Studies Utilizing the Portable Electromagnetic Ballistocardiograph

I. Abnormal HIJK Patterns in Hypertensive and Coronary Artery Heart Disease

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A practical method of ballistocardiography, easily adaptable to routine office use, is described. The instrument utilized is a portable electromagnetic ballistocardiograph which records the body movements directly. One hundred normal subjects of all ages were first studied by this method. Observations upon the ballistocardiographic findings in patients with hypertensive and coronary artery heart disease are recorded; particular emphasis is placed upon a specific abnormality in the HIJK complex in the ballistocardiograms of many of these subjects.

Progress in ballistocardiography is necessarily dependent upon innovations in the recording instrument. By utilizing an electromagnetic ballistocardiograph built to the electrical specifications described by Dock and Taubman (fig. 1), the ballistic movements of the body can be recorded with accuracy. Our immobile examining table is covered with a portable, firm, wooden, formica-surfaced board; upon this low friction surface, the patient is placed and the ballistic pattern is recorded directly. Any nonmovable, smooth surface table that is available, however, may serve as a recording platform. This method of ballistocardiography provides an inexpensive and accurate technic adaptable to widespread clinical use.

In deciding what type of recording device to use for clinical ballistocardiography, the following considerations were weighed. The original table ballistocardiographs were impractical for every daily clinical use because of their size and cost. The low frequency type of ballistocardiograph is also not suitable for routine use. Since the subjects must hold their breath during a recording, the valuable information to be gained from the respiratory variations of the ballistocardiogram is lost. Furthermore, the clinically significant L and M waves are damped out. Experimentation showed that through simple methods a high frequency ballistocardiogram could be recorded directly from a human body resting upon a hard surface. The choice then lay between a filtered photoelectric pick-up and the electromagnetic recorder. In favor of the former was its superiority in detecting the high take-off of the K wave in coarctation of the aorta; in favor of the latter was its ability to accentuate the notched J wave in myocardial and valvular disease. Against the photoelectric pick-up were the facts that bulbs and batteries must be renewed; that bulb intensity falls off gradually with age; and that adjustment is highly critical. A slight shift in the centering of the shadow on the photocell caused a large variation in the amplitude of the waves recorded. Similar shifts in centering the coil in the magnetic field resulted in less change in the amplitude of the electromagnetic tracing, and the instrument required no renewal of parts with age.

Since under the best conditions ballistocardiogram records vary with phases of digestion, with respiration, and with environmental temperature, the sacrifice of convenience and day-to-day constancy of results, in order to achieve more nearly exact and linear response to body motion under ideal conditions of subject and instrument, seems unwise. From a practical as-
pect, the electromagnetic pick-up is ideal. At a constant setting of the galvanometer, it gives standardized deflections for a given velocity of motion of the coil in relation to the magnet,

![Diagram](image1.png)

**Fig. 1.** The electrical format of the Dock electromagnetic ballistocardiograph.

year after year. The electromagnetic type of ballistocardiograph is the most sensitive in detecting the phenomena in which we are particularly interested, in clinical ballistocardiography.

![Image](image2.png)

**Fig. 2.** The coil of wire, which is imbedded in the most forward portion of the movable platform of the table stand, is placed in position 2 or 3 mm. away from the lowermost Alnico magnet. The light bar of wood, on which the magnets are mounted, is firmly attached by elastic bands. The patient is lying upon the formica table.

I. INSTRUMENT STANDARDIZATION, TECHNIC, AND INTERPRETATION OF RECORDS

Our instrument consists of two parts: a light bar of wood upon which a magnet is mounted, and a table stand which contains a coil of 8,000 turns of No. 40 wire connected to a resistance system, as illustrated in figure 1. The table stand, which must be of adjustable height, is constructed from a standard wooden funnel support. In our modification of the original Dock instruments,¹ the magnet bar is attached firmly across the shins by elastic bands (fig. 2). The coil of wire is placed 2 or 3 mm. away from the proximal magnet. The magnitude and the direction of the current that is induced in the coil of wire by the movement of the magnetic field is recorded by connecting the wire coil system to the lead terminals of the standard recording string electrocardiograph machine. (By mounting a horse shoe HS 2V Alnico (V) magnet upon the wooden bar, which results in a stronger magnetic field, a direct-writing instrument may serve as a recorder.) The strength of the magnetic field remains constant; the coil is always placed in the same position in respect to the magnets; and the galvanometer is always standardized so that 1 cm. equals 1 mv. The only variable is the ballistic body movement; this movement, in the horizontal plane, is reflected exactly by the magnetic bar, which is attached to the lower legs.

