Relationship between Ballistocardiographic Forces and Certain Events in the Cardiac Cycle

By Oscar Tannenbaum, M.D., Jerome A. Schack, M.D., and Harry Vesell, M.D.

The temporal relationships of the various waves of the ballistocardiogram have been studied by means of simultaneously recorded electrocardiograms, femoral pulses, and electrokymograms of the great vessels and heart chambers. A modification of the Dock type of electromagnetic, undamped, direct ballistocardiograph has been employed in this study of 23 normal individuals. The total duration of mechanical systole in the great vessels has been found to correspond closely to the H-L interval. The HIJKL complex of the ballistocardiogram appears to be entirely related to the events of ventricular systole. The M, N and O waves represent after-waves occurring during diastole.

Henderson¹ studied the recoil curves of the heart and circulation as early as 1905 and attempted to derive cardiac output. For many years, little was done with this method until Starr² modified the apparatus and suggested its use not only for the measurement of cardiac output but also as a clinical tool in evaluation of the functional status of the heart. Starr and his co-workers extensively investigated ballistocardiography and described the findings in both health and disease. However, because of the bulkiness of the equipment, the method did not gain widespread clinical application until recently when Dock and Taubman³ described a simple, portable and easily constructed instrument which recorded the ballistic curve directly from the body.

The origin and naming of the various waves of the ballistocardiogram was described by Starr and his associates.² Nickerson,⁴ using a low frequency critically damped instrument studied the origin of the H and K waves by means of mechanical models and clinical observation. Hamilton⁵ investigated the ballistocardiographic forces in relation to cardiac ejection curves and came to the conclusion that the calculation of cardiac output by means of the ballistocardiogram was empiric and should be considered as comparative rather than absolute. He did feel, however, that qualitative study of the ballistic pattern might be of value in clinical medicine.⁶

With the advent of electrokymography in a stable, practical form,⁷ an excellent means of studying the temporal relationship of the ballistocardiogram to the events of the cardiac cycle was established. We have studied the relationship of the ballistocardiographic waves to the electrokymogram in the normal state.

Material and Methods

Twenty-three normal subjects ranging in age from 18 years to 38 years were selected. Ten were male and 13, female. The usual clinical criteria were used to judge these subjects normal: namely, history, physical examination, electrocardiogram, x-ray films of the chest, urinalysis and hemogram. The studies were all carried out at the same time of the day, usually three hours after eating. No attempt was made to secure a strict basal state. The following four events were simultaneously recorded on a four-channel, direct-writing oscillograph, the characteristics of which have been described elsewhere⁸: (1) the electrocardiogram lead I, (2) electrokymogram, (3) ballistocardiogram, (4) femoral sphygmo-gram. All tracings were taken with the subject in the recumbent position and with the breath held in midinspiration. Electrokymograms were obtained in the postero-anterior projection. The following points were selected: (1) midportion of the aortic knob, (2) pulmonary artery at the left cardiac border, (3) high left ventricle, (4) left ventricle near the apex. All recordings were made at a paper speed of 25 mm. per second.

The electrocardiogram was selected as the com-

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mon reference point for the timing of the various phases of the cardiac cycle. It was felt that the electrocardiogram was subject to little variation and did not have the lag factor present in the carotid sphygmmogram.11

The electrokymograph was of the type described by Henny and Boone14 consisting of a 931A RCA photocell, a high voltage power supply and a 120 cycle filter. The x-ray generator was of the full wave rectification type and was operated at 5 milliamperes and between 60 and 75 kilovolts, depending on the thickness of the subject. The movements were recorded with a delay of 0.02 second which is inherent in the equipment and presumably due to the filter.15 Repetitive tracings taken from identical points on the cardiac border in the same individual on successive days were found to be similar in contour and temporal relationships. However, the amplitude of these successive tracings was not constant. This difficulty has been encountered by other workers,14, 15 and is characteristic of the method.

The ballistocardiograph was of a modified electromagnetic (variable reluctance) type as described by Dock. This inscribed curves of the type obtained by the Starr table.15 Our modification consisted of the following: the coil consisted of a core of soft iron measuring 15 mm. by 10 mm. by 2 mm. and was wound in layers with 4,000 turns of number 40 enameled wire. This was connected to the recording galvanometer through a filter which consisted of a 2.5 millihenry choke in each lead and a 25 microfarad condenser across the coil. The coil was mounted on a suitable support such as a standard laboratory stand. It was placed exactly 10 mm. from the Alnico V magnet which is mounted on a wooden bar that is secured to the shins of the subject by means of elastic bands. The magnet measured 1 inch by 1 inch by \(\frac{3}{4}\) inch. The sensitivity of the galvanometer was adjusted so that 1 millivolt produced a 1 cm. deflection.

