The Low Frequency Velocity Measurement Ballistocardiograph

By J. E. Smith, M.D. and Samuel Bryan, M.A.

The velocity measurement ballistocardiograph is described which has filter circuits to eliminate body tremor components. Small adjustable condensers are utilized on the input and output of the filter section to vary the frequency response of the circuit and thus create a sharper cut-off for occasional cases with high amplitude body tremor. The input and output condenser values are not above 5 mfd. in either section. By utilizing this type of circuitry, the lack of wave distortion makes it feasible to measure the ratios of wave amplitudes. The timing device makes it practical to time wave segments from the peak of the R wave, and a single channel recorder can be utilized. Normal standards are described and deviations from normal in coronary artery disease are discussed. The low frequency, velocity measurement ballistocardiograph is easily adaptable for routine office use.

For many years the ballistocardiograph has interested physiologists and research clinicians. The physiologic evaluation of the heart by recording mechanical heart actions which are imparted to the body is an approach made available through the use of the ballistocardiograph. This instrument thus affords a physiologic approach to many types of heart disease and seems to have a great prognostic value.

In the past, different types of ballistocardiographs have been used. Starr has been using a high frequency table and recording motions imparted to the table as a means of measuring forces of ballistic impact. Nickersson has built a special table which can be critically damped and which has a low frequency of oscillation (1.5 cycles per second). Brown has designed a table model with a high frequency oscillation similar to Starr’s table, but with special electronic recording devices for simultaneous electrocardiograph and ballistocardiograph records on separate channels. Dock has published techniques of recording ballistocardiograph waves that utilize direct body pickups without the use of special ballistic tables. He first utilized the principle of the glycerine capsule placed against the head, later changing to the photoelectric cell in which the ballistic impact altered the amount of light source to the cell, and still later to a coil and magnet device which was placed directly on the body just below the knees. The coil was allowed to move with the body, and the magnet was held in such a way that it could not move; thus a difference of electric potential was created which could be measured on a string galvanometer.

Most of the electrical devices applied directly to the body have been displacement measuring devices. The most common and generally used is the photoelectric cell which is now available commercially. Strain gages have been advocated, and these are also displacement measuring devices. The coil and magnet principle, however, is a velocity measuring device, and the wave amplitude is based on the rate of displacement.

The measurement of the velocity of body motion shows only slight effect from respiration since the velocity of diaphragmatic motion is so slight (although actual displacement of the body is high enough to interfere with displacement recordings). The amplitude of the velocity ballistic wave is lower in expiration normally and correlates with Starling’s law as venous filling of the heart during expiration is decreased. In patients with arrhythmias, the velocity waves following a long compensatory pause are always of greater amplitude, apparently due to the increase in diastolic filling. This again shows correlation with Starling’s law.

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INSTRUMENTATION

The magnet and coil device is an electrical signal generator in which the signal generated is proportional to the relative velocity between them. It is inherently capable of wide range frequency response since it is not used as a seismic or ballistic device.

The magnet is suspended by means of a compliant pivot (razor blades) from the stand which houses the coil. (See fig. 1.) Comparative records were taken to determine the effect of this type of support for the magnet upon the ballistocardiograph tracing compared with the tracings obtained when the magnet was independently supported. Since no noticeable differences were obtained, the effect of the compliant mounting was therefore considered to be insignificant.

A series of tests was then undertaken to validate the velocity characteristic of the ballistocardiograph. It should be noted that the nature of the ballistocardiograph is affected by the associated equipment and the recording apparatus as well as by external vibrations originating in the building or personnel in the vicinity.

It was decided to determine the response of the system (coil-network filters-recorder) by injecting test signals from a suitable low frequency oscillator (Krohn-Hite or Hewlett-Packard) by means of a low impedance input in series with the pick-up coil. The output of the ballistocardiograph was then recorded on a Sanborn Visocardette. By using selected frequency intervals and adjusting the input signal to a constant amplitude the response of the system was then traced on the recorder.

