Electrokymographic Studies of the Normal Cardiac Cycle

By Henry Mednick, M.D., John B. Schwedel, M.D., and Philip Samet, M.D.

Normal subjects were studied by employing two electrokymograms simultaneously. By comparing the sequence of events in the carotid pulse, auricle and ventricle, measurements were made of the phases of the cardiac cycle. The normal electrokymogram is discussed and illustrated. Simultaneous electrokymography of the right- and left-sided chambers and vessels of the heart provides a simple method for comparing synchronicity of events in normal and pathologic states. Data obtained in normal subjects is presented.

Cardiologists and physiologists have long sought to develop clinically feasible methods of recording and studying the mechanical and electrical phases of the cardiac cycle in intact man. No one will deny that success has crowned efforts to record the electrical potentials developed in the heart. Recording of peripheral arterial and venous pulsations and heart sounds has also become routine procedure. One of the remaining hurdles has been the recording of the motion of the heart borders. Among the methods used for the latter purpose the roentgenokymogram is the best known. Applications of this method proved to be limited in scope.1-7 In the past two decades various attempts have been made to record the heart border, as seen fluoroscopically, with the aid of a photoelectric tube.8-11 The most successful device currently in use was developed by Henny and Boone.12, 13 This consists of a multiplier photoelectric tube with a fluorescent screen activated by the roentgen rays which have passed through the subject being studied. Filters are employed to remove interference created by the roentgen tube. Henny and Boone employed a simultaneous recording of the carotid pulse as a timing device. Luisada and co-workers14,15 have used the heart sounds, while Anderson16 has resorted to the electrocardiogram.

Electrokymography has proved to be of great value. Accurate recording of the motions of the cardiac contour is now possible and studies of the various phases of the cardiac cycle, especially the isometric relaxation phase, have been undertaken.17-19 Studies of asynchronous contractions of the auricles and ventricles in normal individuals and in those with bundle branch block have been reported.20, 21 Confirmation of assumptions made in the course of these investigations has been achieved by correlation of electrokymographic curves with intra-auricular and intraventricular pressure curves.22 The possibility of determining stroke volume and cardiac output with this technic is under investigation.23, 24 A recent review of electrokymography has been published.25

We have been interested in correlating the electrical and mechanical events of the cardiac cycle and in measurement of the phases of the cardiac cycle in heart disease. With this view in mind we have undertaken a study of a group of normal individuals. As a further aid in our investigation we have recently been employing two electrokymographs with simultaneous recording of either the carotid pulse or an electrocardiogram. This has been made possible by the use of a direct writing tri-beam Technicon. We now feel that a direct writing recorder is a necessity because it enables immediate visualization allowing for adjustment of the photoelectric cell if unsatisfactory curves are obtained.

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Technic

Initially a Cambridge Simpli-Trol* electrocardiograph was used; this permitted simultaneous recording of an electrokymogram, carotid pulse, and heart sounds. Because of frequent superimposition of the curves and because immediate visualization of the recording was not possible we found this instrument limited in application. With the acquisition of a direct writing Technicop our work was greatly facilitated. This instrument has devices for eliminating 60 cycle interference, and for critical damping of each stylus. There is a 100 per cent frequency response to almost 50 cycles per second.

The electrokymograms were all taken with the subject in the sitting position and the photoelectric pickup tube between him and the fluoroscopic screen. Fluoroscopy was done at 70 kilovolts and 4 milliamperes. Because of the sharper end points obtained the paper speed was 25 mm. per sec. rather than 50 mm. per sec. Tracings were taken in the posteroanterior and in both oblique positions thus allowing for complete exploration of the cardiac contour. Two Cambridge electrokymogram pickup units were employed. The carotid pulse tracing was obtained by placing a pulse-microphone over the vessel, the current of which was fed through one channel of the recording apparatus.

The results will be presented in three groups. In the first group the photographic recorder was used. In the second group a single electrokymogram was recorded with the direct writing machine and in the third group two electrokymograms were recorded simultaneously with this machine.

Data

The subjects used in the studies were patients on the medical and surgical services of this hospital in whom the presence of cardiac disease was ruled out by history, physical examination, fluoroscopy and electrocardiography. Electrokymograms were taken with the patient in the sitting position. During the recording period the patient was instructed to stop breathing in mid-inspiration and to avoid straining.