By introducing the iron core the sensitivity of the pickup system was increased manyfold, and thus we were able to employ a large gap between the coil and the magnet to facilitate standardization. A standard gap of 10 mm. was employed, thus allowing comparison of the amplitude of records. The filter was used to attenuate the high frequency vibrations due to muscle tremors as well as much of the stray alternating current present. The filter introduced no lag. This was determined in the following manner: The coil was mounted on its support 10 mm. from the magnet which was attached to its wooden mount. A silver contact was fixed about 6 mm. from the magnet. A similar silver contact fixed to a swinging arm acted as a switch to close a circuit which introduced a 1 millivolt signal into one channel of the galvanometer. The other channel of the galvanometer was connected to the pickup coil. Thus when the swinging arm struck the contact on the mount of the magnet, two signals were simultaneously intro-

duced, one mechanical and the other electrical. These were recorded at a speed of 50 mm. per second. The take-off points on the two curves so inscribed were exactly simultaneous. A similar procedure was employed with the subject connected and the blow delivered to the shoulder. No lag was observed. With this system repeat tracings taken at weekly intervals upon the same subject were identical in all respects. Thus the variable reluctance direct ballistocardiograph may be expected to yield completely reproducible tracings when used under the conditions of standardization described.

The femoral pulse was recorded by means of a piezo-electric pickup as described by Miller and White13 which is free of lag.

![Fig. 1. Simultaneous recording of the electrocardiogram, ballistocardiogram, electrokymogram, and femoral sphygmmogram; paper speed 25 mm. per second; time lines are 0.04 second apart. (See text for discussion.)](http://circ.ahajournals.org/doi/abs/10.1161/01.CIR.27.2.587)

All deflections obtained were related to the onset of the QRS complex of the electrocardiogram. Measurements were compared in cycles of equal duration in a given subject. The following intervals of the electrocardiogram were measured: R-R, P-R, QRS, and Q-T. The ballistocardiograms were analyzed as follows: the onset ("h") and the peak of the H wave to the peaks of each of the succeeding waves (for example, I, J, K, L) were measured. The time interval from the initial QRS wave of the electrocardiogram to the peak of each ballistic wave was measured.

The points measured on the electrokymogram were the conventional ones described by Boone

* Onset of H wave is designated "h".
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and co-workers, Heyer, Engström and co-workers, and Anderson. In the great vessels (pulmonary artery at the left cardiac border and the aortic knob) the rapid ejection phase of the ventricles was measured from the beginning of the rise of the anacrotic limb to the peak. From this point to the incisura was considered the period of reduced ejection. Total ejection time was represented by the sum of the rapid and reduced ejection phases. The isometric contraction phase was not measured because of the difficulty of delineating this portion of the curve. The ventricular electrokymogram was similarly analyzed. Because of the marked variability in these curves, we were unable to draw any satisfactory conclusions from them. Similar difficulties have been encountered by other observers. We have consequently utilized the pulmonary artery and aortic curve. The validity of these has been substantiated by comparison with intraluminal pressure curves. The various points on the curves of the electrokymogram were related to the onset of the initial QRS wave of the electrocardiogram.

In relating the electrokymographic curves to the ballistocardiogram, the factor of lag due to transmission time of the pulse wave in the great vessels had to be considered. The transmission time from the ascending aorta to the aortic knob has been reported by various observers to be 0.015 second. The lag factor for the pulmonary artery is of a similar degree. We have determined this to be 0.015 second by means of successive recordings of the electrokymogram of the pulmonary artery near the root in the right anterior oblique and at the left cardiac border in the postero-anterior projection.

The femoral pulse curve was related to the initial QRS of the electrocardiogram and to the waves of the ballistocardiogram.

