On Certain Abnormal Ballistic Complexes: Their Relationships to Other Mechanical and Electrical Events of the Cardiac Cycle

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Ballistocardiograms were recorded simultaneously with intra-atrial and intra-aortic pressure curves, heart sounds, electrokymograms and electrocardiograms in patients with various types of heart disease. In several of these subjects, in addition to the usual ballistic waves, abnormal sets of ballistic complexes occurred. In some individuals, one or more of these abnormal ballistic complexes was so prominent that it dominated the entire ballistocardiogram. By correlating the abnormal ballistic waves with other dynamic and electrical events, we have secured information which throws light on the genesis of certain abnormal waves and of the so-called H wave in the ballistocardiogram.

Ballistocardiograms of individuals with heart disease may show a wide variety of abnormalities. Starr, Hamilton, Nickerson, Brown, and others have described many abnormal ballistic patterns associated with various clinical entities. The purpose of this study has been to establish a physiologic basis for some of these abnormal waves, by recording ballistic and other circulatory phenomena simultaneously.

Material and Method of Study

Recording Methods and Equipment. The ballistocardiograms used in this investigation were the original electromagnetic and the modified photoelectric (Sanborn) types developed by Dock and Taubman. Through the courtesy of Dr. Isaac Starr, we were also able to obtain one to three tracings by the table ballistocardiograph in each of our patients for comparative study. Ballistocardiograms taken with these three sets of instruments were found to check accurately in form and timing. Catheterizations of the right atrium and aorta were done by the small plastic catheter technic utilizing a Lilly capacitance manometer as described by Fitzpatrick,

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Schnabel, and Peterson. The time lag of this arrangement was about 0.002 second. The electrokymographic equipment was of the type developed by Henny, Boone, and others, and manufactured by the Cambridge Instrument Company. The time lag of this instrument has been calibrated at 0.015 second with a frequency range of 1 to 35 cycles per second. The apex impulse was recorded by means of a glycerine capsule. The deflections were amplified through a Lilly capacitance manometer. The phonographic, lead II electrocardiographic, and other recordings were all taken on a Sanborn tribeam instrument with film speeds of 25 mm. and 75 mm. per second.

Technically, it was impossible to record all the hemodynamic phenomena simultaneously, and as a result, multiple recordings in various combinations of three were taken simultaneously with the phonocardiograph and/or the electrocardiograph. In order to avoid unnecessary repetition and confusion in presentation of the data, some of the illustrations were traced from the actual records with the electrocardiogram used for reference.

Selection of Patients. Subjects were selected in whom abnormal sets of ballistic waves could be isolated from each other and from the usually recorded waves by a distinct separation in time. Suitable examples were found in patients with the following types of disorders:

1) Complete atrioventricular heart block with a slow ventricular rate. 2) Prolonged atrioventricular conduction time with presystolic gallop sound. 3) Congestive heart failure with presystolic gallop sound. 4) Constrictive pericarditis with a loud third heart sound in protodiastole. 5) Asynchronous ejections of the two ventricles. 6) Combinations of the above mentioned abnormalities.

Method of Study. All subjects had rested in the recumbent position for half an hour prior to the
beginning of the study. They were instructed to stop breathing momentarily without straining, while the recordings were being made. Initially, a ballistocardiogram was obtained simultaneously with an electrocardiogram and a phonocardiogram. Examination of the preliminary tracings made it possible to determine the exact position of the abnormal ballistic complex in the cardiac cycle, and hence gave a clue to the origin of the hemodynamic impact. If such inspection showed that an abnormal ballistic complex appeared in diastole, at either the early or the late phase of ventricular filling, the right atrium was catheterized, and electrokymographic recording of the right ventricular border movements were made. If abnormal ballistic waves were present in systole, electrokymograms of the aortic and pulmonary arterial pulsations, as well as intra-aortic pressure curves, were taken. An apex impulse was recorded in all patients studied. In a few patients, studies of the mechanical events of both the right and left sides of the heart were made with catheterization and electrokymogram, on separate occasions, in correlation with the ballistocardiographic waves.

As an illustration of the recordings obtained in this study, figure 1 shows a normal ballistic complex from a healthy medical student, recorded simultaneously with heart sounds and electrocardiogram, at a film speed of 75 mm. per second. The usual H, I, J, K waves and the vibrations in diastole are clearly defined.

**RESULTS**

*Studies on Diastolic Ballistic Complexes.* Diastolic ballistic complexes were seen in our subjects either following atrial contraction or in protodiastole. Patients with complete A-V heart block show small ballistic complexes following each atrial contraction.3, 11, 19 Figure 2 is a record obtained from a patient with complete A-V heart block. It shows a series of small ballistic deflections in diastole and a faint atrial sound (A) following the P wave of lead II of the electrocardiogram. The systolic complex is essentially normal, except that no H wave is present.