It should be noted that no attempt has been made as yet to determine the absolute velocity of the human body in this study. It is felt that this information is of academic interest only, since any device used would require extensive and laborious calibration procedures, and in the case of electronic devices be subject to line voltage variations, magnet strength, and other factors. As a matter of research interest, information on absolute velocities and displacements of the body due to the heart pulse should be undertaken.

![Fig. 1. The low frequency, velocity measurement ballistocardiograph is shown with the vertical steel rod that holds the magnet.](image)

The intrinsic value of the ballistocardiograph lies in the pattern of the tracing. Absolute amplitudes of velocities would be difficult to correlate, so we have used wave ratios and timing of waves as means of extracting significant data from the tracings. Thus, tracings of variable amplitudes for whatever reason may be directly compared.

Filters whose effect may be varied were built into this ballistocardiograph to eliminate the higher frequency signals not believed to be originating in the heart pulse. These high frequency components may be due to various factors such as 60 cycle hum picked up from the power mains, body tremors, ambient building vibrations, and other extraneous sources (See circuit diagram, fig. 2.).

Previous experience has indicated that the region of 2 to 8 cycles per second would cover most of the fundamental frequencies of body motion, and therefore the filtering was designed to have minimal effect in this region.
while strongly attenuating frequencies above this range.

It can be seen from the calibration curves (fig. 3) on this model ballistocardiograph that the frequency response holds up quite well to about 8 cycles per second with the 2 microfarad (mfd.) output condenser and gives a reasonably flat response to about 6 cycles per second with the rapid roll-off filter (3 mfd. output; 5 mfd. input).*

When the frequency response of a system shows a decreasing response at the rate of 6 decibels (one-half) per octave of frequency increase, then a velocity pickup will yield a displacement signal. Investigators using velocity pickups are cautioned to determine the frequency response of their recording system to ascertain the nature of the tracing (velocity, displacement or partially integrated). A velocity recording has different characteristics from a displacement recording, and therefore tracings should be validated as either velocity or displacement recordings for comparison purposes. Intermediate tracings should be compared by means of frequency response characteristics rather than using signal lags and timing as a basis of estimating the amount of integration.

A velocity recording of a given harmonic motion differs from a displacement recording basically in that the peak of the velocity wave precedes the peak of the displacement wave by 90 degrees. Further, where the motion is complex, the higher frequencies receive greater relative amplification when studied as velocities and thereby reveal events which might be obscured in displacement recordings. However, the problem of suppression of high frequency ambients becomes more demanding in velocity recording; hence, the need for adequate filters. (Compare A and D in figure 5.)

Timing of the peaks of ballistic waves is affected by the following: (a) the nature of the recording—velocity, displacement or intermediate; (b) time delay in the filter or associated equipment; (c) time lag of the timing reference signal in relation to ballistic waves, for example, carotid pulse.

For comparison purposes, it must be noted that any filter, attenuating within the frequency range of body tremor, will probably cause some signal delay. Thus the filter demonstrated in figure 3 using no condenser (frequency response curve B) has a signal lag of .01 to K wave peak when compared with a coil and magnet with no filter. The frequency response curve shown in figure 3, using a 2 mfd. output condenser (curve C), has a signal lag of .02 second to K peak. The rapid roll-off filter using 3 mfd. output, 5 mfd. input condensers (frequency response curve D) has an average time lag of .03 to H and I peaks and .04 to J and K peaks. The timing relationship of velocity and displacement is shown in figure 4.