**Table 1.—The Relationship of the Various Waves of the Ballistocardiogram to Each Other and to the Onset of Electrical Systole**
(Time in Seconds)

<table>
<thead>
<tr>
<th></th>
<th>R-R</th>
<th>h*</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>QIH</th>
<th>QH</th>
<th>QL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.58</td>
<td>0.08</td>
<td>0.04</td>
<td>0.04</td>
<td>0.06</td>
<td>0.05</td>
<td>0.01</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Max</td>
<td>1.12</td>
<td>0.14</td>
<td>0.08</td>
<td>0.08</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>Mean</td>
<td>0.74</td>
<td>0.11</td>
<td>0.05</td>
<td>0.06</td>
<td>0.09</td>
<td>0.09</td>
<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.13</td>
<td>0.018</td>
<td>0.014</td>
<td>0.01</td>
<td>0.015</td>
<td>0.019</td>
<td>0.018</td>
<td>0.019</td>
<td>0.023</td>
</tr>
</tbody>
</table>

* Denotes onset of the H wave to the peak of I. All others designate the peak of the ballistic wave.
† Denotes Q wave when present or onset of R to onset of the H wave of the ballistocardiogram.

Results

1. Inter-relation of the Various Waves of the Ballistocardiogram. Table 1 summarizes the relationship of the various waves of the ballistocardiogram to each other. It will be noted that these relationships were quite constant and varied little from the mean. Comparison of the H–I, I–J, J–K, and K–L intervals with cycle length (R–R) revealed no significant correlation at the cardiac rates observed.

2. Relation of the Ballistocardiogram to the Electrocardiogram. The interval between the onset of the P wave of the electrocardiogram and the beginning of the H wave ("h") of the ballistocardiogram varied from 0.12 second to 0.20 second with an average of 0.17 second (see table 2).

The relationship of each of the deflections of the ballistocardiogram to the onset of electrical systole was constant. Table 1 relates the onset of electrical systole to peaks of the various ballistic waves. It will be noted that the total variations of the Q–I, Q–J, and Q–K intervals did not exceed 0.08 second. Q–L had a much wider range, 0.17 second. Q–H had the least variation, 0.05 second.

3. Relation of the Ballistocardiogram to the Electrokymogram. The onset of the anacrotic limb of the aortic electrokymogram was almost synchronous with the peak of the H wave. The interval was −0.02 second, ±0.026 second. It is of interest to note that 14 of the 22 measurements relating the peak of the H wave to the onset of the anacrotic limb of the aortic electrokymogram occurred from −0.02 to +0.02 second. The onset of the anacrotic limb of the pulmonary artery electrokymogram was more nearly synchronous with the onset of the H wave ("h") than with the peak of the H wave of the ballistocardiogram. This interval was 0.006 second, ±0.03 second.

The peak of the anacrotic limb of the aortic
electrokymogram corresponded in time to the peak of the J wave of the ballistocardiogram with a mean of 0.005 second, ±0.01 second. A similar time relationship existed between the peak of the anacrotic limb of the pulmonary artery electrocardiogram and the J wave with a mean of −0.005, ±0.04 second. The relationship of the peak of the L wave of the ballistocardiogram to the incisura of the aortic wave of the electrokymogram ranged from plus to minus 0.05 second, with two exceptions. The mean was 0.005 second, ±0.06 second. When the peak of the L wave was related to the incisura of the pulmonary artery
electrokymogram from 0.10 second to 0.24 second, with a mean of 0.13 second and 0.17 second respectively. The H–J interval (0.08 to 0.14 second, mean 0.11 second) was in close agreement with the duration of the phase of rapid ejection. The reduced ejection phase in the aortic electrokymogram and pulmonary artery electrokymogram agreed closely with the measurements of the J–L interval which ranged from 0.13 second to 0.24 second with an average of 0.17 second.

5. Relation of the Femoral Sphygmogram to the Ballistocardiogram and the Aortic Electroky- mogram. The onset of the ascending limb of the

<table>
<thead>
<tr>
<th>Table 2.—The Relationship of Certain Ballistocardiographic Waves to the Ejection Phase in the Great Vessels Electroky- mogram</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Time in Seconds)</td>
</tr>
<tr>
<td>Min. ...............</td>
</tr>
<tr>
<td>Max. ...............</td>
</tr>
<tr>
<td>Mean ...............</td>
</tr>
<tr>
<td>Sigma ..............</td>
</tr>
</tbody>
</table>

* “h” denotes the onset or foot of the H wave.
† “H” denotes the peak of the H stroke.
‡ “I” denotes the peak of the I-J stroke.
§ “L” denotes the peak of the K-L stroke.

Negative sign signifies the event precedes the reference wave of the ballistocardiogram; positive sign signifies the event follows the reference wave of the ballistocardiogram in time.

curve of the electrokymogram, the interval was found to be −0.02 second, ±0.04 second.