All resting ballistocardiograms are taken under basal conditions, which consist of 15 minutes of rest upon the table at least four hours after the last meal. The patient removes his shoes and remains lightly clothed. Hemoglobin and basal metabolism determinations are performed routinely on every subject, for marked anemia or hyperthyroidism results in an increase in amplitude in the ballistocardiogram while hypothyroidism results in a decreased amplitude. Ballistocardiograms are done on all subjects following the performance of the two step exercise test.⁷ ⁸ The number of trips required is two-thirds of the number specified in Master's tables. A ballistocardiographic study is considered normal only if a normal pattern is found after exercise as well as at rest.
Tissue elasticity is the shaft of our ballistic pendulum. The body mass and innate tissue elasticity must play a role in determining the amplitude of the ballistic pattern obtained directly from the movement of the body on the table. Upon the configuration of the HIJK segment of the ballistic pattern, these factors have little influence, and so are of minor clinical importance. Most patients fall into the average group as concerns the body mass factors. Because we are cognizant, however, of the possible variation in amplitude, which may be produced by extremes of body mass and tissue elasticity, we have used a standardized shoulder blow produced by a weighted pendulum of specified length upon our subjects during the recording. The ballistic patterns produced by these shoulder blows in a footward direction are all of similar configuration but vary in amplitude from subject to subject. We have found it difficult to predict whether the movement of any subject on his viscoid subcutaneous tissue, following the shoulder blow, will be average, great or small. As a rule, obese persons have better than average “shoulder blow” ballistocardiograms, while persons beyond the seventh decade of life have a natural amplitude below the average. One would interpret a ballistocardiogram of low amplitude but normal configuration as a normal record if it is known that the shoulder blow resulted in a ballistic pattern of small amplitude. We have found it quite satisfactory in practice to substitute a sharp finger percussion of varying intensity in place of the standardized pendulum blow. These finger percussions to the shoulder in a footward direction result in deflections which, in the average subject, are more than twice the amplitude of the principal waves in the ballistocardiogram. The shoulder blow ballistic patterns provide a check upon technic. If a shoulder blow results in sharp deflections of good amplitude in association with a bizarre ballistocardiogram of low amplitude, the sharp deflections produced by percussion serve as proof that the ballistocardiogram has been accurately recorded.*

A normal ballistocardiogram (fig. 3), obtained by this direct recording of body movement, is quite similar to the normal records described by Starr. In the interpretation of ballistocardiograms, we use the classification described by Brown, Hoffman, and de Lalla of grade 1 to grade 4 deviations from the normal pattern. The normal ballistocardiogram can be read at a glance. A constantly recurring series of oscillations, with the HIJK complex clearly prominent and acutely defined is what we expect of a normal (fig. 3). The amplitude of the ballistic waves is measured directly from the length of the deflections as

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* As illustrated in figures 8 and 12.
II. Use on a Group of Normal Subjects

To provide a control series using this ballistocardiographic technic, records were taken on 100 consecutive subjects, in whom, by clinical examination and evaluation of history, there was no reason to suspect heart disease. Sixty-two were over 50 years of age. All blood pressure readings were in the normal range for the respective age groups. The youngest subject was 10; the oldest 75 years of age. Only 3 ballistocardiograms from the subjects under 50 years of age were considered abnormal; these 3 abnormal tracings were among the 32 records taken from presumably normal persons in the fifth decade of life. Of the 48 subjects in the sixth decade, 22 per cent had ballistocardiograms which were classified as grade 3 or 4. Another 8 per cent demonstrated grade 1 or 2 changes, particularly after exercise. Starr's\textsuperscript{11} statistics suggest that a high proportion of these patients with abnormal ballistocardiograms will show evidence of heart disease over a 10 year period as compared with the patients with normal ballistocardiograms. Of the 14 subjects over 60, 6 had normal ballistocardiograms and 3 showed minimal abnormalities. Undoubtedly, the increased incidence of aortic rigidity, emphysema, and flabby abdominal muscular tone which accompanies aging, as well as asymptomatic myocardial changes, accounted for these abnormal ballistocardiograms in persons without evidence of heart disease.\textsuperscript{2}