That these ballistic complexes are related to atrial contractions can be seen in figure 3, which shows recordings obtained in another patient with complete A-V heart block. Figure 3A shows the relationship of the right atrial pressure curve to the P waves of the electrocardiogram. In figure 3B, the series of small ballistic deflections of atrial origin can be seen following the peaks of the right atrial pressure curve.

Figure 4 demonstrates the atrial origin of the H wave in a third patient with complete A-V heart block. This continuous tracing clearly shows that when the P-R interval is of normal duration, a small H wave is present in the ventricular ballistic complex. When the atrial and ventricular contractions are widely separated the series of small atrial ballistic deflections are evident and no H wave is seen in the ventricular ballistic complex.

![Fig. 1. Ballistocardiogram of a healthy medical student, taken simultaneously with phonocardiogram and electrocardiogram. Film speed 75 mm. per second.](image1)

![Fig. 2. Ballistocardiogram of patient S.Z. with complete A-V heart block, taken simultaneously with phonocardiogram and electrocardiogram. The atrial and ventricular ballistic complexes are circled in dotted lines. Film speed 25 mm. per second.](image2)

To further demonstrate the dynamic relation of atrial systole to the series of small diastolic ballistic deflections, studies obtained from patient J. C. with arteriosclerotic heart disease, congestive failure, prolonged P-R conduction time, and a presystolic gallop sound are shown in figure 5. The gallop sound could be heard, as shown in the sound record (G); and felt, as shown by a small presystolic thrust in the apex impulse recording. These events oc-
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curred immediately after the peak of the right atrial pressure curve, and were thus associated with atrial contraction and ventricular filling.

The manner in which late diastolic ballistic movements followed the P wave of the electrocardiogram and the increase in pressure in the right atrium in our patient with presystolic gallop sound and a small presystolic apical thrust are present. The familiar series of small ballistic deflections follows the peak of the intra-atrial pressure curve in the usual manner.

![Image of recordings](http://circ.ahajournals.org/)

**Fig. 3A and 3B.** Recordings obtained from patient C. J. with complete A-V heart block, showing relationships between the ballistocardiogram and the intra-atrial pressure curve and the electrocardiogram.

![Image of recordings](http://circ.ahajournals.org/)

**Fig. 4.** Continuous tracing of patient L. K. with complete A-V heart block, showing the atrial origin of the H waves.

gallop rhythm is illustrated in figure 6. Patient W. S. had severe hypertension, complicated by congestive failure. He had a mechanical pulsus alternans as shown in the electrokymographic recordings of the left ventricular border and of the aorta. The first left ventricular contraction is more complete and results in a larger aortic pulsation than that of the second. The systolic ballistic complex is seen to vary in amplitude with the strength of the beat. It is interesting to note that the diastolic ballistic complex at the end of the first beat is larger than that of the following systolic complex. A presystolic gallop sound and a small presystolic apical thrust are present. The familiar series of small ballistic deflections follows the peak of the intra-atrial pressure curve in the usual manner.

The upward deflection of this complex, occurring just before the ventricular ejection, may be interpreted as an H wave. Mechanical alternans is not present in the right intra-atrial pressure curve or in the diastolic ballistic complex.

Figure 7 shows recordings made from patient J. M., who has chronic constrictive pericarditis. A loud third heart sound in early
Sound E.C.G. 

Rt. atrial pressure curve 

Apex impulse 

B.C.G. 

E.K.Y. 

Aorta 

E.K.Y. 

Pulmon. artery 

Fig. 5. Recordings obtained from patient J. C. with arteriosclerotic heart disease, prolonged P-R interval, left bundle branch block, and presystolic gallop rhythm. The arrow points to the onset of pulmonary arterial pulsation. The notch at the middle of the upward limb of the E.K.Y. is a distortion caused by the onset of the adjacent aortic pulsation.

Sound E.C.G. 

Rt. atrial pressure curve 

B.C.G. 

Apex impulse 

E.K.Y. 

Lt. vent. 

Fig. 6. Recordings from patient W.S. with severe hypertension, presystolic gallop rhythm, and mechanical pulsus alternans.

diastole (G) ("the diastolic heart beat") is associated with an abrupt outward thrust of the apex impulse record, a rapid outward movement of the right ventricular wall as seen in the electrokymogram, and a rapid fall in the intra-atrial pressure. A series of small ballistic deflections very similar to those produced by active atrial contractions is seen to occur simultaneously with these events.