It should be noted that the basic curve outline is not changed by filters when compared with the curve obtained with the coil and magnet. In our experience the timing of our 2 mfd. filter is very close to the Starr type of high frequency ballistic table. Also, the rapid roll-off filter (3 and 5 mfd.) has timing nearly identical with the displacement ballistocardiograph without the filter (fig. 4D). In spite of the timing similarity obtained from

* Circuit analyses and frequency response studies were done by Mr. Irving Levine, electronic scientist, Sound Section, U. S. Bureau of Standards.
displacement records and from the velocity recording made in conjunction with the 3 and 5 mfd. filter combination, the two do not yield recordings of the same character. The 3 and 5 mfd. filter used with a velocity pickup gives a velocity recording which is attenuated starting at a frequency of about 5 cycles per second. It should be noted that in many normal individuals it is possible to obtain an excellent velocity ballistocardiograph with only a coil and magnet in the absence of external ambient vibration interference. This can be seen readily in figure 4A. However, in most cases of coronary heart disease it is nearly impossible to obtain useful velocity ballistocardiograms from a coil and magnet only, as signal (or velocity) is of lower amplitude, and the signal-noise ratio becomes larger (ratio of body tremors to signal). Also, the higher the frequency amplitude response of the recorder, the more susceptible the recording becomes to ambient vibrations. This effect is more noticeable in recordings of patients with coronary disease.

The fundamental frequencies of body motion if of a frequency lower than 5 cycles will be velocity tracings, and above 5 cycles will be partially integrated into intermediate velocity-displacement recordings. This technic does yield useful clinical information in that the velocity characteristic of the body motion is substantially retained while strongly filtering body tremors and other extraneous signals.

![Fig. 4. Simultaneous tracings of velocity and displacement to show timing relationship and phase shift. These are taken on a Sanborn Poly Viso at a paper speed of 25 mm. per second. The carotid pulse has a .02 second lag from tubing. The velocity curves of A, B, C, and D are made with frequency response curves of A, B, C, and D of figure 3.](http://circ.ahajournals.org/Downloaded from http://circ.ahajournals.org/)

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Ambient Vibration Interference

In the use of velocity measurement pickups, a phenomenon which we have labeled ambient vibration interference must be understood before clinical measurements can be utilized. We have utilized the term ambient vibration interference because of the similar problem in sound engineering utilizing similar electrical apparatus. The sound engineers call this ambient noise interference and except for differences in the frequency range, the problem is similar.

The literature that has been published to date shows convincing evidence that this phenomenon is not understood by clinicians and explains to a great extent why some investigators have been unhappy about the various electromagnet devices used for velocity measurement.

Ambient vibration interference usually has its origin in two sources. (1) The most important source is the table on which the patient and instruments rest. It is difficult to use any wooden table that is not fixed to the walls and the floor for measurements of body velocity. Since either the magnet or coil is fixed to the table, any table movement distorts the body velocity waves. The actual motion of the table is slight, but due to the high velocity of displacement and the sensitivity of the pickup, the amplitude of ambient interference may be appreciable. In ballistic curves of young normal individuals the main distortion occurs in the H wave and variations in the HI segment in relation to the IJ segment. This will also produce great variations in the amplitude of the L wave. In the main, however, ambient vibration interference is not easily recognized because of the wide amplitude of the IJK complexes. In the older ages where velocity is lower in normal people, the ambient vibration interference is more serious and may completely distort the record. (2) The other source of ambient vibration interference is in the building structure in which the table is resting. In general, if the building is of reinforced concrete construction, there will be little interference. However, in many older buildings, especially with wooden beam supports and wooden floors, people walking in adjacent rooms and corridors will produce changes in velocity waves; and we have seen distortion produced by people standing next to the recording table that seems to be from transmitted vertical forces from heart beats into the floor.

Once an investigator is conscious of the effect of ambient vibration interference, the problem is simple to test for. (1) To test for building interference, place the instrument, partially supported on a pillow, on the ballistic table, and support the magnet in the usual manner. Start up the recording machine and walk around the room and the table. Any deflection of the baseline is due to vibration from the building transmitted into the table. Under ideal conditions there should be no deflection of the recorder even if people jump up and down in the room. (2) To test for ambient vibration interference from the table, place the patient on the table and fix the instrument so that the magnet is deflected by the table instead of the patient. If there is any motion in the table or a deflection of the baseline under these circumstances, then ambient vibration interference is coming from the table and may produce some distortion on the velocity record. In general, ballistic velocity curves taken with the patient on the floor of a reinforced concrete building will show no evidence of such interference.

