Standardization of the Ballistocardiogram by Simulation of the Heart’s Function at Necropsy; With a Clinical Method for the Estimation of Cardiac Strength and Normal Standards for It

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The interpretation of ballistocardiograms has been attacked by a method entirely new; a physiologic experiment performed at necropsy. While the subject lies on the ballistocardiograph a normal diastolic pressure is created and the heart’s function is simulated by injecting fluid into the aorta and pulmonary artery, the amount injected at each instant being recorded. The resulting ballistocardiograms can be directly compared with many aspects of cardiac function. The amplitude of the ballistocardiogram measures the maximum force exerted by the heart in moving the blood and preliminary normal standards for this estimate of cardiac strength have been set up.

The theory of the ballistocardiogram aims to account for the recorded waves by forces generated by the heart, and imparted to the blood. At the first attempts to define this relationship many assumptions were necessary, the chief of which concerned the contour of the cardiac ejection curve. Thus Starr, Rawson, Schroeder and Joseph1 and Starr and Rawson2, assumed that this curve for man was similar to a curve measured in an experiment on an anesthetized dog; while Hamilton, Dow and Remington3 employed a curve which had been calculated from measurements of aortic elasticity made in several dogs and one cadaver soon after death. Though differing in some details, the conclusions drawn from these studies agreed in the essentials; the deflections of the ballistocardiogram were attributed to forces generated by the heart when the blood was moved, and the contour of the tracing was related to the shape of the cardiac ejection curve.

Experiments, interrupted by the war, have now been performed on fresh cadavers in which the cardiac contraction was simulated by injecting fluid into the aorta and pulmonary artery in amounts recorded at each instant of time. By obtaining ballistocardiograms simultaneously, we found ourselves in a position to compare these records with the movement of the “blood,” and so to put the theory on much firmer ground. Over one hundred such comparisons have been made. The results show that the contour of the ballistocardiogram is mathematically related to the cardiac ejection curve; this presentation will stress this aspect of our results.

In addition, these experiments have permitted us to test our old conceptions of the genesis of ballistocardiograms,1,2 confirming many and disproving some of them; most important, the new techniques have provided a method of testing the accuracy of any esti-
mate of cardiac function we may set up. Thus we explored a new approach to the estimation of cardiac output and found that the proposed method was too inaccurate. Nevertheless, from this line of thought came a method of estimating the contour of the cardiac ejection curve from the ballistocardiogram. Finally a simple method was devised for estimating the maximal force developed in any systole, in relative terms, from the ballistocardiogram. This method proved to have an accuracy equal to that of the auscultatory estimate of systolic pressure, so normal standards were set up for it.

**Apparatus**

Figure 1 shows the general arrangement of our experiments.

A pair of 100 cc. glass Luer syringes were used to inject the fluid. The end of each, cut off by the glass blower, was replaced by a tightly fitting rubber cork perforated to contain a glass tube 1.8 cm. in internal diameter. The 2 syringes fitted side by side into a wooden holder into which they were firmly fixed by a yoke screwed down. Another set of screws bearing on a plate which fitted over the rubber corks and was perforated to admit the glass tubes, held the corks firmly in place in the end of the syringes.

The handle of the glass piston of each syringe was in contact with a single metal cross bar forming a “T” with a single metal piston which traveled through a long wooden cylinder firmly attached to the base of the syringe holder. The top of this cylinder was slit and through this slit projected a thin sheet of composition board, whose base was firmly set in the metal piston. In this sheet was the slit which provided the optical record of the position of the syringe pistons at every instant.

The syringe holder was clamped to a heavily constructed table containing a block of concrete in a compartment just below its top. We have not weighed the table but 2 men could lift it only with great difficulty. The long dimensions of the syringes were set at right angles to the long axis of the subject on the ballistocardiograph so that the movement of the pistons, and of the fluid in the syringes and cannulas, was at right angles with the line in which the ballistocardiogram was recording the forces and so did not affect this record until the fluid was turned into the great vessels.

Fig. 1.—Arrangement of Apparatus. For description see text. Parts of the apparatus not shown are: The syringe holder to which the syringes are clamped; the cylinder and the metal piston which guides the T piece driving the syringe pistons and supports the light beam slit; the weighted table to which the syringe holder is clamped; and the padded mallet used to drive home the syringe pistons and simulate systole. Also not indicated are the descending limbs of the aortic and pulmonary artery cannulas which go directly away from the reader, the side tubes on the same cannulas which would project directly towards him, and the pressure bottle attached to a side tube on the pulmonary artery cannula. The pressure bottle, shown in the figure, which is attached to the femoral artery is raised above the level of the artery to provide diastolic pressure.
Both cannulas were glass tubes 1.8 cm. in internal diameter. In the position used in the experiments the 1st limb of the aortic cannula extended horizontally 27 cm. from the point of attachment to the syringe. The tube was then bent to a right angle (the 1st angle) and extended directly downward for 16 cm. making the second limb. It was then bent to another right (the second angle) and the third limb extended 6 cm. headward to its tip. There was a slight constriction 2.5 cm. from the end for tying the cannula into the aorta. The corresponding limbs of the pulmonary artery cannula were 25, 11 and 5 cm. The first angle was also a right angle but the second angle was of 45° so that the third limb projected headward and downward, a position which better fitted into the pulmonary artery. This cannula was also provided with a constriction for tying it in place.

Both aortic and pulmonary cannulas had small side tubes of 5 mm. internal diameter at the first angle and the pulmonary cannula had a second side tube located near the syringe junction. The latter was attached to a perfusion bottle. During "systole" these side tubes were closed by rubber tubes and pinch cocks. This arrangement permitted clots to be washed out and bubbles to be caught and expelled from the system at the start of the experiments.

When in position the aortic and pulmonary artery cannulas were pushed hard against the end of the similar tubes emerging from the syringes and held in place by rubber hose connections.

Several smaller glass cannulas, from 4 mm. to 6 mm. in internal diameter, were made for insertion into femoral arteries; the largest which could be inserted was used. This was attached by a rubber tube to a pressure bottle filled with water or saline and set at, or above, a level corresponding to the diastolic pressure.

Either tap water or physiologic salt solution was used to fill the system.

A Hamilton manometer with a lead tube 70 cm. long was mounted on the wall beside the ballistocardiograph. Its period of vibration, when full of fluid was 150 per second. The needle, of 16 gage, was inserted into the root of the aorta.

The three optical recording systems were of the usual type, and the beams were directed into the moving film camera so that ballistocardiogram, blood pressure and ejection curve were recorded simultaneously on the same film.

In order to drive home the pistons and reproduce systole a number of devices were employed. A double pump driven by cams and an electric motor was built but it proved less satisfactory than simpler methods. Pushing the syringe pistons home with the hand provided smooth and satisfactory systoles, but by this means it was very difficult to secure the rapid initial acceleration which one expects from a normal heart, and we usually obtained ballistocardiograms abnormal in form. So these "hand systoles" were used to secure records when slow acceleration was desired. To secure more rapid acceleration we struck the metal piston with a mallet, heavily padded with sponge rubber to soften the blow. We first used a sledge hammer weighing 3 lb., supported by a fixed iron rod thrust through a hole bored in the handle so that the head swung on a radius of 30 centimeters. Later we used a very large wooden mallet designed for driving tent pegs and obtained from army surplus property. It weighed 15.5 lb. and the head was 20 cm. in diameter. Supported by an axle penetrating the handle, it swung on a radius of 90 cm. We had expected to pull the mallet back to a certain arc, and by dropping it, strike a measured blow, but we found we could secure smoother and more satisfactory curves by keeping the hand on the mallet head throughout the swing and pushing it home after the piston had been struck.