Studies on a Type of Abnormal Systolic Ballistic Complex. Figure 8 shows the studies made on patient M. R. She has congenital heart disease with interatrial septal defect. The ballistocardiogram shows two upward deflections prior to the J wave; one before and the other after the onset of the QRS complex of the electrocardiogram. The upward deflection before the QRS complex is associated with a group of presystolic vibrations in the apex impulse record, and is probably atrial in origin. The ventricular ejections are not synchronous. A reduplication of both the first (1, 1') and the second (2, 2') heart sounds is recorded phonographically. The pulmonary arterial ejection curve precedes the aortic ejection curve of the electrokymogram.

Fig. 7. Recordings from patient J. M. with chronic constrictive pericarditis, marked elevation of venous pressure, and a loud "diastolic heart beat" (G) in protodiastole.
and the intra-aortic pressure curve. The apex impulse shows a group of larger vibrations at the beginning of the ventricular contraction. The second upward deflection in the ballistocardiogram is observed to start with the systolic apical vibrations, which occurs after the QRS complex of the electrocardiogram, and immediately after the onset of the pulmonary arterial ejection. Thus, in this tracing, two prominent upward deflections appear in the ballistocardiogram during systole, corresponding to the asynchronous ejections of the two ventricles.

Figure 9 was recorded from patient A.S. with rheumatic heart disease, mitral stenosis, prolonged P-R interval with a presystolic auricular ballistic complex, also shows an abnormal systolic ballistic complex (fig. 5). The electrocardiogram demonstrates a bundle branch block. Studies of the complete electrocardiogram show this to be of the left bundle branch block type. The illustration again shows asynchronism of the ventricular contractions as indicated by the electrokymographic studies. This phenomenon is accompanied by a bifid systolic complex in the ballistocardiogram.

**FIG. 8.** Recordings from patient M.R. with congenital heart disease, interatrial septal defect, and splitting of the heart sounds.

and auricular fibrillation. An opening snap sound (o. s.) is recorded. The electrokymogram suggests that ventricular asynchronism is also present. The ballistocardiogram again shows two prominent systolic ballistic complexes. These complexes appear to correspond to asynchronous ejections of the two ventricles as shown by the electrokymographic recordings of the aorta and the pulmonary arterial pulsations. The first of these two upward deflections in the ballistocardiogram starts with the apical thrust and could be interpreted as an H wave.

The records obtained from the patient J.C. (presented above to show the association of the normal ballistocardiogram, the systolic excursion greatly exceeds the diastolic, so one can properly believe that the forces exerted by the many blood impacts in systole exceed those generated in diastole. However, in patients with heart disease, the hemodynamic forces other than those which are produced by the main ventricular contraction may become quite prominent. For this reason, ballistocardiograms of these individuals may show in addition to the usual ballistic waves, one or more sets of abnormal ballistic complexes. Sometimes, such
complexes may be large enough to dominate the entire ballistocardiogram. An understanding of the physiologic basis of these abnormal ballistic complexes is important in the interpretation of the abnormal ballistocardiograms.

The diastolic waves seen in the ballistocardiogram have aroused much interest and speculation. Hamilton and his associates\(^2\) believed that the L, M and N waves are related to waves oscillating back and forth in the ascending aorta. The O wave was thought to have its origin in the reflection of the pressure wave at the arterioles in the lower part of the body. On the other hand, Starr and Mayock\(^8\) in their study of abnormal ballistocardiograms, contended on clinical grounds that large diastolic waves were probably produced by a sudden inrush of blood into the heart under certain pathologic conditions. More recently, Dock and Taubman\(^9\) reported large L, M, and other diastolic waves in patients with rheumatic carditis and in other disease conditions where the rate of return of blood into the ventricles was thought to be increased and rapid. We are able to demonstrate diastolic complexes associated with gallop rhythms, which seem to favor the views held by Starr and by Dock and their associates. The series of small diastolic ballistic deflections produced by passive ventricular filling may be regarded as a factor in the formation of the terminal portion of the ascending limb of the L wave, and the M, N, O vibrations in the ballistocardiogram seen in the early part of the diastole in certain individuals. This belief is strengthened by our observation that these "after vibrations" in ballistocardiograms taken on healthy individuals with a loud third heart sound (fig. 1), are usually very well defined and prominent. Studies of the circulatory dynamics of these healthy individuals indicate that ventricular filling is completed in a short space of time in early diastole, and that ventricular ejection is forceful.