In figure 5, tracings are shown to illustrate the amplitudes of ambient vibration interference as related to frequency response. These tracings are made on the same person while resting on an ordinary commercial wooden treatment table. The building structure is wood frame and of temporary construction. During the time that these tracings were recorded, a water cooling system was running in the next room. A was recorded with a coil and magnet pickup with no filter. The ambient interference is of such amplitude that the primary velocity record is impossible to interpret. B, C, and D are recorded on frequency response curves B, C, and D of figure 3. The interference vibrations in D look similar to some illustrations that have recently been published.
Timing of Ballistic Waves

With the velocity measurement type of ballistocardiograph, the phonocardiographic pickup recorded simultaneously with the ballistocardiograph is generally adequate as a basis of timing. This is especially true in timing the diastolic phases of the cardiac cycle as the second heart sound is based on mechanical changes and is much better for diastolic timing than the electrocardiograph. However, in many cases of valvular disease the heart sounds are inadequate for timing purposes.

The QRS wave of the electrocardiograph fortunately falls in a period of low electrical potentials when the ballistic waves are recorded and precedes the nadir of the I wave by an average of .12 to .16 second and precedes the H wave deflection by .05 to .09 second. The QRS then could be recorded theoretically on the same string at this point.

It seems that the ideal method is one that would enable us to increase the QRS potentials of the electrocardiograph and decrease the ballistocardiograph potentials at the same time. In difficult cases the pure ballistic waves could be decreased in amplitude while the QRS was increased in amplitude. By a method of this type we could use lead II of the electrocardiograph and dampen the amplitude of ballistic waves as necessary for timing purposes. Using any standard lead as a method of timing has a distinct advantage over chest leads. The heart sound recorder is placed over the apex, and it is difficult to use chest electrodes at the same time in the same area. In this way an accurate method of timing could be devised to fit all cases and still use only a single channel electrocardiograph machine.

This problem was solved in the following manner. A 1 megohm potentiometer was inserted in the ground lead of the ballistocardiograph (negative lead). (See fig. 2.) It was found that 1 megohm was sufficiently high to remove the ballistic signal from the electrocardiograph circuit and record the electrocardiograph only. By decreasing the resistance, it is possible gradually to increase the amplitude in the ballistocardiograph and decrease the amplitude of the electrocardiograph. As the resistance is decreased, the QRS is decreased and correspondingly the ballistic impact waves are increased in amplitude. This enables us to vary the amplitude of the QRS and ballistic waves as desired, and this timing method can be adapted to any ballistic wave regardless of amplitude or contour. Figure 6 shows the ballistocardiograph and electrocardiograph recorded simultaneously.

Fig. 5. This shows the effect of ambient vibration interference when related to frequency response. A, B, C and D represent tracings taken with frequency response A, B, C and D of figure 3.
The Normal Velocity Ballistocardiograph Wave

As in Starr's original designation of the ballistic waves, the first deviation from the baseline is designated as the H wave, which is considered to be partly due to auricular systole and partly to the apex thrust of the heart. De Lalla has described a footward deflection that precedes the H wave and has labeled this the G valley. This has been seen frequently in patients with slow pulse rates. The G valley may be due to the deceleration in the ventricles of a footward traveling auricular impulse. The I wave is supposed to be caused by the footward recoil of the body due to ejection of blood from the ventricles. The J wave has been ascribed to the impact of blood flow on the aortic arch and pulmonary bifurcation. The K wave represents deceleration of blood in the aorta and smaller vessels.

The causes of the diastolic waves L, M, N, O, are more conjectural. Nickerson believes the L wave to be due to a reflected wave of blood traveling up and then down the long column of the descending aorta. This may correspond to the reflection of blood from the closing of the pulmonary and aortic valves.

