Ballistocardiography

II. The Normal Ballistocardiogram

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In this study, the normal ballistocardiogram is interrelated with various cardiac events in order to establish the origin of its component waves. It is apparent that the ballistic F, G, H, I, J, K, L, M and N waves bear a definite relationship to known cardiac events, although in some cases the temporal positioning of the complexes is shifted by uncontrollable forms of distortion. When calculated correction factors are introduced, the ballistic waves tend to assume their correct temporal relationship. A composite pictorial sketch is presented which shows the temporal relationships of the phonocardiogram, the apex cardiomgram, two commonly observed forms of the normal ballistocardiogram, the electrocardiogram, and the carotid pulse.

In order to establish the origin of the component waves which comprise the ballistocardiogram, it is essential to interrelate the ballistocardiogram with simultaneously registered physiologic events which result from cardiac activity. To date, most investigators have been content with merely establishing the identity of a representative ballistic wave such as the H and then calling the subsequent waves by the usual J, K, L, M, N and O terminology. When such procedure is used, a simultaneously registered electrocardiogram is generally adequate as its R wave occurs approximately prior to the ballistic H wave. The carotid pulse has also been used for establishing such relationship as it has been considered a fair indicator of the onset of mechanical systole. The possibilities of the phonocardiogram as a timing reference were suggested by Starr and his associates in 1939 and more recently by Gubner. Jones and Goulder recently stated that their limited experience with the phonocardiogram as a reference tracing indicates that it is a more reliable measure of the onset of mechanical systole. DeLalla observed that the ballistic H wave is nearly synchronous with the first heart sound. Nowhere in the literature is there any evidence to indicate that anyone has taken full advantage of the phonocardiogram as a means for timing the mechanical events in systole and diastole as related to ballistic activity.

Messer and co-workers have shown that the phonocardiogram is a more accurate reference tracing than the electrocardiogram for the exact timing of the beginning of mechanical systole and diastole. Others have noted that inaccuracies occur in the determination of the exact onset of mechanical systole by the use of the carotid surface pulse. Although the electrocardiographic R wave is helpful as a rough reference for indicating the beginning of mechanical systole, comparative measurements indicate that the carotid pulse is more reliable than the electrocardiographic R wave but less precise than the phonocardiogram.

The beginning of mechanical systole is indicated in the carotid pulse wave by the rapid or primary deflection which represents the beginning of the rapid ejection of blood into the aorta. Factors such as the amount of pressure which is applied to the artery and the
method of sensing may affect the indicated time of the initial rapid rise in the graph in the form of a delayed onset; the transmission time of the pulse must also be taken into consideration.

Methods and Material

In this investigation, we employed as reference tracings the phonocardiogram, the various peripheral pulses, the apex cardiogram and the electrocardiogram. The subjects investigated consisted of a group of clinically normal men between the ages of 23 and 47 years. Individual body types varied from ectomorphic to endomorphic, but no extremes of any type were present. The professional staff, postgraduate and medical students in the hospital comprised this group. No athletes in training were included and all subjects were in excellent health.

Fig. 1. Simultaneously recorded phonocardiogram, ballistocardiogram and venous pulse. The ballistic F wave registers simultaneously with the auricular pulsation in the phonocardiogram and the venous pulse. Camera speed, 75 mm. per second.

The normal control tracings were obtained at any hour of the day, including in some instances the immediate postprandial period. The type of ballistocardiograph used, its characteristics and the ballistocardiographic techniques employed have been discussed in part I of this paper.

The ballistocardiograms were first analyzed with regard to the events represented in the phonocardiogram, the electrocardiogram, the apex cardiogram, the carotid pulse, radial pulse, femoral pulse, jugular pulse, liver pulsations, epigastric pulsations and the aortogram. We observed that the radial pulse, the liver pulsations and the epigastric pulsations were of little value in evaluating the ballistocardiographic complexes and their registrations were subsequently discontinued. The venous pulse which was taken over the internal jugular bulb is difficult to register consistently when the subject is in a supine position such as is required for ballistocardiography. The limited number of satisfactory venous pulse tracings which were obtained did show a constant and finite relationship to the ballistocardiogram. These registrations were helpful when satisfactorily recorded.

Observations

F Wave. A wave which we shall call the F wave was found to be present in the majority of ballistocardiograms. This wave is a positive deflection of varying magnitude which occurs before the ballistic G wave and may be seen in figure 1. If the cardiac rate is rapid, it may be lost in the preceding complex. In the normal subject the F wave occurs simultaneously with the auricular sound in the phonocardiogram, between the electrocardiographic P and Q waves, and coincides with the auricular wave of the apex cardiogram. When a satisfactory venous pulse was registered, its a wave also coincided with the ballistic F wave. From these observations it is suggested that the ballistic F wave may be of auricular origin.