4. Relation of the Ballistocardiogram to the Ventricular Ejection Phases in the Great Vessel Electroky- mograms and to Electrical Systole. Comparison was made between electrical systole (Q–T interval), mechanical systole as reflected in the electrokymograms of the great vessels, and the H-L interval of the ballistocardiogram. The mean Q–T interval was 0.31 second. The mean mechanical systole of the ventricle as derived from the aortic electrokymogram was 0.30 second, and as derived from the pulmonary artery electrokymogram was 0.34 second. The mean h-L interval was 0.34 second.

The rapid ejection phase of the aortic electroky- mogram ranged from 0.08 second to 0.20 second, and that of the pulmonary artery elec- femoral pulse wave was almost synchronous with the peak of the J wave of the ballistocardiogram. The difference in time between these two was only 0.00 second to 0.05 second, with an average of 0.02 second. The peak of the femoral pulse wave coincides roughly with the bottom of the K wave of the ballistocardiogram, with a difference of 0.01 second to 0.08 second, average 0.03 second. The time interval from the onset of the anacrotic limb of the aortic electrokymogram to the onset of the femoral pulse wave ranged from 0.075 second to 0.135 second, with an average of 0.11 second in 16 of the subjects studied. This interval was in close agreement with the H–J time of the ballistocardiogram, which ranged from 0.08 second to 0.14 second, average 0.13 second.
**Table 3.—The Relationship of the Ballistocardiogram and the Ejection Phases in the Great Vessels**

(Time in Seconds)

<table>
<thead>
<tr>
<th></th>
<th>Rate</th>
<th>ECG</th>
<th>BCG</th>
<th>EKY</th>
<th>BCG</th>
<th>EKY</th>
<th>BCG</th>
<th>EKY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>0.58</td>
<td>0.22</td>
<td>0.27</td>
<td>0.20</td>
<td>0.20</td>
<td>0.10</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>Max.</td>
<td>1.12</td>
<td>0.40</td>
<td>0.42</td>
<td>0.40</td>
<td>0.41</td>
<td>0.14</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Mean</td>
<td>0.74</td>
<td>0.31</td>
<td>0.34</td>
<td>0.30</td>
<td>0.34</td>
<td>0.11</td>
<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.13</td>
<td>0.04</td>
<td>0.036</td>
<td>0.053</td>
<td>0.056</td>
<td>0.014</td>
<td>0.033</td>
<td>0.036</td>
</tr>
</tbody>
</table>

* From onset anacrotic limb of great vessel electrokymogram to the dicrotic notch (hence includes protodiastole).

† From onset anacrotic limb of great vessel electrokymogram to peak of anacrotic limb great vessel electrokymogram.

‡ From peak of anacrotic limb great vessel electrokymogram to dicrotic notch.

**Discussion**

The H wave is the initial headward deflection of the ballistocardiogram. Various theories of its origin have been advanced. Hamilton\(^1\) has related it to the apical thrust and isometric contraction of the ventricles. Nickerson,\(^4\) on the other hand, felt it was produced by auricular contraction, whereas de Lalla and Brown\(^20\) have postulated that its origin was due to the deceleration of the auricular impulse wave by venous arches in the neck, or skull, or both. In our studies the onset of ventricular ejection as indicated by the aortic electrokymogram occurred on the average 0.02 second before the peak of the H wave of the ballistocardiogram, whereas the onset of the H wave ("h") of the ballisto-

cardiogram occurs 0.04 second before the onset of ejection into the aorta. From this data one can infer that the peak of the H wave corresponds to the onset of the rapid ejection phase of the ventricle and that the onset of the H wave ("h") probably is associated with isometric contraction of the ventricle.

In previous studies in man and animal\(^22\) the isometric contraction phase has been found to average about 0.05 second. This would confirm the impression that the period between the onset of the H wave ("h") and the peak of the H wave corresponds to the period of isometric contraction of the ventricle. The average time between onset and peak of the H wave of the ballistocardiogram is about 0.05 second (range 0.04 second to 0.08 second). Furthermore, the onset of the P wave of the electrocardiogram to the onset of the H wave ("h") of the ballistocardiogram varied from 0.12 second to 0.20 second, with an average of 0.17 second (see table 2), which is consistent with the findings of Coblenz and co-workers\(^22\) who, using direct catheter studies, found that the onset of the P wave of the electrocardiogram and the beginning of auricular systole varied from 0.05 second to 0.12 second (0.09 second, average) in the normal subject. This would indicate that the H wave was not produced by auricular contraction and that the formation of the H wave is a result of ventricular function.