MATERIAL

Ten cadavers were employed. The first 4 were needed to develop a satisfactory technic and no records of value were obtained from them. The rest were:

1. February 5, 1947. L. P., female, age 48, weight 78 Kg., height 157 cm. Clinical diagnosis: Jaundice. Pathologic diagnosis: Postnecrotic cirrhosis of the liver. The heart, coronaries and aorta were normal.

2. February 27, 1947. H. W., female, age 14, weight 49 Kg., height 154 cm. Clinical diagnosis: Myasthenia gravis. She died suddenly and unexpectedly. Pathologic diagnosis: Heart normal, minimal atheroma of great vessels; no emboli or infarcts were found.


FIG. 2.
Conduct of Experiments

Whenever an opportunity presented itself, those members of the team who were available assembled at once. While the cadaver was in the morgue, the midline incision was made and the sternum removed. A large cannula was inserted: into the aorta only in the first two experiments, into the pulmonary artery only in the third; and cannulas were inserted into both vessels in the fourth, fifth and sixth experiments. These were tied firmly in place. A small cannula was tied in a femoral artery.

The cadaver was then taken to the laboratory and transferred to the ballistocardiograph. The weighted table was moved alongside and the injection and optical systems connected as shown in figure 1. Fluid was admitted from the perfusion bottles until all clots were washed out and all bubbles expelled through the side tubes which were then closed with strong pinch cocks. The needle of the Hamilton manometer was inserted into the aortic arch. Finally, the three optical systems were aligned and focused.

The perfusion bottle attached to the femoral cannula was hung above the subject at a level chosen to produce normal diastolic pressure in the aorta; in the early experiments, the elevation was 1 meter but in later ones, higher levels were used. When all was in readiness the pinch cock above this cannula was opened, allowing fluid to run into the femoral artery as fast as it would. An observer watched the beam indicating a rising pressure in the Hamilton manometer; when it leveled off he started the camera. After noting that everything was recording he signaled “Go” and one or both

Fig. 2.—Ballistocardiograms, Cardiac Ejection Curves and Aortic Pressure Records Secured Simultaneously. Subject H. W. (curves 5 and 3). Only the aorta was injected. Time above, the smallest interval = 0.01 sec. The white line is the ballistocardiogram, the heavy black line records the travel of the syringe plunger, falling as the syringe is emptied; the lighter black line shown only in the right hand figure is the blood pressure record. The amount injected was 84 cc. in each instance. Alignment is good. The record shown on the left was secured by striking the syringe plunger with the padded mallet, the record on the right, by pushing the plunger in by hand. Note that when the initial acceleration is rapid (left picture), the resulting “normal” ballistocardiogram resembles that found in healthy young adults; when the initial acceleration is slow (right picture), the ballistic deflection is very small until the syringe, stopping abruptly when it reaches bottom, causes a marked “stopping complex.” Ballistocardiograms of this “abnormal” type are found in certain cases with hearts judged abnormal by other criteria.

Subject M. E. (curves 14 and 15). Only the pulmonary artery was injected. The time record, cut off, was similar to that of M. M. 10. The black line rises as the syringe is emptied. The injection was 68 cc. in both right and left pictures. Note that the slowly accelerated and decelerated injection causes little if any deviation of the ballistocardiogram.

Subject J. K. (curve 19). Both arteries injected. Black line above is the syringe record—it rises as the syringe is emptied; the black line next below is the blood pressure reference line; the third black line, at first superimposed over the ballistocardiogram is blood pressure at the root of the aorta; diastolic pressure = 30 mm. Hg, systolic = 75 mm. Hg. The alignment test shows the syringe record to be perfectly aligned with the ballistocardiogram; blood pressure is 0.04 second too far to the right. Note the sharp injection onset and the normal ballistocardiogram. Striking the syringe with the padded mallet imparted a vibration to our recording systems in this subject, this can be seen by the vibration in the blood pressure reference line as well as in the other records.

Subject M. M. (curve 10). A most irregular injection. Syringe record starts below and ends above all other black lines; 91 cc. was injected into pulmonary artery, 97 cc. into the aorta. Diastolic blood pressure was 102 mm. Hg; the peak systolic pressure reached 180 mm. Hg. Note the extremely irregular injection curve. The ballistocardiogram which at first glance seems hopelessly confused, on close inspection is seen to be deflected normally by the repeated starting and stopping of the injection curve, which also affects blood pressure profoundly. Alignment as in M. M. 14.

Subject M. M. (curve 14). Time as in M. M. 10. Upper black line, syringe record, a smooth injection accelerated rather slowly. Thirty-nine cc. were injected into the pulmonary artery, 41 cc. into the aorta. The diastolic blood pressure at the root of aorta was 90 mm. Hg, the systolic 140 mm. Hg. Note the normal blood pressure contour with ballistic aftervibrations appearing after the diastolic notch and the suggestive, but incomplete similarity between ballistic deflections and pressure waves. Alignment test shows blood pressure record to be 0.04 sec. too far to the right, the syringe record to be displaced 0.05 sec. to the left of the ballistocardiogram.
syringe pistons were shoved home. When the light beams came to rest the camera was stopped, the syringes refilled from the perfusion bottles and the systole repeated. The amount of fluid injected, and the shape of the ejection curve were varied as much as we could. The number of such systoles was limited only by the length of time the cadaver was available.

The cadaver was then sent back to the morgue where the position of the cannulas was verified and the vessels carefully inspected for obstruction by clots and for lesions of the vascular system. The necropsy was then completed in the usual manner. Meanwhile, in the laboratory, the manometer and the syringe records were being calibrated, the ballistocardiogram having been calibrated before as well as after the experiment. Tests for alignment of the light beams completed the experiment.

Analysis of the records. The records of the syringe piston position, the “cardiac ejection curve,” were measured by a microscopic measuring machine known as a Keith-Lucas Comparator.* Various systems of measuring were tried, and a magnification of 12.5 diameters proved most satisfactory. The X-axis, time, was measured from the measuring engine scale; the Y-axis was read at each interval of time by counting the millimeter lines on the-record photograph and interpolating to 0.1 mm. The accuracy of this procedure was determined by remeasuring the first two points of each curve after an interval long enough for the operator to forget the previous reading; the test-retest correlation was 0.99. We started by measuring the curves at intervals of 0.02 second but intervals of 0.04 second proved more satisfactory, and all the curves reported here were measured this way. Hence, we recorded the position of points on our curves at each 0.04 sec. intervals.

In reading ballistocardiograms, the time of the peaks and valleys was identified exactly with the measuring engine scale but the depth and altitude of the waves was read by the naked eye, as ballistocardiograms are usually read, for we wished to include the error of thus reading them in our calculations. Also, the edge which seemed sharp to the naked eye was often blurred when magnified and it was doubtful whether magnification permitted greater accuracy. In accord with our practice in the clinic, distances were read to the nearest millimeter, the half being used occasionally when there was doubt as to which value should be chosen. These peaks and valleys were plotted and joined by straight lines, which represent the record with sufficient accuracy.

After measurement both ballistocardiograms and the ejection curves were plotted on cross section paper, 0.2 inch representing 1 mm. on the photograph and 0.04 second. The differentiations were performed as shown in figure 3 and the integrations as shown in figure 6.