III. Ballistocardiogram in Essential Hypertension

Sixteen patients with uncomplicated essential hypertension had ballistic patterns well within the range of normal. The blood pressure range was 140/90 to 185/110 in this group of patients. The youngest was 20, the oldest 47 years of age. Urine examinations were negative, the eye ground findings were minimal, and the patients had no complaints referable to hypertension. Figure 3 is the ballistocardiogram of an asymptomatic 32 year old man, J. M. His blood pressure was 185/100. The electrocardiogram was normal. The ballistocardiogram also was within normal limits. The upper tracing was taken under basal conditions; the lower after performance of a two step exercise test.

It is our concern in young hypertensives to rule out coarctation of the aorta. The very prominent J-K stroke in this latter case was helpful in eliminating this as a cause of the hypertension. Brown and co-workers\textsuperscript{12, 13} have shown that a short J-K stroke is characteristic of coarctation of the aorta. It should be noted that an increase in the amplitude of the J-K stroke is seen frequently in normal subjects of a tall, thin habitus\textsuperscript{14} after having performed the two step exercise test. The I-J amplitude may remain equal to the pre-exercise I-J or increase, but not to the degree that the J-K does. An increased J-K stroke is found commonly in normal ballistocardiograms in hypertensive persons. When the J-K stroke becomes the most prominent ballistic deflection because of a proportional decrease in I-J amplitude, we have found this to be indicative of myocardial dysfunction. Dock\textsuperscript{2} has shown that the J-K stroke may become markedly increased during the expiratory phase in ballistocardiograms taken of pregnant women. The ballistic patterns revert to normal within two weeks post-partum in these patients.

In 22 patients with hypertension, who were entirely free of complaints suggesting coronary insufficiency, but in whom there was evidence of definite vascular disease, only 2 normal ballistocardiograms were obtained. None of these patients was in heart failure. Five of these patients had electrocardiogram findings characteristic of left ventricular hypertrophy. Seven patients showed left ventricular hypertrophy and negative T waves in leads I and II, and in V\textsubscript{4}, V\textsubscript{5} and V\textsubscript{6}. Ten patients had normal electrocardiograms. The normal ballistocardiogram patterns were obtained from subjects...
with normal electrocardiograms. Upon attempting to determine whether there was a specific abnormal wave pattern obtainable from patients with hypertension, we found that the ballistocardiographic abnormalities were qualitatively similar in 75 per cent of the abnormal tracings. The fact that this abnormality became more marked in the more severe hypertensive states suggests that this particular abnormality represents evidence of the effect of hypertension upon the myocardium. Actually, the abnormality in these cases depicts not the hypertensive effect upon the heart, but the heart's atypical cardiac ejection wave in response to hypertension. We apply the term “deep K stroke pattern” to describe this abnormality. Starr's was the first to describe the deep K stroke pattern in hypertension. He called it the “late downstroke type” pattern. The ballistocardiographic findings consisted of “a shallow and indefinite I wave, followed by a slow, often fluctuating rise to J, terminated by a sharp downstroke J-K occurring late in systole and making the most prominent feature of the record.” Evidence was provided to show that this configuration is due to abnormal curves of blood velocity in the great vessels, the maximum expulsion velocity not being obtained until late in systole. It should be noted that the diminution of amplitude of the HIJ complex is as important a factor in this abnormality as is the prominent J-K stroke. The HIJ complex is the ballistic representation of cardiac output in normal subjects. In these patients, the cardiac output does not diminish in proportion to the lessening of the HIJ wave, but merely gains its ballistic representation later in systole. Animal experiments demonstrated that this type of abnormality could be produced by asphyxia. We prefer the term deep K stroke pattern rather than late downstroke pattern because of the fact that this configuration may occur as early in systole as the J-K of a normal ballistocardiogram, as indicated by the time interval between the peak of the radial pulse wave and the end of the J-K downstroke. Starr's experience suggested that this ballistic abnormality indicates serious myocardial dysfunction. This difference in amplitude between the HIJ and the J-K waves appears to be greatest in patients with long standing hypertension or those who have progressed to the malignant state, when the strain on the myocardium can be assumed to be maximum.