G Wave. This is a negative deflection, observed by DeLalla, which precedes the ballistic H wave. Our observations also show the presence of a G wave and our records show that it is related to the third component of the first heart sound which is the opening of the semilunar valves and the beginning of mechanical ventricular systole (fig. 2). Our records also show that the second positive peak of the apex cardiogram which denotes semilunar valve activity (fig. 3), as well as the onset of the surface carotid pulsation, coincide with the G wave (fig. 4). The onset of the c wave of the venous pulse coincides with the ballistic G wave.

H Wave. This wave appears to occur simultaneously with the fourth component of the first heart sound which is best registered on the stethoscopic phonocardiograms (fig. 2). The ballistic H wave also coincides with the second negative deflection, on the descending slope of the negative wave or the rise of the systolic plateau in the period denoted as systole in the apex cardiogram (fig. 3). Some temporal variations have been observed in this respect which may be due to phase shift effects upon the ballistocardiographic complexes described in part I of this paper.

The fourth component of the first heart

* Since the completion of this paper, a reference to this wave has been made by Luisada, A. A. and Contro, S.: On the time relationship of the waves of the ballistocardiogram, Acta Cardiologica, 5: 847, 1951.
sound has been ascribed to the acceleration of blood in the great arterial vessels during the ejection phase of ventricular systole. The above observation, together with that concerning the ballistic I wave, offers an alternate possible cause of the fourth component of the first heart sound and will be discussed in a later communication. The apex of the venous pulse c wave appears to occur simultaneously with the ballistic H wave.

I Wave. The ballistic I wave seems to register at the end of the fourth component of the first heart sound (fig. 2). The I wave appears to terminate with the coarse vibrations in the apex cardiogram which denote systolic activity, or, in a different apex configuration, it may occur at the end of the maximal ejection phase (fig. 3).

![Fig. 2](image)

**Fig. 2.** Simultaneously registered phonocardiograms, ballistocardiograms and electrocardiograms which show: (1) The ballistic F wave is related to the auricular sound of the phonocardiogram. (2) The ballistic G wave occurs with the opening of the semilunar valves. (3) The ballistic H wave is related to the fourth component of the first heart sound. (4) The ballistic I wave occurs with the terminal portion of the fourth component of the first heart sound. (5) The ballistic J wave occurs with the early coarse vibrations in systole. (6) The ballistic K wave is related to the closure of the semilunar valves. (7) The ballistic L wave is related to the opening of the atroventricular valves. (8) The ballistic N wave corresponds to the rapid inflow phase or the third heart sound. Camera speed, 75 mm. per second.

![Fig. 3](image)

**Fig. 3.** Simultaneously registered phonocardiograms, ballistocardiograms and apex cardiograms which show their interrelationship. Some inherent phase distortion is evident in the ballistocardiograms. Camera speed, 75 mm. per second.

We have further observed that the ballistic I wave occurs with the anacrotic notch of the surface carotid pulsation and at times slightly delayed, but always occurs prior to the peak of the surface carotid pulse (fig. 4). Similar variation due to respiratory effects or phase displacement was noted in the abdominal aortogram where the ballistic I wave was simultaneous with the beginning of the incisura or occurred within about 0.04 second prior to the incisura (fig. 5). The onset of the femoral surface pulse was roughly simultaneous with
Simultaneously registered phonocardio-grams, ballistocardiograms and carotid pulsations of two subjects with differing heart rates and different degrees of phase distortion. The upper tracing shows more clearly the relationship of the ballistic G wave and the onset of the carotid pulse, the ballistic I wave with the anacrotic notch, and the ballistic K wave with the dicrotic notch of the carotid pulse. Camera speed, 75 mm. per second.

The ballistic J wave seems to register with the coarse vibrations in early systole which are generally well registered in the stethoscopic phonocardiogram (fig. 2). In one subject it was found to occur simultaneously with a systolic click in the phonocardiogram. No definite relationship to the ballistic I wave as was observed by Hamilton16 (fig. 6).

J Wave. The ballistic J wave usually is related to the ascending slope of the femoral pulse and roughly with the peak of the carotid and abdominal aortic pulsations (figs. 4, 5, and 6).

K Wave. The ballistic K wave occurs with the second component of the second heart sound13 which is due to the closure of the semilunar valves (fig. 2). We have not found the ballistic K wave to coincide with the peak of the apex cardiogram has been observed.
of the femoral pulse as was observed by Hamilton but to coincide with the descending slope of the femoral pulse (fig. 6). The dicrotic notch of the carotid pulse and the peak of the ballistic K wave are usually simultaneous with the L wave. The normal ballistocardiographic patterns were divided into two different groups depending upon the presence or absence of the L and M waves. At times abortive L and M waves could be found, whereas at other times a prolonged K peak was observed. A sharp, "normal" K peak was also observed in the absence of L and M waves.

The ballistic L wave when present coincides in temporal positioning with the fourth com-

![Diagram](image-url)
ponent of the second heart sound which is the opening of the auriculoventricular valves (fig. 2). This is further confirmed by the fact that the L wave is simultaneous with the negative deflection O present in the apex cardiogram between the peak caused by the closure of the semilunar valves and the peak of the rapid filling wave. The \( v \) wave of the venous pulse appears to coincide with the ballistic L wave.