The blood pressure curves were not analyzed in detail and we contented ourselves with recording systolic and diastolic pressure.

The mathematical analysis was performed by Dr. Starr and Dr. Horwitz with the technical assistance of Mrs. M. W. Murray.*

Results

Good records when the injection was into the aorta only were obtained in eighteen, thirteen and four “systoles” in Experiments 1, 2 and 4, respectively. When the injection was into the pulmonary artery only, good records were secured in sixteen and six “systoles” in Experiments 3 and 4. When both arteries were injected simultaneously, ten, twenty-six and

* Because of the great labor involved in the mathematical computations described here and in other parts of this paper we investigated the use of the differential analyzer in the Moore School of Electrical Engineering of the University of Pennsylvania, and we are indebted to Mr. George W. Patterson for instruction and advice on this subject. The three integrations could be readily performed by this instrument but it would take considerable time both to set up the analyzer for the solution of our particular problem and to convert our curves into a form suitable for use in the analyzer. It was concluded, then, that this instrument would not be of great aid at this stage of our work and the computations were performed with the assistance, first of a Monroe, and later of a Marchant calculator.
Fig. 3.—Two Ballistocardiograms and the Corresponding Cardiac Ejection Curves with Three Differentiations of the Latter. First Row: Left, a plot of the ballistocardiogram of J. K., curve 5 (see fig. 2); right, of J. K., curve 3 (fig. 2). The scale indicates millimeters of deflection on the photographic record. The calibration showed that 280 Gm. displaced the light beam 1 cm.

Second Row: The cardiac ejection curves corresponding to the ballistocardiograms above them. The scale indicates millimeters of deflection on the photographic record. The calibration indicated that a movement 1 mm. on the photograph corresponded to the ejection of 4 cc.

Third Row: The first derivatives of the cardiac output curves given above them made with a Δ time of 0.04 sec. These curves, therefore, are plots of velocity against time. The scale (right) is the same as in the row above; i.e., 1 unit corresponds to 1 mm. deflection on the photograph and so to an ejection velocity of 100 cc. per sec.

Fourth Row: The second derivative, acceleration. The scale, otherwise making the drawing too small, has been arbitrarily increased by a factor of 2.5. Therefore, one unit on the scale equals an acceleration of 1000 cc. per second.

Fifth Row: The third derivative of the cardiac output curve, or the first derivative of acceleration. The scale is the same as for the second derivatives in the fourth row, so that one unit equals a rate of change of acceleration of 1000 cc. per sec. each 0.04 second.
six good records were secured in Experiments 4, 5 and 6, respectively.

Typical records are illustrated in figure 2, and, as the results can best be described with
the record before one, the legend of this table has been made unusually ample, and the description in the text will be brief.

A comparison between the ballistocardiogram and the calculated third derivative of the cardiac ejection curves in seven typical systoles are given in figure 4. When inspecting these results one must recall that artefacts of 1 mm. or less, due to extraneous causes such as the movements of the elevators in the building, are seen in many ballistocardiograms and exact correspondence with the theory must not be expected.

Other results of the mathematical analysis will be found in the tables, where correlation coefficients and formulas of regressions, with standard deviations about them, are given. This analysis was designed to explore the relationship between the deflections of the ballistocardiogram and the forces generated by the heart. This relationship has proved to be close.

**Discussion**

We chose our method of attack for a reason that was, to us, compelling. It promised that both the cardiac output and the form of the cardiac ejection curve could be measured with an accuracy not yet approached in experiments on living men or animals, and we believe that this goal has been attained. But the question must certainly be raised whether results obtained soon after death would provide knowledge applicable to conditions in the living.

A chief reason for the belief that results obtained in our fresh cadavers may be applied to the living is the similarity of the ballistocardiograms in the two conditions. The sizes and patterns we find in the living we can produce in the cadaver subjects. It is true that with the cannulas described, the I wave tends to be smaller in relation to J than is usual in the clinic, but using cannulas with a longer third limb entirely corrects this. It seems easy to explain why recent death does not change the records. Independent of metabolism, which cases at death, the ballistocardiogram records forces generated within the body, and it would be distorted only by changes in the physical properties of the body which would interfere with the normal transmission of such forces.

Physiologists in the past have not hesitated to apply measurements of aortic elasticity made after death to conditions existing in living subjects; nevertheless, the problem presented must be carefully considered.

Tapped once on the head, a living subject on the ballistocardiogram undergoes a series of damped vibrations which are easily identified between systolic complexes, especially when the pulse rate is slow. Similarly tapped on the head, fresh cadavers undergo vibration at the same average rate; the cadavers of our present series behaved similarly. Interruptions by cardiac forces make it hard to estimate the degree of damping with accuracy in the living and the comparison is rough, but certainly the damping does not appear to differ materially in the two conditions. Judged by their vibration properties, the body tissues in our experiments did not seem to have greatly changed since death.

Further assurance was sought by a study of the pressure volume relationships. In our cadavers, after the diastolic blood pressure had been brought to normal, the smooth injection of a normal stroke volume into the aorta gave a perfectly normal pressure curve, with a normal dicrotic notch. Figure 2 gives an example. It is true that in some of our records, vibrations unfamiliar to those accustomed to peripheral pulse records appear on parts of the pulse wave, but this is to be expected in pressures taken from the aortic arch; it was found in animals by Frank. With the diastolic and systolic pressures normal and the pulse wave of normal contour, the aortic elasticity seems to have been essentially normal in our experiments. We did no similar experiments on the pulmonary artery but we believe that normal elasticity, demonstrated in the aorta, can be safely assumed for the pulmonary artery.

As far as we can detect, the physical properties of the body on which our method depends are essentially normal in our fresh cadavers; hence, we regard this type of preparation as suitable for many kinds of physiologic experiments. We do not, however, wish to minimize the unusual difficulties inherent in experiments of this kind, and these will now be discussed in detail. Some of these difficulties would apply
to any type of physiologic experiment performed in fresh cadavers; others pertain only to our special interests.

Difficulties and uncertainties. Every effort was made to obtain material as fresh as possible but some time elapsed after death before necropsy permission could be secured and after this was obtained the apparatus took considerable time to set up. Thus, slight rigor mortis had sometimes set in before the experiments could be begun. Also the time at our disposal was strictly limited by commitments to have the necropsy completed by a certain time. In addition, the normal interests of the pathologic department, the concern of clinicians to verify or disprove their diagnoses and the use of necropsies for teaching created demands on the available material which rightly had precedence over our highly unorthodox interests.

There was a fear, which experience showed to be not well founded, that repeated injections of water or salt solution might spoil the tissue sections by making the tissue edematous, and so might interfere with the routine pathologic studies. Such difficulties account for the fact that we had but ten opportunities to work in two and one-half years. Indeed, it was only because of most helpful cooperation from many people and the fact that Dr. Starr's laboratory was located within the hospital near the morgue, that this type of work was possible at all.

Other difficulties pertained to our particular problem but many proved less than we had anticipated. We feared that postmortem clots would obstruct the aorta and pulmonary artery, and that we should find it impossible to dislodge them, but the completion of the necropsy always showed all large vessels to be clean and unobstructed.