Figure 4 is the ballistocardiogram of A. J., a 38 year old man whose only complaint was recurrent headaches. His blood pressure was 195/110. Examination of the eye grounds showed angiospasms. The heart was of normal size on roentgen study but the configuration suggested left ventricular hypertrophy. The electrocardiogram was normal; the ballistocardiogram (fig. 4) showed normal waves under basal conditions. After performance of the two step exercise test, there was a shortening of the I-J stroke in comparison to the J-K deflection and an increased respiratory variation. This ballistocardiogram was graded 2.

The ballistocardiogram of M. G., a 40 year old woman, who had clinical evidence of malignant hypertension with no cardiac complaints, is illustrated in figure 5. An electrocardiographic study revealed left ventricular hypertrophy. The eye grounds showed hemorrhages, exudates and papilledema. The ballistocardiogram taken with basal conditions shows the prominent ballistic movement to be the downward J-K stroke. The HIJ amplitude is abnormally reduced. The principal cardiac output velocity is being generated late in systole. The precise interpretation of the large KLM complex is not certain. It may be correlated with
the auscultatory finding of a protodiastolic gallop rhythm.

Figure 6 is the ballistocardiogram of B. W., a 38 year old man, with chronic nephritis in uremia. The blood pressure was 240/140. The urea nitrogen was 130 mg. per 100 cc., and the potassium was 18.4 mg. per 100 cc. The marked difference between the amplitude of the H1J wave and the J-K stroke is again noted. The former almost disappears in some phases. The patient was markedly anemic, and the circulation time was rapid. This probably accounts for the increased amplitude of the most prominent waves. An increased amplitude in the

ballistocardiogram is characteristic of an abnormally high cardiac output. The electrocardiogram showed minor myocardial changes.

IV. Patients with Coronary Artery Disease

The classification of Brown and associates is helpful in describing the ballistocardiogram in the group of subjects with complaints of angina pectoris. Often, in this group, we have found that the only ballistic abnormality detectable is some degree of the short I-J and deep J-K stroke pattern. As is so common in coronary artery disease, this abnormality may be seen only in the expiratory phases. Furthermore, the deep K stroke pattern may be detectable only after the subject has performed a two step exercise test, the increase in myocardial effort causing this pattern to appear or to become more prominent. The deep K stroke ballistic abnormality is easily fitted into the gradation classification of Brown and co-workers. The abnormality in a grade 3 or a grade 4 ballistocardiogram, using this classification, is usually more bizarre than the prominent J-K stroke pattern and could suggest, in a postcoronary patient, extensive myocardial damage. (In these abnormal, bizarre patterns, the routine concomitant pulse wave record becomes of great importance in correctly identifying and interpreting the waves.) The deep K stroke pattern usually results in a grade 1 or grade 2 classification unless it is extremely accentuated. This may be the earliest ballistic abnormality in coronary insufficiency.

Of how much prognostic significance the degree of ballistic abnormality in angina pectoris is, is not absolutely certain. Many patients will have to be followed for long periods of time. Dock has found that people with coronary artery disease whose ballistocardiograms are classified grade 3 or 4 according to Brown, should be given a poor prognosis on a statistical if not individual basis. While sudden death may occur in these cases, as in heart block or aortic stenosis, many may live for long periods of time. The serious significance of abnormal ballistocardiograms even in patients thought to have no heart disease is proved by Starr's statistical analysis of a 10 year follow-up. He has also emphasized the good prognosis that can be attached to the finding of a normal ballistocardiogram following the healing of a myocardial infarction.

The incidence of abnormal ballistocardiograms is strikingly high in our patients with symptoms suggesting coronary insufficiency. Statistically, this is the same in patients with angina who have not suffered a coronary closure as in those whose angina follows the healing of a myocardial infarction. The latter group, however, has a higher proportion of grade 3 or 4 ballistocardiograms.