Group 1. Seventeen subjects were studied with a single electrokymogram with simultaneous recordings of the heart sounds and carotid pulse waves. In the posteroanterior position tracings of the left ventricle, left auricular appendage, pulmonary artery, ascending aorta and right auricle were made. In the left oblique position tracings of the left ventricle, right ventricle, ascending aorta and left auricle were taken. Whenever the quality of the tracings permitted, measurements of the various phases of the cardiac cycle were taken (see table 1). No fewer than four complexes were measured

![Table 1. Measurements Obtained from 33 Subjects](http://circ.ahajournals.org/)

<table>
<thead>
<tr>
<th>Data</th>
<th>Total Cases—All Methods</th>
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<tbody>
<tr>
<td></td>
<td>No. cases</td>
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<td>Carotid</td>
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<td>Isometric contraction</td>
<td>52</td>
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<tr>
<td>Total ejection</td>
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<tr>
<td>Left Ventricle</td>
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<td>Isometric contraction</td>
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<tr>
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<td>Ejection—Pulmonary Artery to Carotid Ejection</td>
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<tr>
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<td>15</td>
</tr>
<tr>
<td>P Wave to A Wave Right</td>
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</tbody>
</table>

+ Indicates that right is ahead.

† Technicon Cardiograph Co., New York, New York.
in each tracing and when a chamber was recorded in several views the average of all views was determined. The onset of systolic ejection in the pulmonary artery and in the ascending aorta was compared by using the onset of carotid ejection as a reference point. Similarly the sequence of opening of the tricuspid and mitral valves was measured by using the carotid incisura as a reference point. The beginning of the first heart sound was useful in identifying the onset of the isometric contraction curve of the left ventricle, and the carotid incisura (after a correction was made for a delay of 0.03 seconds) was useful in indicating the onset of the isometric relaxation curve of the left ventricle.

Fig. 1. Simultaneous electrokymograms of the left auricle, left ventricle, and carotid pulse tracing (top to bottom). The variations in the shapes of the curves is apparent, but the time relationships are constant. The peak of the “C” wave of the auricle is simultaneous with the downstroke of ejection in the ventricle and the upstroke of carotid ejection. The closing of the aortic valve is indicated by the carotid incisura and the upstroke of isometric relaxation of the ventricle. The opening of the mitral valve is indicated by the auricular V wave and corresponds to the end of the isometric relaxation curve indicated by a short downstroke on the ventricular tracing. Auricular contraction inscribes the downstroke of the A wave.

Group 2. Twelve additional subjects were studied in the same fashion as group 1 with the following changes: A three channel direct writing recording machine was used; the heart sound tracing was replaced by a simultaneous electrocardiogram (usually Lead II); measurements of the onset of the Q wave of the electrocardiogram to carotid ejection and of the
onset of the P wave to the A waves of the electrokymogram were made.

Group 3. With the acquisition of a second electrokymogram our technic was altered so that simultaneous tracings of two heart borders or the two great vessels could be obtained. The variations in the shapes of the curves in normal individuals is again apparent. The onset of auricular systole of the right auricle can be seen to precede that of the left auricle. (Compare the peaks of the A waves in the upper tracing with those in the middle tracing). The A wave of the left auricle cannot always be recorded (2A). The C and V waves are reflections of ventricular activity and are practically simultaneous.

In the posteroanterior position it was found that tracings of both auricles could always be obtained by placing one photoelectric cell over the lower portion of the right heart shadow and the other cell at the junction of the pulmonary artery and left ventricular contour. In the latter position a tracing of the left auricular appendage was always obtained even when this chamber was not apparent to the fluoroscopist. Simultaneous tracings of the left auricle and left ventricle were also made in the posteroanterior position. By rotating the subject into a slight right anterior oblique po-

Fig. 2. Simultaneous electrokymograms of the right auricle (top), left auricle (middle), carotid pulse (bottom, 2A and 2B) and Lead II of the electrocardiogram (bottom 2C). The variations in the shapes of the curves in normal individuals is again apparent. The onset of auricular systole of the right auricle can be seen to precede that of the left auricle. (Compare the peaks of the A waves in the upper tracing with those in the middle tracing). The A wave of the left auricle cannot always be recorded (2A). The C and V waves are reflections of ventricular activity and are practically simultaneous.

