0.004 second, and that on the right with the vectorcardiogram traced counterclockwise but more open than the reference was obtained by retarding lead I by 0.004 second. Such small differences in time phase are imperceptible in simultaneously recorded electrocardiograms even with the paper speed double the usual value. They are certainly imperceptible in these electrocardiograms which](image)

![Fig. 10. Effect of changes in time-phase between horizontal and vertical components of a generated vectorcardiogram. (a) Lead I advanced 0.004 second; (b) reference; (c) lead I retarded 0.004 second. Duration of complex = 0.09 second.](image)
were recorded on a cathode ray tube. If such differences can be obtained with simultaneously recorded electrocardiograms, the possible errors introduced by attempting to construct the vectorcardiogram from leads which may have been recorded some minutes apart can be realized. All of the variations produced by changes in heart rate, position of the subject, respiration, etc., superimpose their effects on the graphically constructed vectorcardiogram. Although some of the errors can be avoided by using all three standard lead electrocardiograms in the construction and constantly checking to see that leads I + III = lead II, the difficulty is considerable and the results of graphic construction are questionable.

CONCLUSIONS

Considering the results of both analysis and experiment, it would seem that reproduction of the vectorcardiogram with accuracy within the limits imposed by normal biologic variations can be obtained if the time-constant of the single R-C coupling network in the amplifiers is approximately 2 and if the time constant of the single R-C network to produce high-frequency attenuation is 0.002. These correspond to a lower half-power frequency of approximately 0.08 cycle per second and to an upper half-power frequency of approximately 80 cycles per second. For many cases, smaller bandwidth than this would be satisfactory. However, some studies of high-frequency phenomena associated with electrical activity of the heart may require a higher upper half-power frequency.

It is important that all amplifiers used to reproduce the vectorcardiogram have almost identical frequency characteristics if the undesirable effects of unequal phase shifts are to be avoided.

The fact that satisfactory reproduction of the higher frequency components can be obtained with an upper half-power frequency of 80 cycles per second means that it may be possible to construct a direct-writing vectorcardiograph and thus avoid the requirement of photographic processing. It should be emphasized that the equipment requirements considered in this study are based on those components of the electrocardiograms whose variations are known to have clinical significance. It is entirely possible, for example, that higher frequency components of the electrocardiogram may be assigned clinical importance in the future in which case the equipment requirements outlined may not be satisfactory.

Unless extreme care is exercised in the construction of the vectorcardiogram by graphic means, errors are possible in both the configuration of the loops and the direction in which they are traced. The careful use of simultaneously recorded, standard-lead electrocardiograms avoids some of these difficulties. However, there is considerable question regarding the accuracy obtained when sequential records are employed, because of the difficulty of determining corresponding points in waves which may be recorded at different heart rates, with different phases of respiration, and with different conditions of muscular activity.

SUMARIO ESPAÑOL

Para reducir los efectos de potenciales extras causados por temblor muscular, perspiración e interferencia de circuitos eléctricos, es deseable restringir el alcance de la frecuencia del vectorcardiograma de rayo cátodo. Análisis matemático de ondas ideales y experimentos con un generador electrocardiográfico fotoeléctrico indican que el alcance de la frecuencia entre la medio frecuencia de 0.8 a 80 ciclos por segundo es satisfactoria para la propia reproducción de la mayoría de los vectocardiogramas. Muchos investigadores construyen el vectocardiograma gráficamente del electrocardiograma. En este estudio se demuestra que, aunque lo electrocardiogramas no sean registrados simultáneamente a velocidad del papel mayor que lo usual, estos vectocardiogramas pueden ser incorrectos.

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Circulation. 1953;8:914-919
doi: 10.1161/01.CIR.8.6.914
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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