In a series of 108 patients, none of whom
had suffered a coronary thrombosis, but in whom, by means of history, the diagnosis of coronary insufficiency was made, 8 normal resting ballistocardiograms were found. After performance of exercise, only one of these remained normal. These statistics are in accord with the findings of Brown and his co-workers in a study of a similar group of patients. Because of the high incidence of abnormal ballistic patterns in this group of subjects, we accept the fact that an abnormal ballistocardiogram in a patient with angina pectoris is an important evidence that coronary disease is present. Thirty-nine per cent of these patients with angina pectoris had ballistocardiograms which were no worse than grade 1 resting, and 28 per cent had grade 3 or 4 resting ballistocardiograms. We cannot expect the ballistocardiogram to provide information as to which patient will develop coronary thrombosis, by the severity of the abnormality seen in the pattern. Other factors besides insufficient myocardial blood supply, such as cardiac failure, ventricular scarring, or arrhythmias may play a role in causing the abnormal pattern. Nevertheless, an abnormal ballistocardiogram is the rule rather than the exception in patients with coronary insufficiency. And as a corollary, we would be surprised to find extensive coronary artery disease in a patient, no matter what his complaints, whose electrocardiogram was normal and whose ballistocardiogram was physiologic, both at rest and after the exercise test.

The ballistocardiogram of A. S., a 55 year old obese woman, with complaints of frequent chest pain, is illustrated in figure 7. Her blood pressure was 165/100. The physical examination was noncontributory. Because of the clinical history, a diagnosis of coronary artery disease was entertained. The electrocardiogram was normal and the ballistocardiogram was physiologic. We ascribed the patient’s complaints, finally, to radicular pain secondary to scoliosis of the cervical and upper thoracic spine.

In figure 8, the ballistocardiogram represented is that of a normotensive, thin 55 year old woman, R. J., with complaints of frequent substernal oppression. The electrocardiogram is normal. The resting ballistocardiogram demonstrates an expiratory diminution in the HIJ complex. After exercise, there is a diminution in amplitude and the K stroke becomes the principal deflection. The resting ballistocardiogram is classified grade 1; after exercise, it is grade 3. The shoulder percussion is recorded and shows satisfactory amplitude and configuration.

![Figure 7](image1.png)

**Fig. 7.** A. S., female, age 55. Blood pressure 165/100. A case of chest pain due to scoliosis of the cervical and upper thoracic spine. Normal ballistocardiogram.

![Figure 8](image2.png)

**Fig. 8.** R. J., female, age 55. Blood pressure 140/85. The basal ballistocardiogram shows respiratory variation. After exercise, there is a diminution in amplitude, with prominence of the K stroke. Note shoulder blow deflections.

In figure 9, we see an example of a ballistocardiogram which shows a striking deep J-K deflection pattern under basal conditions. M. S. is a 45 year old normotensive man, with left chest and shoulder pain alleviated by nitrates. The electrocardiogram shows minor myocardial changes. In this case, we find the two step exercise test resulting in a ballistic pattern which more nearly approaches normal. While this improvement in pattern suggests a better prognosis, it will be necessary to follow
this group of patients, whose cardiac muscle work pattern improves with exertion, to evaluate the true significance of this finding.

In figure 10 is demonstrated an abnormal ballistocardiogram, resulting from effort. P. R. was a 44 year old normotensive white man who had been treated for peptic ulcer for many years. For the past 10 months, he had been complaining of precordial pain on effort. Repeated electrocardiograms were entirely normal. The resting ballistocardiogram is within normal limits. Exercise causes an increase in the amplitude of the inspiratory complexes, and a marked abnormality of the expiratory complexes. This marked variation of amplitude with respiration is abnormal, and is frequently seen in patients with coronary artery insufficiency and hypertensive heart disease. The physiologic causes and effects of this change in cardiac output with respiration have been investigated by Otis and his co-workers, Dock2 and Starr and Friedland.28

The resting ballistocardiogram in figure 11 is grade 1 because of the poor amplitude in the expiratory phase. The ballistocardiogram taken immediately following the completion of a two step exercise test shows bizarre, low voltage complexes in the expiratory phase, and the deep K stroke pattern configuration in the inspiratory complexes. The latter ballistocardiogram is classified grade 3. M. B. was a patient whose complaints of angina pectoris on effort have been present for 14 months. The electrocardiogram revealed slight S-T elevation in V1, V2, V3 and diphasic T waves in limb lead II, a Vr and all the V leads. In this case, the value of the exercise test in accentuating abnormalities of the ballistocardiogram is again seen. That putting the heart to work should bring out abnormal ballistic patterns in disease states, is not at all surprising. The ballistocardiograph, in a sense, records a test of heart function. Makinson,17 in a study of the ballistocardiographic responses to exercise, found that diseased hearts usually demonstrate a combination of diminished amplitude and abnormal configuration in the ballistocardiogram, following the performance of exercise by the patient.