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nally a tracing of Lead II of the electrocardiogram and of both auricles was taken. The major advantage of simultaneous electrokyphography is that it does away with the objections which might be raised as to the validity of comparing events occurring in different cardiac cycles by use of a reference point. The

cated by the peak of the wave. The next event is the closure of the mitral valve which is marked by the beginning of the downstroke of isometric contraction of the left ventricle (fig. 1B). This is reflected on the auricle by the bulging back of the mitral leaflets and the upstroke of the C wave. When the intraven-

Fig. 3. A. Electrokymograms of the pulmonary artery (PA) and the ascending aorta (Asc.A.). B and C. Electrokymograms of the ascending aorta and the left ventricle (LV).

measurements obtained by studying 24 subjects in this fashion are tabulated in the table. Figures 1 to 3 illustrate results obtained by simultaneous electrokyphography in group 3. In figure 1 the upper tracing is that of the left auricle, the middle was obtained from the left ventricle and the lower tracing is that of the carotid pulse. The contraction of the auricle is marked by the down stroke of the A wave (figs. 1A and 1C), the onset of which is indi-

tricular pressure reaches the diastolic aortic pressure the aortic valve opens and the ejection phase starts. The opening of the aortic valve is marked by the upstroke of the carotid pulse, the downstroke of the ventricular tracing and is reflected in the sudden drop of the C wave of the auricle. The closure of the aortic valve is indicated by the incisura of the carotid pulse tracing and usually coincides with the end of the systolic downstroke of the ventri-
cle (a correction of .03 seconds must be made in the carotid tracing due to the time required for pulse travel plus instrumental delay). The isometric relaxation phase is inscribed as an upward convexity on the ventricular curve and ends with the opening of the mitral valve indicated by the V wave of the auricle (fig. 1B). Diastolic filling of the ventricle occurs and the cycle is then repeated. It is apparent that with these three simultaneous tracings the events of the left side of the heart can be plotted chronologically.

In figure 2 simultaneous tracings of the auricles are illustrated with that of the right auricle in the upper tracing, that of the left auricle in the middle and that of the carotid pulse in the lower tracing in figures 2A and 2B. In figure 2C an electrocardiogram is substituted for the carotid pulse tracing. It is apparent even on superficial examination that there is a great variation in normal individuals in the exact character of the curves and therefore hasty conclusions as to the presence of valvular disease must not be drawn. The apparent bulging of the auricle in systole illustrated in the upper tracings of figure 1B and 2B is not due to mitral insufficiency but is due to distortions superimposed by the adjacent ventricle and pulmonary artery.

Figure 3A demonstrates the aorta, pulmonary artery and carotid pulses and figures 3B and 3C demonstrate aorta, left ventricle and carotid artery (top to bottom). Because of the great individual variations in the curves obtained by this method we feel that conclusions based on the shape of the curve alone are too subjective to be considered valuable. Objectively one may make observations as to the direction of the curve and time intervals between the various waves.

RESULTS

The measurements obtained from the 53 subjects studied are tabulated in table 1. The last column is a compilation of the data obtained in the three groups with the number of cases in which each particular measurement could be made. The maximum deviation in either direction is included, with a plus sign indicating that the event in the right side of the heart occurred before that in the left. All measurements were estimated to .01 second.

Although the final averages are shown in thousandths of a second. Figure 4 is a composite drawing of the electrokymographic curves ar-

\[ \text{Carotid} \]
\[ \text{Asc A} \]
\[ \text{PA} \]
\[ \text{LA} \]
\[ \text{RA} \]
\[ \text{LV} \]

\[ \text{Fig. 4. Schematic diagram of tracings of the carotid artery, ascending aorta (Asc.A.), pulmonary artery (PA), left auricle (LA), right auricle (RA), and left ventricle (LV). The tracings have been drawn to correspond with the average time values indicated in the chart. The dotted lines connect simultaneous points in the left ventricle, left auricle, ascending aorta, and carotid artery. The delay in the carotid tracing is corrected by setting the line .03 seconds to the right.}\]
ranged so that the sequence of events corresponds to the average times obtained.

In terms of the cardiac cycle the data may be interpreted as follows: The right auricle contracts about .02 second before the left. After an isometric contraction phase of .04 second the semilunar valves open, with the pulmonary valve about .01 second ahead of the aortic valve. (This may vary from .03 second before to .02 second after). The systolic ejection phase follows with its duration varying with the pulse rate. After an isometric relaxation phase of .16 second for the left ventricle (varies from .07 to .14 second) the mitral valve opens, with the tricuspid valve opening .025 second ahead of it.

Conclusions

1. Simultaneous electrokymography offers a practical method for timing the cardiac cycle in normal individuals, and for comparing the sequence of events in the right and left sides of the heart.

2. The shape of the curves obtained varies greatly and conclusions as to typical patterns in heart disease must await further evaluation with large series of patients. Objective statements can be made regarding the direction of the heart borders (as reflected on the tracings) and regarding the sequence of events.

3. This method may prove to be of great value in correlating mechanical and electrical events in the heart especially in the presence of conduction defects. In order to establish normal values as a basis for such investigation the present study was undertaken.

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