We feared that when the syringes were struck by the padded mallet there might be a direct mechanical transference through the building to the record, and the weighted table was designed to prevent this. We studied striking the table directly and this imparted almost no vibration to the record. In Experiment 4, however, there was undoubtedly direct transference of the shock of striking the syringes to all the records when the blow was strong, for the manometer reference line was thrown into vibration, as was the blood pressure record, and the shock tended to change the ballistocardiogram's base line slightly. Figure 2 shows such a record. Such effects had not appeared in previous records, nor did they recur in any subsequent experiment; hence, unable to reproduce the difficulty, we were forced to the belief that in Experiment 4 the heavy table had been so placed that an unusual harmonic in the building had been created, the blow starting vibrations which were transmitted through the table and floor, to the wall on which the mirrors were mounted.

We expected that findings when the necropsy was completed would throw light on our errors and perhaps cause us to discard experiments. The lungs, collapsed throughout the experiments, were often noted to contain excess fluid. In Experiment 3, multiple emboli were found in small pulmonary vessels. In all experiments, however, the great vessels were found normal or nearly so, and in the belief that the ballistocardiogram depends on the movement of blood in these vessels, we did not discard any results secured because of abnormality discovered in the tissues or small vessels.

Other difficulties were surmounted by a gradual improvement in apparatus and technic. We soon found that to produce normal ballistocardiograms we must have an injection technic that gave rapid acceleration early in systole and gradual deceleration in the latter part. When systole was produced by pushing the syringes with the hand the results were just the reverse, velocity increasing gradually and stopping with a jerk when the syringes hit bottom. Figure 3 (upper right) gives an example of this, and the records were highly informing, though the abrupt cessation of ejection was probably not analogous to anything that occurs during life. The use of the padded mallet secured the rapid initial acceleration we desired and a rubber cushion—together with the development of sufficient skill—enabled us to stop the moving pistons gradually and without hitting bottom with a jerk.

Occasionally, we had difficulty getting smooth ejection curves because of some sticking of the syringe pistons in their barrels, or fric-
tion between the metal piston and its cylinder; occasionally the padded mallet, if struck slightly obliquely against the metal piston slipped and caught again, so that bizarre curves were sometimes obtained. Figure 2 shows the record of a systole in which this happened twice. Although we regarded these as failures at the time of the experiment, the records of such “abnormal systoles” proved of great value in the study of the genesis of abnormal ballistocardiograms.

We attempted to keep the diastolic pressure at a normal level and usually succeeded, but until the calibration at the end of the experiment the height of this pressure had to be estimated roughly from the position of the light streak. In Experiment 4, this estimation was incorrect and the diastolic pressure was always lower than normal.

We found it difficult to secure two 100 cc. glass syringes of exactly similar diameter so that a difference of a few cc. often appeared in the amount injected simultaneously into the aorta and pulmonary artery. We do not doubt that differences of this amount occur normally during the respiratory cycle, and mention it only to account for the small differences given.

Finally, in contrast to the struggle of securing the material and of setting up the elaborate apparatus in a great hurry, once all was in order the experiments presented no difficulty. “Systoles” of all kinds and types were then run off with ease and dispatch. A few of these records could not be analyzed because the beams ran off the film, or coincided or were too faint to be read, but we discarded none for any other reason. This study is based on 97 satisfactory records of these artificial systoles.

The relation between the ballistocardiogram and cardiac function. We believe that the records shown in figure 2 and that the transcriptions and calculations given in figures 3 and 4 are a fair sample of our data. Inspection of these figures, and indeed of the data as a whole, leads to the apparently inescapable conclusion that there is a mathematical relation between the curve of cardiac output at every instant and the ballistocardiogram, that the latter is related to the third derivative of the former, and that the deflections of the ballistocardiogram follow the curve of the cardiac output by a brief interval in time. This relation holds despite large differences in aortic pressure; the systolic pressure varied from 75 to 180 mm. in our experiments.

To this last statement certain reservations must be made, and the first is concerned with artefacts. Since aftervibrations follow a single blow delivered experimentally1 we have every reason to expect that a force delivered early in the cardiac ejection curve will set up similar aftervibrations which will cause the latter part of the record to deviate from a true account of the forces then present. Close inspection of the records (figures 3 and 4) shows clearly that this is the case. When no strong force is applied early in systole (as in records shown in figure 3, upper right, and figure 4, M.M. 14 and 26), the ballistocardiogram late in systole corresponds closely to the third derivative of the ejection curve, but if there is a strong force early in systole (figure 3, upper left, and figure 4, JK 8, L.Po 1 and 3), its aftervibrations cause the latter part of the record to deviate from the forces then present. We have, therefore, confirmed the original concept1 that the part of the curve recorded early in systole will often give a better representation of the forces which originate it than will that recorded later.

The second reservation is emphasized by the fact that a single differentiation of the cardiac ejection curve does not account for the I wave of the ballistocardiogram. The reason for this seems clear and will be discussed later.

Despite these reservations, by our techinic of injecting the vessels we produce a ballistocardiogram which, when the I wave is neglected, is surprisingly similar to the simple third derivative of the injection curve. We believe that we see the reason for this relationship and that it can be best explained, nonmathematically, by a simple analogy:

Figure 5 shows a man in a small suspended room, the room free to move in the plane of the printed page, but this movement is restrained by a spring. The movement of the room represents the ballistocardiogram. The man within the room is leaning back against
the wall and has the nozzle of a hose in his hand, this is attached to a pressure tank on the floor beside him. At A, all is in equilibrium: the nozzle is closed, no water is flowing, and no forces are being exerted. At B, the man has opened the nozzle, the stream has started but as yet it has not reached the opposite wall. At this instant the jet effect due to acceleration of the fluid entering the nozzle drives the man backward and the room is pushed to the reader's right. This effect persists until, as at C, the stream of water reaches the wall opposite. Then the force exerted at the nozzle is neutralized by that now exerted against the wall, equilibrium is restored and the spring returns the room to its original position. The man now opens the nozzle wider. Again for a brief interval, as in D, the force developed at the nozzle exceeds that against the wall, and so the room moves again to the reader's right. As soon as the increased stream strikes the opposite wall, the forces balance once more and equilibrium is again restored. If the man now diminishes or stops the stream, the force against the wall exceeds that at the nozzle for a brief period, as at F, and the room moves to the reader's left until the end of the diminished or stopped column of water reaches the wall, when equilibrium is again restored.

This analogy makes plain the fundamental fact that must be grasped to understand the ballistocardiogram: the room is moved by forces which escape neutralization within it. The magnitude of these escaping forces depends on the rate of change of the force generated at the nozzle, the amount of increase (or decrease) which takes place in the time interval required...
for the stream to cross the room. Thus, the room is moved by the first derivative, the rate of change of the force; force is the product of mass times acceleration, the latter the second derivative of the fluid displacement curve in time. Thus, the movement of the room, and the ballistocardiogram are related to the third derivative of the cardiac ejection curve.

This analogy is, of course, an oversimplification and it explains only two of the three main waves of the ballistocardiogram. Instead of the man simply squirting the hose, as in figure 5, he should squirt through a curved tube with collapsible walls. The point may be better comprehended by thinking of figure 5 as representing the happenings in the long thoracic and abdominal aorta. To visualize the happenings in the heart, ascending aorta and pulmonary artery, one may think of a second man with a second hose, pointing the nozzle in the opposite direction towards the wall on the reader’s right with the nozzle tip only a short distance away from this wall. His stream of water is larger than that of the first man, but as the time taken by the stream going from nozzle to wall is much shorter, because the distance is shorter, proportionately less energy will escape to move the room than when the course is longer. This new man opens his nozzle a little before the man pictured in figure 5 and as the jet starts, the escaping forces move the room first to the reader’s left, the I wave, and as the jet diminishes, to the right, contributing to the J wave. As the stream of the new man reaches the wall the man pictured opens his nozzle. The starting of his stream contributes to the J wave, its stopping makes the K wave. Thus, the clinical ballistocardiogram is not an exact reproduction of the third derivative of the cardiac ejection curve; it is the algebraic sum of two third derivatives of this curve of opposite signs, one placed a little before the other in time.