**M and N Waves.** Regardless of the presence or absence of the ballistic L or M waves, the ballistic N wave was found to occur with the third heart sound in the stethoscopic phonocardiogram (fig. 2). Also, the ballistic N wave occurs simultaneously with the peak of the rapid filling wave (fig. 3) or it may be slightly delayed. The slight delay may be explained by the phase shift phenomenon discussed in the first part of this paper.

**DISCUSSION**

The various peripheral pulsations and the phonocardiograms which were registered on normal subjects in this study indicate that the various component waves of the ballistocardiogram bear a definite relationship to these physiologic events. In some cases, the ballistic waves coincide exactly with the events that are distinctly registered in the sphygmograms and the phonocardiograms. Sphygmographic and phonocardiographic events are reasonably well known and one is definitely tempted to draw conclusions as to the origin of the ballistic waves which tie in so closely. In other cases, the ballistic events do not occur exactly synchronously. In these cases, the natural frequency and degree of damping of the subject were determined. From these values, the approximate degree of phase shift could be estimated. An exact evaluation cannot be obtained as other variables are present which cannot be accounted for. However, when an approximate correction factor is added, the ballistic waves seem to approach a temporal positioning which bears a distinct relationship to the complexes of the sphygmogram and phonocardiogram.

For ballistocardiographic studies it should be possible to devise a table or chart wherein the approximate phase shift that occurs in the subject may be readily determined if the underdamped oscillation is registered by the technic described in part I of this paper. The amount of phase shift that may be present in the instrument may be also compensated for although, as previously discussed, a well-designed instrument should introduce minimal distortion of this type.

In view of the fact that no one ballistocardiogram shows all observed relationships discussed in this paper, it was felt that a composite pictorial sketch would be helpful. Two patterns of ballistocardiogram and their relationship to the phonocardiogram, the apex cardiogram and the electrocardiogram are shown in figure 7.

**Conclusions**

In the ballistocardiograms of normal subjects as registered by the photoelectric displacement type ballistocardiograph, the following observations were made:

1. A positive deflection which precedes the G and H waves was noted which we have arbitrarily named the F wave. It bears a temporal relationship to the auricular sound in the phonocardiogram, to the auricular wave in the apex cardiogram, to the auricular wave in the venous pulse, and to the P and Q waves in the electrocardiogram. These relationships suggest that the ballistic F wave is of auricular origin.

2. The G wave was observed to occur at the time of the third component of the first heart sound on the phonocardiogram, at the time of the second positive deflection in the apex cardiogram, and at the onset of the surface carotid pulse. These physiologic events represent the opening of the semilunar valves.

3. The H wave occurs with the fourth component of the first heart sound. When related to the apex cardiogram, the H wave is temporally related to the various waves denoting systolic activity immediately following the opening of the semilunar valves.

4. The I wave appears to be related to the terminal portion of the fourth component of the first heart sound, and terminates with the
coarse wave components which are related to the first heart sound in the apex cardiogram. The I wave also occurs with the anacrotic notch of the carotid pulse, the beginning of the incisura of the aortogram, and the onset of the femoral pulse.

5. The J wave occurs with the terminal coarse vibrations of systole as indicated by the stethoscopic phonocardiogram and, generally, with the peaks of the carotid pulse and abdominal aortogram.

6. The K wave registers with the second component of the second heart sound and with the vibrations in the apex cardiogram which denote the closure of the semilunar valves. The dicrotic notch of the carotid pulse and the ballistic K wave are also temporally related.

7. The L wave when present occurs at the time of the opening of the auriculoventricular valves as denoted by the fourth component of the second heart sound and by the valley which precedes the rapid inflow phase of blood into the ventricles.

8. The N wave occurs with the third heart sound and with the peak of the rapid filling wave of the apex cardiogram.

9. When displacement type ballistocardiograms are registered simultaneously with other physiologic events on normal subjects, the temporal relationships as discussed may not be exactly simultaneous. The cause is apparently due to phase distortion which occurs in the subject's body and the major corrective factors may be determined by calculation. It is almost impossible with our present knowledge and technics accurately to eliminate all variables as they affect phase displacement in the ballistocardiogram. At best, and until we can completely circumvent all forms of distortion, the timing of the ballistocardiogram with respect to other physiologic events of cardiac origin can only be approximated.

Sumario Español

En este estudio el balistocardiograma normal se interrelaciona con varios acontecimientos cardiacos de manera de establecer el oxigen de las ondas componentes. Es aparente que las ondas F, G, H, I, J, K, L, M y N balísticas tienen una relación definitiva a acontecimientos cardíacos, aunque en algunos casos la posición temporal de los complejos se cambia debido a formas de distorsión no controlables. Cuando los factores de corrección se introducen, las ondas balísticas tienden a asumir las relaciones temporeras correctas. Un esbozo gráfico compuesto se presenta que demuestra las relaciones temporeras del fonocardiograma, el cardiograma del ápice, dos formas corrientemente observadas del balistocardiograma normal, el electrocardiograma y el pulso carótido.

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