The principal wave in the resting ballistocardiogram, figure 12, is the L wave. The I-J deflection is indefinite and of poor amplitude.
The necessity for accurate identification of waves by a timing device is demonstrated clearly. After exercise, the ballistocardiogram becomes completely bizarre and unintelligible. One shoulder blow is recorded to confirm the validity of the record. The basal record is grade 3, and the exercise ballistocardiogram is grade 4. The patient, C. G., was a mild hypertensive with markedly incapacitating angina pectoris. The electrocardiogram showed minor myocardial changes and a low T1.

F. F. is a patient with a story of weakness and angina. She had made an uneventful recovery from a myocardial infarction 18 months before this study. Repeated electrocardiograms showed findings indicative of a healed posterior wall myocardial infarction. The ballistocardiogram, figure 13, at rest, was grade 3. Exercise results in a marked deep K stroke pattern. The patient was holding her breath in expiration during this recording, which accounts for the regularity of the ballistocardiogram. It is our routine to record a section of the ballistocardiogram tracing while the patient is holding his breath in deep expiration, under basal conditions; this procedure may show an abnormality not otherwise demonstrable. On the other hand, Brown and his associates, 21 have shown that if expiratory breath holding results in a more normal ballistocardiogram in patients with angina pectoris, there is a good possibility that they will be benefited by the wearing of an abdominal binder.

M. H., age 54, is another example of a patient who had a previous myocardial infarction, and who presented himself with complaints of incapacitating angina pectoris. The blood pressure was 140/90. The erythrocyte sedimentation rate was 14 mm. in 1 hour by the Westergren method. The electrocardiogram shows evidence of a healed anterior wall myocardial infarction. The ballistocardiogram, figure 14, demonstrates maximal abnormality. It is grade 4 resting and after effort.

Extremely abnormal resting ballistocardiograms, such as figures 13 and 14, were found in 40 per cent of our 80 patients, who had survived a myocardial infarction; and an additional 20 per cent became grade 3 or 4 after performance of an exercise test. Six of these 80 patients had normal ballistocardiograms at rest. Only 3 remained normal after effort. The time interval between the coronary thrombosis and the ballistocardiographic study was greater than 21 months.
than one year in 63 cases. The ballistocardiogram may prove to be a valuable prognostic guide for these patients. We have noted a significant correlation between the severity of angina or incapacitation in these subjects and the degree of abnormality in the ballistocardiogram. In doing serial studies immediately after the erythrocyte sedimentation rate has returned to normal and after the electrocardiographic records show no further change, a gradual improvement in the ballistocardiographic pattern appears to parallel the patient's clinical recovery. Although some patients with persistent grade 3 or 4 abnormalities do make apparent clinical recovery, it is our impression, to date, that the postcoronary patients who develop ballistocardiograms that more nearly approach normal have the better functional recovery.

**Summary**

We have described our observations of ballistocardiographic patterns obtained from a large number of patients. All of the records were taken by our modification of the direct table electromagnetic ballistocardiograph of Dock. This instrument, we must stress, was designed for office and bedside use.

One hundred normal subjects were studied. Patients in variable stages of hypertension were observed. It was noted that the ballistocardiogram patterns assumed abnormalities that paralleled the severity of the hypertension and the associated changes in the electrocardiograms in the respective cases. The frequent occurrence and the significance of the deep K stroke pattern has been stressed.

The ballistocardiogram may be the only confirmatory evidence of coronary artery disease causing angina pectoris. The value of the use of the two step exercise test in ballistocardiography has been demonstrated. In our observations of patients after coronary thrombosis, we have found ballistocardiography to be helpful in evaluating the functional recovery of the myocardium.

From our experience, we feel that routine ballistocardiography is an important diagnostic and prognostic guide in the study of heart disease.

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