The bearing of the new data on our former concept. In the early reports, the ballistocardiogram was related to the second derivative of an assumed cardiac ejection curve. A family of such curves, moved serially in time, and added or subtracted from one another according to sign, gave a result which in many ways resembles that now secured by once more differentiating the original curve. The old theory failed to account fully for the “K” wave, which was accordingly regarded as largely an artefact, an overswing from the immediately preceding J wave. However, as soon as clinical studies had begun we encountered patients with cardiac disease whose ballistocardiograms showed a K wave the depth of which far exceeded the height of the preceding J wave; this idea, then, was abandoned. Also, Hamilton and co-workers have supplied evidence that not only the K wave but also the waves which follow it represent forces. Our new data completely supports this contention; indeed, the ballistocardiogram is proving to be much closer to a true record of the forces than we originally believed possible.

It is interesting that in the clinical studies, our practice has not been inconsistent with the finding that the ballistocardiogram is related to the third derivative of the cardiac ejection curve. By calculating cardiac output by the area method, we integrated the ballistocardiogram, the result then being related to the second derivative, acceleration, and hence to cardiac force. Our cardiac output method was based on the assumption that the heart’s output would be proportional to the force exerted, and in normal conditions, when the ballistocardiogram is normal in form, this appears to be generally true. In preferring the area method to the altitude method (both described in the first paper), we were proceeding in the right direction, though for incompletely understood reasons. For a rough, quick and easy method of estimating cardiac output we have no improvement over the area method to suggest at this time. A preliminary report on its accuracy has already been published; the study reported in this paper, chiefly concerned with abnormal ballistic forms and lacking a large number of “normal” records, does not permit a final standardization against absolute values at this time. The original concept that cardiac output is underestimated by our formula when the ballistic form is abnormal has been completely verified.

Another conclusion drawn from our original theoretic concepts was that the form of the
Fig. 6.—Repeated Integrations of Two Dissimilar Ballistocardiograms Compared with the Corresponding Cardiac Ejection Curves. The scale to the right of the ballistocardiogram records the deflection of the record in mm. from the base line selected. The calibration 1 mm. deflection = 28 Gm. = 27,440 dynes.

The integrations were all performed with a ∆ time of 0.01 sec. by plotting and counting squares. The integrations were started where the I – J lines of the ballistocardiograms crossed the base line. Two base lines were used in integrating each ballistocardiogram and the two integrals which resulted are plotted together to permit comparison. They start close together but diverge considerably. The scale to the right of the first integral indicates the sum of the units (squares) at each instant of time. Each of these squares represents an area 1 mm. × 0.01 sec. The scale to the right of the second integral also indicates the sum of the units (squares) at each interval of time. Each of these squares now represents an area with dimensions of (1 mm × 0.01 sec.) × 0.01 sec. The scale to the right of the third integral (dotted line) pertains primarily not to it but to the cardiac ejection curve (solid line) which stands beside it. This scale is in cc. ejected and it was obtained from the calibration of the syringes. The plotted third integrals have been fitted to this scale by setting their ends to bracket the total amount ejected.

The third integrals were estimated, as were the first two integrals, as sums of squares, each in this case with an area with dimensions of [(1 mm. × 0.01 sec.) × 0.01 sec.] × 0.01 sec. To make the calculated curve fit the scale determined, the sum at each instant of time was divided by a factor
ballistocardiogram depended on the form of the cardiac ejection curve. The evidence for this now amounts to proof, for by varying the form of the ejection curves we produce corresponding changes in the resulting ballistocardiograms. Most of the abnormal forms seen in clinical records can now be reproduced at will, so that the knowledge of their genesis has been greatly advanced by the experiments reported here. Even when the ejection curves are, by accident, most irregular, as in that recorded in figure 2, MM10, the ballistocardiogram still follows the forces. Hence many, but by no means all, of our original ideas have been verified.

In addition, the new data have stimulated new lines of thought. We are now in a position to raise our sights, to attempt measurements of cardiac function of a type impossible by other methods and, of the greatest importance, to measure the accuracy of any new scheme we may set up.

Estimation of the cardiac output at every instant of systole by integrating the ballistocardiogram. The demonstration of a close relationship between the ballistocardiogram and the third derivative of the cardiac ejection curve raises the question of whether this curve, the cardiac output at each instant of systole, cannot be estimated by integrating the ballistocardiogram three times. In this connection one should recall Abramson's attempt to estimate cardiac output per beat from the second integral of the ballistocardiogram. Figure 6 depicts a test of the idea by integrating two experimentally produced ballistocardiograms completely different in form; the legend gives the mathematical details. The problems which presented themselves were as follows:

The first concerned the point on the ballistocardiogram when integration should be started. A natural place to begin is the point where the H-I line of the ballistocardiogram crosses the base line. Then, when the integration of the I wave has been completed, one should reverse the sign and proceed to integrate the J wave, and the rest of the curve in the usual manner, the reversal of signs allowing for the difference in direction of the flow of blood rounding the aortic arch. A more simple procedure is to neglect the I wave and to start the integration where I-J crosses the base line, and this was used in the examples given (figure 6). For some curves, we used both starting places and the final results were not very different.

The second problem is when to stop the integration. We added the duration of systole to the time of our starting point and stopped there.

The third problem is concerned with the selection of the base line, and this is critical as it makes considerable difference in the results. We proceeded by trial and error, selecting what appeared to be the best base line by inspection. If the first integral did not return to zero when systole was over, as acceleration certainly should, we moved the base line up or down and repeated the primary integration, seeking a curve which returned close to zero or two curves whose ends bracketed it. The second integration, leading to velocity, was handled the same way. At the end of the third integration the curve should remain horizontal or fluctuate about a horizontal line; if it continued up or turned down, the choice of the base line was questioned. Usually we had to be satisfied with curves whose ends bracketed the situation we desired. Thus, in figure 6 (lower right), the true third integral obviously lies between the two dotted lines. We proceeded, therefore, until we secured base lines that most nearly satisfied us, and the same base line was always used for the first,

which proved to be 301 for the curves on the left and 360 for the curves on the right. If our accuracy was such that this figure had proved to be a constant for all curves, then the cardiac output at every instant could be estimated accurately from the third integral of the ballistocardiogram. The fact that the factors needed did not agree well indicates the uncertainty of the procedure. But it should be noted that the third integral reproduces the contour of the ejection curve with considerable accuracy. At one place, the start of the third integrals on the left, the calculation is more accurate than the measurement, for on close inspection under the microscope the gradual start could be seen clearly, though it was not recorded by measurements made every 0.04 sec. and so does not appear on the solid line.
second and third integrals. Moving this line as little as 0.25 mm. often made a large difference in the resulting curves.