In the velocity measurement type of ballistocardiograph the ballistic afterwaves in normal people are nearly sinusoidal in character and may represent the natural decay of a vibrating body mass on its elastic tissue supports with each heart beat. This is probably true in normal people only to the extent of an “in phase” relationship to oscillating blood and body vibration. Actually, the ballistic afterwaves are related to real circulatory events and not to simple decay waves. In some of our cases of aortic insufficiency the L waves are of much greater amplitude than the J wave. In coartation the L wave is much smaller than the N wave. Thus, the deep K in aortic insufficiency and the short K in coarctation are definitely related to changes in the afterwave pattern. Furthermore, in many cases of coronary disease the most prominent wave is an L wave.

In the development of normal standards of the velocity waves, 100 normal people between 20 and 30 years of age were examined; 75 were males, 25 were females. In this group, all had normal double two-step exercise tests as well as blood pressure readings below 150/90, and no clinical evidence of cardiac or pulmonary pathology.

The peak of the R wave was used as a time base. The time of occurrence of the H wave, I wave, J wave, and K wave was measured. These measurements are referred to as the R–H, R–I, R–J, and R–K intervals.

Also, the relative amplitudes of the segments H to I, I to J, and J to K, were measured. To do this the HI is expressed as percentage amplitude of the IJ, and the JK is expressed as a percentage amplitude of the IJ segment. This type of measurement stresses wave form rather
than absolute amplitude and follows the outline used by Jones and Boulder.8

The use of wave ratio measurements is clinically feasible and shows excellent percentage correlation among most normal adults. The use of absolute units for velocity measurement will undoubtedly be of clinical importance when instrumentation can be standardized and clinical technics thoroughly understood. At present, due to the diverse types of equipment and technics, absolute values of velocity measurement are purely theoretic. The clinician, however, will be able to compare amplitudes of velocity measuring devices from normal to abnormal; and thus by comparison he will be able to interpret low and high velocity of body motion. In studies done on the same patients at daily intervals, there is only slight variation in amplitudes made under the same environmental conditions. The magnet has a placement marker and, since the space relationship of the coil end magnet is fixed, relative amplitudes on the same person are quite similar. Even if wide variation in magnet placement should take place, with variation in amplitudes, the measurement of wave ratios rarely exceeds one standard deviation in repetitive studies. The timing has been constant for the same individual.

STANDARDS FOR VELOCITY BALLISTOCARDIOGRAMS

Normal Subjects. These standards are based on the findings in 100 normal people between the ages of 20 and 30 years. There were 75 males and 25 females.

(1) Timing:

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<th>Males (75)</th>
<th>Females (25)</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
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<tr>
<td>R-K</td>
<td>.30</td>
<td>.02</td>
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<tr>
<td>R-J</td>
<td>.21</td>
<td>.01</td>
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<tr>
<td>R-I</td>
<td>.14</td>
<td>.01</td>
</tr>
<tr>
<td>R-H</td>
<td>.08</td>
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(2) Wave Ratio Measurements:

<table>
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<tr>
<th></th>
<th>Males</th>
<th>Females</th>
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<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
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<tr>
<td>Percentage HI of IJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>6</td>
<td>47</td>
</tr>
<tr>
<td>Percentage JK of IJ</td>
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<td>128</td>
<td>8</td>
<td>133</td>
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Since it can be said that the measurements in the majority (95 per cent) of all normal subjects will fall within plus or minus 2 standard deviations, any observations falling close to or above 3 standard deviations from the mean should be carefully investigated before judgment of normality is made.

There were no detectable higher frequency components in the ballistic waves of these normals (above 8 cycles). Thus, whether measured with coil and magnet or filters, there was no notching of the HI, IJ, or JK segments. Occasional normals showed two distinct components of the H wave peak, however, and timing was made to the first peak.

Statistical evaluation reveals that these differences in timing are true differences ($p$ is considerably less than .01 in all cases) and thus separate standards for males and females should be utilized.