The ballistic waves of atrial origin were first reported by Starr and Schroeder,\(^4\) and an analysis of these waves in patients with complete A-V heart block was made by Nickerson.\(^11\) He felt that the first atrial ballistocardiographic deflection was upward and labeled it H. Recently, de Lalla, Epstein, and Brown\(^13\) reported similar diastolic patterns of atrial origin, but differed with Nickerson in believing that the first atrial ballistocardiographic deflection was in a downward direction, and was probably related to deceleration of blood and impulse wave by the ventricles. This deflection (G) was found to come immediately after the small upward wave labeled H by Nickerson. Dock and Taubman\(^18\) also observed deep downward ballistic waves due to deceleration of blood in diastole, in patients with protodiastolic and presystolic gallop rhythms. This study, however, shows that the diastolic ballistic complexes resulting from atrial systoles, and those occurring in individuals with protodiastolic and presystolic gallop rhythms are very similar to one another. These complexes usually consist of a series of small deflections. It is often difficult to determine which one of the waves is the initial deflection. Furthermore, it is possible to reproduce almost identical diastolic ballistic complexes in individuals with bradycardia, by tapping gently on the shoulder, and thereby imparting a tiny footward movement of the body. These findings lead us to believe that those forces resulting from atrial systole and/or ventricular filling lack the abruptness necessary to cause one clearly defined deflection in the ballistocardiogram.

Currently, there is some difference of opinion in regard to the origin of the H wave. Starr and Schroeder,\(^4\) and Hamilton\(^2\) related the beginning of cardiac movements in isometric contraction to the H wave. Nickerson,\(^11\) however, showed that when atrial contraction is in normal temporal relation to ventricular contraction, the H wave is produced by the initial upward ballistic deflection of the atrial ballistocardiogram. Because H waves may be seen in some cases of auricular fibrillation, de Lalla and his associates\(^19\) concluded that the H wave represents a force produced by the apex thrust as well as by atrial contraction. This study shows that any one of the upward deflections in the atrial ballistocardiogram may form the H wave. Whether the H wave is caused by the initial upstroke of the diastolic ballistic complex or another of its upward components will depend upon the duration of the P-R interval.
In the cases we have studied, the H wave was found to start at the time of the apical thrust when the P-R interval was within normal limits. The so-called H wave sometimes seen in patients without active atrial contraction, as in auricular fibrillation, can be properly attributed to ballistic waves caused by asynchronous ejections of the ventricles.

It is of interest to note that the double peaked systolic ballistic complexes have been encountered almost exclusively in patients in whom the pulmonary arterial ejection precedes that of the aortic. A combination of early pulmonic ejection and right ventricular hypertrophy is found to give a maximum ballistic effect. When the right ventricular ejection happens to lag behind the left ventricular ejection, the relatively weak ballistic result is usually lost in the main ballistic complex of the left ventricular contraction and ejection of blood into the aorta. This observation could very well explain why "many cases of bundle branch block have normal ballistocardiograms."  

The present study naturally raises the question of the quantitative distorting influence of the ballistic waves of atrial systole, ventricular filling, ventricular asynchronism, and waves of other undetermined origin upon the amplitude of (I + J) in both normal and abnormal conditions. The degree of any such influence would proportionately limit the usefulness of the measurement of these waves as an index of velocity of systolic ejection  and of cardiac output. Further studies should be designed to provide a satisfactory answer to this important question.

**SUMMARY**

1. A correlated study of ballistocardiograms with electrical and mechanical events of the cardiac cycle has been made on patients with various types of heart disease.

2. The results obtained from this study show: (a) A rapid, forceful diastolic ventricular filling wave occurring either in protodiastole or in presystole can account for large diastolic ballistic waves seen in an abnormal ballistocardiogram. Diastolic apical thrust and gallop sound are usually present.

(b) Atrial systole causes a series of small ballistic deflections. When the P-R interval is of normal duration, part of this complex produces an H wave in the ballistocardiogram, which usually begins at the time of the apical thrust.

(c) In some cases, waves which might be interpreted as H waves are seen in the absence of active atrial contraction, as in cases of auricular fibrillation. These H waves can be attributed to asynchronous ejections of the ventricles.

3. It is evident that the abnormal ballistic complexes may either increase or decrease the amplitudes of the H, I, J waves in the ballistocardiogram, thus limiting the value of using the I + J stroke for the estimation of cardiac output and the velocity of systolic ejection. In certain cases, the abnormal ballistic waves may even distort the whole ballistocardiogram making its interpretation exceedingly difficult.

**ADDENDUM**

Since this paper was submitted for publication, we have observed two upward ballistic deflections during systole in patients with a significant degree of mitral insufficiency. The first of these two upward deflections could be interpreted as an H wave in such patients with auricular fibrillation.

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