Finally, there is the problem of giving absolute value to the coordinates of the third integral. In our experiments, the cardiac output being known, the factor needed can be estimated. In the examples in figure 6, it was 1/301 and 1/360. The average value which would be applicable to any ballistocardiogram appears to be approximately 1/300 but after integrating ten experimental curves according to the method given we found that the scatter was very great; in one curve, moving the base line 0.5 mm. changed the factor ten-fold. The uncertainty is increased by the repeated integration, and small errors are greatly magnified. For this reason we cannot advocate the triple integration of the ballistocardiogram as a practical method of estimating the cardiac output quantitatively at this time. On the other hand, the contour of the cardiac ejection curve is attained quite accurately by triple integration, and the examples given in figure 6 are typical of our other experience.

**Estimation of cardiac strength.** Our results demonstrate clearly that the ballistocardiogram is more closely related to the heart’s force than to its output, so that estimates of force should be more accurate than these of output. This knowledge dates from the first publication,1 but at that time an estimate of the heart’s force from the ballistocardiogram, without any means of testing its accuracy, would have been little more than idle speculation. The efforts were then directed towards the estimation of cardiac output, a field in which the results could be compared with those secured by other methods and thus in some measure the correctness of our ideas could be tested, despite the fact that the absolute accuracy of the available cardiac output methods was unknown. Obviously we are now in a position to test our ideas against measurements with a far greater reliability and may properly ask ourselves questions unanswerable before.

Consider how cardiac force might be estimated from the ballistocardiogram, and how the error of such a method could be ascertained. Our experiments permit comparison between two forces; first, the cardiac force, or rather that portion of its energy output expended on moving the blood; and second, the force tending to move the body which is recorded by the ballistocardiogram. This second force can be directly calibrated in grams or dynes by noting the deflection of the light spot when a known weight moves the table. Therefore our data show that

$$\frac{d}{dt} \text{(Cardiac Force)} = K \text{Ballisto Force} \quad (1)$$

Since any force = Mass × Acceleration

$$\frac{d}{dt} (MA) = K \text{Ballisto Force} \quad (2)$$

and

$$MA = K \int \text{Ballisto Force} \, dt \quad (3)$$

The results have put us in a position to compare ballistocardiograms with the forces required to produce them. We are not yet ready to calculate the “cardiac” force in absolute units, but it can be estimated in relative terms if one makes an assumption regarding mass.

Mass is not the cardiac output because blood is pushed on ahead of that leaving the heart; it is not the total blood volume because, the vessels being elastic, this is not moved as a unit at any instant. We need to know the mass accelerated at every instant of systole and a quantitative estimate of this seems far beyond us. Indeed, mass might vary with time, but the good correspondence throughout systole between the ballistocardiogram and the first derivative of acceleration indicates that mass is a constant for any subject; hence, we propose to handle it as such.

We estimate acceleration in the syringes, not in the great vessels, and as the latter may be of different diameters in different subjects, acceleration in the vessels may be different from that recorded by an amount which differs with each subject. However, the product of mass × acceleration will be the same in the syringes as it is in the vessels injected, for this product is independent of the diameter of the vessels.2 The length of the vessels, however, is a factor in the situation, and should be taken into account in the calculation of force from our records of acceleration. Obviously, to obtain the vessel length of any subject...
During life the best assumption is that the length of the vessels will be proportional to the length of the body; the sitting height might be better but it was not measured for our subjects. We propose, therefore, to calculate the force imparted to the blood, in relative terms, by using the acceleration derived from our records and a factor for mass which varies directly with the height of each subject. As it happens, our subjects are very nearly the same height; 5 of the 6 being between 153 and 157 cm. tall, so that the effect of this adjustment is less than random errors for most subjects. We believe, however, that this factor for mass should be employed and that in interpreting records obtained on children its importance might be great; we cannot hope to obtain evidence either to support or disprove the conception from our present data.

Having decided on what seems the best method for calculating force the next question concerns what aspect of the heart’s energy output can best be estimated from ballistocardiograms and also what measurement may be most rewarding. From previous work on assessing the strength or weakness of the human heart, an attractive goal for the first attempt seemed the estimate of the maximal force delivered in any systole, a cardiac characteristic that is surely closely related to the concept of strength and weakness. We therefore searched for some aspect of the simultaneous ballistocardiograms that would permit us to estimate the maximal force delivered in any systole.

Many considerations inclined us towards using the spread of the record, as measured by I and J waves, for this purpose: first, to produce normal ballistocardiograms in our experiments the maximal force was delivered early in systole and these waves immediately followed; second, the general correspondence between the spread of ballistocardiogram and the force delivered was perfectly apparent even at the experiments themselves (when the operator struck a hard blow with the mallet the ballistocardiograph light spot was widely deflected, while a soft blow moved the spot but little); third, clinical experience has shown that in healthy young adults the I and J waves are large, while in many patients with chronic heart disease, especially elderly persons with long standing coronary heart disease, these waves are small or absent; fourth, the I and J waves occur early in systole where the ballistocardiogram reflects the forces most accurately; and finally, if one employs the sum of heights, or areas of two waves on opposite sides of the base line, the error of misplacing the base line is avoided or minimized. We therefore studied the correlation between several aspects of the I and J waves and the maximal force of cardiac contraction, the peak of the acceleration curve multiplied by a constant, M, corrected for body length. Tables 1 and 2 and figure 7 give the results. In order to express the estimates of maximal force, given in the vertical coordinates in figure 7, in per cent of a standard value, we have selected the force yielding ballistocardiograms of the average size found in healthy young men and arbitrarily placed it at 100 per cent.

The simplest measurement, the spread of the ballistic record or the vertical distance between the valley of I and the peak of J, was tried first. The correlation, \( r = 0.93 \), was excellent. Then, because the corresponding dot diagram (fig. 7, A) suggests slightly that the regression might be curved, we correlated our estimate of force with the square root of this same measurement on the ballistocardiogram. Again, the correlation, \( r = 0.93 \) is excellent, but not better than the first estimate.

Finally, because our results (Equation 3) suggested that the ballistocardiogram should be integrated before comparing it with cardiac force, we studied the relationship between the sums of the areas of the I and J waves and the corresponding estimates of maximal force. The dot diagram (fig. 7, C) showed plainly that this regression was curved; hence we correlated with the square root of these areas which significantly improved the scatter (fig. 7, D). The correlation, \( r = 0.83 \), is again highly significant but it is proved by Fisher's z test\(^{10}\) to be definitely poorer than those secured by using the altitude of the waves.

Obviously there is a close relation between the spread of the ballistocardiogram and the maximum cardiac force; indeed it is a little
STANDARDIZATION OF BALLISTOCARDIOMETER

Fig. 7.—Dot Diagrams and Regressions (y on x) Showing the Relations between "Cardiac" Force and Certain Aspects of the Simultaneous Ballistocardiogram. Force is on the vertical coordinate of each diagram. The scale has been constructed as follows. Ballistocardiograms from 54 healthy men of from 20 to 39 years of age inclusive were selected. The vertical distance from the valley of I to the peak of J was measured for a typical large and a typical small complex of the respiratory cycle of each. The sum of these measurements divided by 2 gave an average value for each subject, and from them an average for the whole group was derived; it equalled 15.3 mm. The force corresponding to this value on the regression in diagram A above was set arbitrarily at 100 per cent. Thus, 100 represents the force which gives a ballistocardiogram of average size in healthy resting young adult males in all the dot diagrams.

A, Force and the vertical I + J distance. The scale on the horizontal coordinate is in millimeters (10 mm. = 280 Gm.).