The peak of the aortic and pulmonary artery curves of the electrokymogram corresponded closely in time to the peak of the J wave of the ballistocardiogram, the difference on the average being only from plus to minus 0.005 second. Thus the peak of J wave corresponds to the end of rapid ejection of both ventricles. When one compares the time from the peak of the H wave to the peak of the J wave of the ballistocardiogram with that of the rapid ejection phase of the aortic electrokymogram, there is rather close correlation (see table 3). One will note that the H–J time ranged from 0.08 second to 0.14 second, with an average of 0.11 second, which was equal to the time of rapid ejection of the left ventricle as measured in the aortic electrokymogram. The latter had an average time of 0.13 second with a range of 0.08 second to 0.20 second. This is in keeping with the
concept that the H−I stroke accompanies early ventricular ejection, and that the peak of the J wave demarcates the end of the rapid ejection phase of the ventricle.

The reduced ejection phase of the left ventricle as measured in the electrokymogram of the aorta ranged from 0.12 second to 0.25 second, with an average of 0.16 second. As has been shown previously, the peak of the J wave occurred at the same time as the peak of the anacrotic limb of the aortic curve of the electrokymogram, and the peak of the L wave of the ballistocardiogram, on the other hand, occurred at the same time as the incisura. Hamilton noted this relationship of the peak of the L wave to the incisura of the central pulse. When the J−L time of the ballistocardiogram is compared with the reduced ejection phase of the great vessels there is close correlation (see table 3). From these observations the L wave thus represents in reality a forced movement and not a passive after-vibration. It consistently occurred at the incisura, which for all intents and purposes is part of effective ejection phase of the ventricle (including protodiastole).

It should be emphasized that the onset of ventricular ejection occurred at the peak of the H wave of the ballistocardiogram and ended at the peak of the L wave (opening and closure of the semilunar valve). The rapid ejection phase corresponds to the H−J interval and the reduced ejection to the J−L interval. Thus the H−L interval serves as a measure of ventricular systole. As might be expected, this H−L interval varies little with increase in cardiac rate, the changes in rate affecting almost solely the M, N, O interval, or diastole.

Brown and de Lalla measured the H−K time and found it proportional to the size of the subject, and from this observation have stated that it is proportional to the transmission time of the aortic wave. Hamilton found that the peak of the femoral pulse is on the average coincident with the valley of the K wave of the ballistocardiogram. He could not change this relationship by occluding the arteries of the legs with pressure cuffs. Nickerson found a change in the K wave in subjects with coarctation of the aorta and felt that the shortening of the aorta or constriction of this vessel led to a disappearance of the K wave. Further, he placed cuffs on the thighs and raised the pressure therein to above systolic levels for a period of 15 minutes, then released the constriction, causing a reactive hyperemia of the lower extremities. This produced an increase in the slope of the I to J movement of the ballistocardiogram and a decrease in the relative depth of the K wave.

In our studies we have measured the interval from the onset of ventricular ejection (on the aortic electrokymogram) to the onset of the femoral pulse wave, and have found an average time of 0.11 second, which compares with the transmission time of the pulse wave observed by others. Furthermore, this transmission time coincides with the H−J time (see table 4). The H−K time is almost twice as long (average 0.20 second). The H−K time is equal to the time of transmission of the pulse wave from the root of the aorta to the onset of the tibial pulse. The K wave may thus very well represent the reflection of the blood column in the arterioles in the distal part of the lower extremities. This may explain the increased I−J stroke and diminished depth of the K wave reported by Nickerson after induced reactive hyperemia of the lower extremities.

**Summary**

Simultaneous electrocardiogram, ballistocardiogram, aortic and pulmonary artery electrokymograms and femoral sphygmogram were recorded in 23 normal subjects.

The onset of ventricular ejection occurred at
the peak of the H wave. The onset of the H wave ("h") to the peak of the H wave represented isometric contraction phase of the ventricle. The peak of the J wave occurred at the peak of ventricular ejection phase of the aortic electrokymogram. The peak of the L wave of the ballistocardiogram was coincident with the incisura of the aortic electrokymogram. The rapid ejection phase corresponded to the H–J period and reduced ejection to the J–L period. The H–J time was equal to the transmission time of the pulse wave from the root of the aorta to its arrival at the femoral artery. The K wave may represent reflections of the blood column striking the arterioles in the distal part of the lower extremities.

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