The standards of wave ratio measurements and timing were made with respiration suspended during quiet respiration as near mid-inspiration as possible. During quiet respiration, there is a decrease in amplitude or velocity curves in expiration, and in most of our normal subjects the percentage relationship of each wave segment is maintained. In a few normal subjects, however, while breathing, some beats at maximal point of expiration lowered the IJ amplitude so that the HI segment was in slightly higher percentage. Even in these cases, the HI did not exceed 75 per cent of the IJ segment. Also, when the potentiometer is used for timing and the ballistic amplitude is decreased, the T wave exerts an influence on the H wave amplitude so that
there may be some time delay from R to H and change of percentage relationship between HI and IJ segments.

It must be realized that changes in these measurements may result from environmental ambient vibration interference (faulty technic) and electrical circuits that change the frequency response characteristics. These standards are based on a coil and magnet pickup with no filter for timing purposes and a filter using the 2 mfd. output condenser (frequency response C of fig. 3) for measuring of wave ratios. The 3 and 5 mfd. condenser (frequency response curve D of fig. 3) system should be used only as an auxiliary filter to measure wave ratios in the cases where body tremor components are of very high amplitude.

Fig. 8. Case of healed myocardial infarct. Electrocardiograph returned to normal following complete healing. The displacement curve looks normal, but the change in the IJ slope represents changes in velocity and acceleration that are readily seen. The fast paper speed (75 mm. per second) shows amplitude relationship and phase shift when displacement, velocity and acceleration are compared in relation to higher frequency components such as notched J waves. The displacement curve has been amplified twice normal to show abnormality of form.

Fig. 7. The velocity waves from five persons with proved coronary artery disease. In A, double amplification is used with frequency response curve B of figure 3 to show high frequency notching. When the velocity ballistic waves were recorded, these cases were healed and ambulatory.
Patients with Coronary Artery Disease. In 50 cases of known coronary heart disease we have found no cases in which velocity measurements fell within these standards of normal, and the majority of the velocity curves were so completely changed that the various wave segments could not be identified with certainty. In this group of 50 patients we have selected only patients in which acute episodes of coronary occlusion with electrocardiograph confirmation had taken place. However, in patients with pulmonary diseases such as emphysema, the ballistocardiogram may deviate widely from these normal standards even though evidence of coronary artery disease is not present. There are five cases illustrated from this group of 50 cases in figure 7.

The finding of consistently abnormal ballistic curves in coronary disease is not in complete accord with the findings of other investigators who have been using displacement measuring devices. Velocity is a more sensitive index of abnormality than is displacement due to the relative higher frequency. In figure 8 a tracing from a patient with healed myocardial infarction is shown. It should be noted that the displacement curve seems to be normal, but the velocity and acceleration curves look entirely different. The fast paper speed (75 mm. per second) shows the relationship. The slope change of the IJ segment on the displacement curve is difficult to see but represents a rather marked change in velocity and acceleration. The notching of the J wave is readily seen in velocity curves and is even more prominent on the acceleration curves. This patient had typical history of myocardial infarct with electrocardiographic changes. After healing, the electrocardiogram returned to normal.

Summary and Conclusions

1. The low frequency, velocity measurement ballistocardiograph has been described.

2. The influence of ambient vibration interference on velocity measurements has been discussed, and the importance of this phenomenon has been emphasized.

3. The timing of ballistic waves has been discussed, and a simple device for the recording of the QRS of the electrocardiograph and the ballistocardiograph has been demonstrated.

4. Typical velocity curves have been demonstrated in normal subjects and in patients with coronary artery disease.

5. Normal standards for velocity waves have been described, based on the analysis of 100 normal people between the ages of 20 and 30 years.

6. The measurement of the velocity of body motion seems to have great clinical application, and the diagnostic value in coronary artery disease has been presented.

Addendum

Since the preparation of this paper Gubner has described a similar method of superimposing the R wave of the electrocardiographs and the ballistic wave for timing purposes. (Gubner, R.: Circulation 4: 239, 1951).

Acknowledgment

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J. E. SMITH and SAMUEL BRYAN

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