B, Force and √I + J distance. The scale on the horizontal coordinate is in millimeters.

C, Force and the sum of the areas of the I and J waves. The scale on the horizontal coordinates is in mm. sec. × 100.

D, Force and the square root of the sum of the wave areas. The horizontal coordinate is in mm. sec. × 100.

E, Force and the vertical I + J distance. Scale as in A. The three regressions (y on x) were calculated from experiments in which only the pulmonary artery was injected, in which only the aorta was injected and in which both were injected together. The diagram shows the contribution of each side of the heart to the ballistocardiogram at any force, but when the forces are very small the estimate is inaccurate.

closer than these correlations indicate, for part of the scatter is due to errors of measuring the two curves. For estimation of these errors, both the I and J distance on the ballisto-
cardiogram and the difference between the first two points on the cardiac ejection curve were re-read, after a period of several months, and in ignorance of the first reading. The correlation between the first and second readings, the test-retest correlation, was 0.99 in each instance. These values permit us to obtain a truer value for the correlations between cardiac force and the I and J waves, a maneuver called correcting the coefficient for attenuation.11 This raises the coefficients given in table 1 by 0.01; thus 0.93 becomes 0.94, the latter being a better indication of the true relationship.

At first glance it might appear that the superiority of the sum of the I and J vertical heights, or the square root of this distance, over the sum of the wave areas or its square root, throws doubt on the validity of Equation 3, as this suggests that the ballistocardiogram should be integrated before comparing it with force. However, we are correlating with maximal and not with total force, and maximal acceleration usually occurs in the very first instant of ejection. Successive derivatives of this part of the curve are the same in value as figure 3 shows, so that it is not necessary to integrate the ballistocardiogram in order to estimate initial force.

The validity of Equations 2 and 3 is supported by a study of the latter part of the curves. The linear depth of the K waves, correlated with the maximum calculated forces directed footward, gives a coefficient of only 0.34, which is just significant. But when compared with the corresponding maxima of the first derivative of the same forces, the correlation rises to 0.90, which is extraordinarily good and significantly better than 0.34. At the beginning of systole the situation is less complex because the force first manifesting itself escapes neutralization by other forces.

**Contribution of right and left hearts to the ballistocardiogram.** Regressions of the same type, correlating our estimate of force with the vertical I and J distance, have also been calculated from data secured in those experiments in which the aorta and the pulmonary artery were injected separately. The correlations are in table 1 and the regression equations in table 2, the dot diagrams of some of them being plotted in figure 7. The results permit us to ascertain the contribution of the two sides of the heart to the total impact, a problem previously considered.2 Apparently, in normal ballistocardiograms the movement of the blood in the pulmonary artery contributes about 45 per cent of the total, that in the aorta about 68 per cent. It is to be noted that the sum of these is 113 per cent, and this suggests that some of the vectors overlap and neutralize each other when both arteries are injected together. The slight difference in the size and position of the two arches is probably enough to account for this. The contribution of blood in the pulmonary artery to the ballistocardiogram proves to be somewhat larger than that originally estimated.2 In Experiment 4, in which the aorta and pulmonary artery were injected both separately and together, the results are consistent with those secured from the data as a whole.

**Calculation of maximal cardiac force.** The maximum of the heart’s force which results
in the acceleration of blood in any systole can be calculated from the ballistocardiogram (the answer being given in relative terms) by equations derived from the regressions given in table 2. With a ballistocardiogram calibrated so that 280 Gm. deflected the light spot 1 cm., one would proceed as follows. If the vertical distance from the downward directed peak of I to the base line is 4 mm., and from this base line to the upward directed J peak is 8 mm., using regression A in table 2, we have

\[ 6.6 (4 + 8) - 1 = 78 \text{ per cent} \]

The answer is in per cent of a standard cardiac force, the average maximum force developed by the systoles of healthy young men lying at rest. This average value for men has been arbitrarily set at 100 per cent. The average value of 49 healthy women, 20 to 39 years of age, was exactly 75 per cent of the corresponding value for men.

It must be kept in mind that this standard of force is not a normal standard, so that the result obtained does not of itself measure the normality of any given case. In all subjects the force of the beats varies with the respiratory cycle. The equations in table 2 and the calculation above give an answer not adjusted for the size of subjects; persons who are small give lower values than the standard because their small hearts beat less forcefully than do larger hearts. Also, as experience shows that the spread of the ballistocardiogram decreases with age in healthy persons, older hearts beat less forcefully than younger ones. The standard deviation being 17 per cent of the mean value for men, the accuracy of the estimation is such that two-thirds of the single estimates will deviate from the true value by an amount which is less than this. For both sexes together, because of the smaller mean value, this figure is 20 per cent. If the problem before one requires greater accuracy than this, the averaging of several estimations would supply it.

The scatter of our method may appear large, and compared with the methods available to physicists and chemists it is indeed very large. But our method of estimating cardiac force compares favorably with the methods available to clinicians, for it is not inferior to the estimate of systolic pressure by the auscultatory method. Correlating the auscultatory and intra-arterial pressure measurements (Ragan and Bordley’s

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<td>Equation</td>
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<td>A</td>
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a respiratory cycle and averaging the results. In practice, however, it suffices to select by inspection a typical representative of the smallest and another of the largest complexes and to average measurements made on these. However, a step is saved if the normal standards are made for the sum of these measurements rather than for their average; Equations A and B in Table 3 have been set up in that way. In accord with Tanner's views, we have employed regression equations rather than

**Table 3.—Normal Standards for Maximum Cardiac Force in Resting Subjects**

Regression equations from data secured on 100 healthy young adults of both sexes and from 20 to 30 years of age (for obtaining the values to be expected for any subject and the scatter of healthy subjects about the value so obtained). I, J, I₁, and J₁ equal the vertical depths and altitudes of I and J waves in typical large and small complexes of the respiratory cycle. By calibration, 10 mm. deflection = 280 grams.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Regression Equations (y over x)</th>
<th>Standard Deviation About the Regression (y over x)</th>
<th>Absolute values</th>
<th>Per cent of series mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I + J + I₂ + J₂ mm. = 23.6 (subject's surface area sq.m.) - 13.35</td>
<td>6.4 mm.</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>I + J + I₂ + J₂ mm. x pulse rate per min. = 1230 (subject's surface area sq.m.) + 267</td>
<td>466</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>I + J mm. = 7.91 (subject's surface area sq.m.) + 4.48</td>
<td>3.46 mm.</td>
<td>22%</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>I₁ + J₁ mm. = 4.49 (subject's surface area sq.m.) + 1.42</td>
<td>2.54 mm.</td>
<td>23%</td>
<td></td>
</tr>
</tbody>
</table>

ratios and have used body surface area as a measure of the size of the subjects.

The best type of normal standard to use can be decided only on the basis of utility; hence, several types have been calculated and others could be readily set up. Thus we wondered whether an abstract conception such as maximal cardiac force per minute might not have advantages over the maximal force per beat in detecting abnormality. This regression is given in table 3, but the addition of the pulse rate as a factor did not improve the scatter as we had expected. Also because abnormality of ballistic form is so often confined to the smallest complexes, and because the evidence of Brown et al. has suggested that increased difference between largest and smallest complexes indicates myocardial abnormality, we have included in table 3 normal standards for both the smallest and the largest complexes of the respiratory cycle.

To determine from the ballistocardiogram whether the heart's strength is normal, one would proceed as follows. After inspection of the record, one of the smallest and one of the largest complexes are selected as typical of those found on the record as a whole, and the vertical depth of the I and the height of the J waves from the base line are measured for each. If one uses a ballistocardiograph calibrated so that 280 Gm. displaces the light spot 1 cm., the measurements in mm. are used without adjustment; if the calibration differs, the adjustment is inversely proportional. For example, if 280 Gm. displaces the light spot 2 cm., the measurements made on the record should be halved. The sum of these measurements, I + J + I₂ + J₂, adjusted if necessary, is used as in the following example.

If we find: in a typical small complex, I = 2 mm., J = 5 mm.; in a typical large complex, I₁ = 4 mm., J₂ = 7 mm.; and if the patient's surface area is 1.80 sq. m., then

Patient's I + J + I₂ + J₂ = 18 mm.

From table 3, Equation A, we estimate the expected I + J + I₂ + J₂:

\[
\text{Expected } I + J + I₂ + J₂ = 23.6 (1.80) - 13.35 = 29.13
\]

The difference between the expected value and that found:

\[
18 - 29.13 = -11.13
\]

thus the deviation from the expected value is

\[
\frac{-11.13}{29.13} = -38\%
\]

The significance of the deviation, the probability of the case being abnormal, is obtained
by dividing the difference by the standard deviation of Equation A, found in table 3, thus:

\[
\frac{11.13}{6.4} = 1.74
\]

From this quotient, the critical ratio, the probability of abnormality can be found in any book on statistics. Conventionally, only if this ratio exceeds 2 is the result judged significantly different from the normal, but the probability thus demanded, over 97.5 in 100, is so far beyond that on which most clinical judgments are based that one wonders whether a less exacting standard would not be more useful. Certainly, if a probability of this magnitude is not attained the result should not be neglected, as statisticians would so often have us do, for the clinicians’ judgment will be based on other considerations as well, and the sum of several items, each not significant if considered alone, may yield a highly significant result when considered together. If the critical ratio is over 1.30 and the sign of the deviation known, as will be the case when these normal standards are employed, the probability of abnormality is over 10 to 1, which seems sufficient for most clinical purposes.

On the other hand, if greater accuracy is required, the mean of two or more estimates can be used. The significance of the difference between this mean and the expected value is determined by dividing the standard deviation given in table 3 by the square root of the number of estimates, and dividing the difference by this quotient.

Thus, if in the patient mentioned before, we have two estimates, \( I + J + I_2 + J_2 = 20 \), and \( I + J + I_2 + J_2 = 16 \), averaging 18, then:

\[
\frac{11.13}{6.4} = 2.2
\]

The critical ratio, now exceeding 2, meets the more rigid requirements.

It should be noted that these normal standards are not adjusted for the diminution of cardiac force which occurs with aging; whether standards with this factor included would be more useful is difficult to decide. Some elderly people have ballistocardiograms as large as those of young adults; if the normal standards are adjusted for age, these results may be found to lie outside the normal range. While the evidence is still meagre, it suggests that these subjects are actually in better health than the average for their age, that they have indeed preserved the vigor of their youth. For this reason, the age factor has not been included in the normal standards here presented. Without such a factor, the percentage of elderly persons judged abnormal will undoubtedly be large, but this information may be well worth having.

In the estimation of cardiac output from the ballistocardiogram, only complexes of normal form could be employed; no such limitation exists for the estimation of maximal force and any complex, no matter what its form, may be used.

Clinical significance of the result. The information about the heart provided by the new data differs from that available to clinicians before; it does not concern cardiac output, nor is it cardiac work, as this has been calculated from output. One should think of it as an estimate of the heart’s strength or power, and its nature can best be made plain by an example within the experience of everyone.

Let us compare two automobiles, a large powerful car and a small, far less powerful one, and ask ourselves how we could tell them apart by their performance. Both are capable of any speed within the legal limit so that the time ordinarily required to get from place to place will not suffice as a criterion. Tests of maximum potentiality, maximum speed on the level or up steep hills, would distinguish them, but such unusual tests are conducted at a hazard. An easy way of distinguishing on the basis of their ordinary performance is to observe their acceleration from a standing start; for when the light turns from red to green, the more powerful leaves the other far behind. The product of their acceleration and mass, then, would readily establish the difference in power, and the heart’s performance in accelerating the blood should similarly serve to distinguish strong hearts from weak ones.

A final example may make the new viewpoint still clearer. In figure 8 are two hypo-
theoretical cardiac ejection velocity curves. In one, the velocity rises rapidly so that its maximum is attained early in systole, as is true of normal hearts. In the other, velocity rises slowly and its maximum is attained in the latter part of systole, as often occurs in weakened hearts. The tests hitherto available will not distinguish the difference between these two situations, for the cardiac output, the area under each curve, is the same in both, and cardiac work, as it is usually calculated from cardiac output, might be the same in both.

Nevertheless, we know by experience that rapid lifting of a load requires more strength than lifting it slowly and, like a weakening man, the weakening heart—though unable to exert normal force—can maintain its output by lifting its load more slowly. It is this important aspect of cardiac function, the rate of lifting the load, which can be measured by the ballistocardiogram, which thus provides evidence of the strength or weakness of the heart.

However, certain reservations must still be made. The test described gives information about only one aspect of the heart’s work, that employed in imparting movement to the blood. Not recorded by the ballistocardiogram is that part of the heart’s force which is employed in overcoming resistance. This latter is related to the blood pressure. How the clinical estimate of blood pressure can be most profitably combined with the data obtained from the ballistocardiogram in an estimate of total strength will be a subject for further study.

The standards set up in this article enable one to test the strength exerted by the heart while the subject is at rest, and not the strength of which the heart is capable. Should tests of maximum capability be thought more valuable, their standards could be readily set up.

**Summary and Conclusions**

1. At necropsy, using cadavers lying on the ballistocardiograph, fluid has been injected into the aorta, the pulmonary artery, and into both together; the amount injected was optically recorded at each instant, while simultaneous ballistocardiograms were taken. By this means, the ballistocardiogram has been standardized and the accuracy of its methods tested.

2. The relationship between the “cardiac ejection curve” and the ballistocardiogram has been studied mathematically; the ballistocardiogram is closely related to the third derivative of the cardiac ejection curve. This discovery has permitted a more exact theory of the genesis of the ballistocardiogram and has considerably increased our knowledge of its relation to cardiac function.

3. The contour of the cardiac ejection curve can be reproduced by triple integration of the ballistocardiogram but the errors, magnified by the repeated integrations, proved too great to permit the quantitative estimation of cardiac output by this method.

4. While the relationship of the ballistocardiogram to the heart’s output is a distant one, its relationship to the heart’s force is close, and this latter has been especially studied.

5. The maximum cardiac force at any systole, calculated in our experiments as the product of maximal acceleration and an assumed mass, can be readily estimated from the spread of the ballistocardiogram, the answer being given in
relative terms. The accuracy of this method has been defined and found equal to that of estimating systolic blood pressure by the auscultatory method.

6. Normal standards for the clinical estimation of the maximal cardiac force of resting subjects are set forth. It is believed that they permit a ready estimate of the strength, or weakness, of the heart’s beating in any case.

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Standardization of the Ballistocardiogram by Simulation of the Heart's Function at Necropsy; With a Clinical Method for the Estimation of Cardiac Strength and Normal Standards for It
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