The Force Ballistocardiogram as an Index of Severity in Congenital Aortic Stenosis

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SUMMARY
Evidence is presented that the ultra-low frequency force ballistocardiogram is a sensitive index of severity in children with congenital aortic stenosis. In 300 normal children no abnormal tracing was found. In 46 children with clinical aortic stenosis, the ballistocardiogram was abnormal in all patients with a transvalvular peak systolic pressure gradient of over 35 mm Hg.

Additional Indexing Words:
Aortic stenosis, congenital valvular
Aortic valvotomy

One of the most frustrating and frequent problems faced by the pediatric cardiologist is that of differentiating between a child with mild and physiologically unimportant congenital aortic stenosis and one whose lesion is severe and therefore potentially dangerous. In an asymptomatic younger child with the typical murmur and thrill of aortic stenosis but no evidence of left ventricular hypertrophy on vectorcardiogram, electrocardiogram, or x-ray, the problem may not be acute as far as clinical management is concerned, since procrastination is probably indicated. The situation is drastically altered, however, when a 12-year-old seeks permission to engage in a competitive sport or to participate in a strenuous physical-education program, and a definite answer must be given.

That aortic stenosis can be a treacherous and lethal lesion has been extensively documented, and it is now generally accepted that when the aortic systolic transvalvular pressure gradient is over 50 mm Hg at a normal cardiac output, or when the calculated aortic valvular area is under 0.5 cm², restriction of competitive activity is indicated, and surgery may be advisable. The errors inherent in estimating this gradient with clinic information have been pointed out by many investigators who have shown that, although the statistical correlation between the electrocardiogram or vectorcardiogram and the transvalvular pressure gradient is high, it is not sufficiently dependable to be used with confidence when making an important decision in an individual patient. The physician examining an adolescent with an aortic stenotic murmur therefore is faced with this dilemma: to allow a patient with a possibly dangerous lesion to engage in competitive sports, thus exposing him to a potentially life-endangering situation; to restrict him to a rather sedentary life, although his heart may be physiologically normal; to accept the risks inherent in left heart catheterization in order to gather sufficient data to ensure a logical decision.

It is the purpose of this paper to present evidence that the ultra-low frequency force (acceleration) ballistocardiogram offers a very reliable method of differentiating mild from severe aortic stenosis and may be used with a high degree of confidence in separating patients truly needing left heart catheteriza—

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tion from those with a loud murmur but low transaortic pressure gradient.

The force or acceleration ultra-low frequency ballistocardiogram is a recording of the acceleration of the body in a head-to-foot direction produced by changes in the center of gravity of the body as blood is ejected by the heart into and through the great vessels. The wave forms so recorded are constant and can be correlated with the physiological events of the cardiac cycle (figs. 1 and 2). The nomenclature of the cardiac events and can be used in this communication is that recommended by the Committee on Ballistocardiographic Terminology created by the American Heart Association.

The first deflection of the ballistocardiogram following the beginning of the P wave of the electrocardiogram is the F-G component. This negative wave segment, representing a footward movement of the body, begins simultaneously with the peak of the a wave from the left atrium and ends with the beginning of ventricular systole (fig. 2). The second constant component, the G-H wave, a positive and therefore headward movement, occurs during isometric contraction of the ventricles and, since it is probably produced by the movement of the heart during isometric contraction, ends in a sharp peak as the first heart sound is produced (fig. 2). The strong negative deflection, which begins with semilunar valvular opening, is the H-I segment, caused by a sharp footward motion of the body as the mass of blood is ejected from the heart into the great vessels during the rapid ejection phase of systole. This footward acceleration reaches its maximum in the child in 50 to 60 milliseconds, and its duration is remarkably constant in the normal child. In children with a condition affecting myocardial contractility, the duration of this segment is often strikingly prolonged, that is, endocardial fibroelastosis or myocarditis, and it therefore can be used as an aid in differentiating myocardial from obstructive lesions.

The I-J segment represents deceleration of the body in a footward direction. This important wave is inscribed as the mass of ejected blood rounds the aortic arch and enters the descending aorta and occurs simultaneously with the peak of the systolic pressure curve from the left ventricle. As will be seen, it is this component that is grossly changed when ejection of blood from the heart into the aorta is compromised. When, as occurs in coarctation of the aorta, the blood is obstructed in its movement from the arch into the distal aorta, the J-K segment is unusually prolonged.

Normally, the J wave returns to the baseline long before the aortic and pulmonary valves close, and the latter segment of systole is characterized by the K-L wave, a positive deflection that terminates with the second heart sound.

The next sharp footward movement of the body, the L-M wave (fig. 1), is inscribed

![Figure 1](http://circ.ahajournals.org/)

*A simultaneous tracing of the ballistocardiogram and left atrial pressure allows a correlation of the ballistocardiogram with the events of diastole.*

![Figure 2](http://circ.ahajournals.org/)

*A simultaneous tracing of ballistocardiogram, electrocardiogram, left ventricular pressure, and phonocardiogram allows a correlation of the ballistocardiogram with the events of systole. See text for explanation.*

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just after semilunar valvular closure. This is a constant and normal finding sharply demarcating the end of systole and may be increased in amplitude in aortic insufficiency and other hyperdynamic states.

The first constant diastolic wave is the M-N component (fig. 1), occurring during rapid ventricular filling. The diastolic waves are, as a rule, less constant than the systolic and vary greatly with the heart rate, the M-N and F-G often summating when the rate is rapid and diastole short.

Perhaps the most striking single factor in the ballistocardiogram in normal children is its extraordinary constancy, both from age to age and patient to patient, and the record of an infant or toddler is almost identical to that of a husky teenager (fig. 3). In a series of 300 ballistocardiograms obtained from normal children entering a YMCA program, not one tracing was found that was considered abnormal. It is this constancy that makes the ballistocardiogram more specific and therefore of more value in the child than in the adult. With aging, as early as the third and fourth decades of life, changes in the ballistocardiogram begin to occur in many individuals, and the sharp demarcation between normal and abnormal seen in youth begins to disappear. These nonspecific changes are thought to represent the earliest manifestations of impaired myocardial contractility due to "normal" aging, incipient coronary insufficiency, or other less known factors. In the normal young adult and child such nonspecific changes do not occur and can be essentially excluded in differentiating a normal from an abnormal tracing; thus an abnormal ballistocardiogram in the young person is almost always indicative of physiologically significant disease.

Methods

The 46 children included in this study varied in age from 5 days to 16 years. All had the classic findings of pure aortic stenosis, consisting of the typical systolic ejection murmur and thrill heard best in the first and second right interspaces and transmitted into the carotid vessels. Many had evidence of left ventricular...
hypertrophy on electrocardiogram, vectorcardiogram, or x-rays, but others had only the thrill and murmur. We purposely made no attempt to complicate this study by direct comparison of the ballistocardiogram with other indirect indices of severity, such as vectorcardiograms or electrocardiograms.

Ballistocardiograms were obtained prior to catheterization with the use of two ballistocardiogram beds supported on jets of air; both systems are designed and manufactured by Astropace Laboratories of Huntsville, Alabama. The bed for children weighing 35 to 120 pounds (fig. 4) consisted of an aluminum platform supported by two disks 12 inches in diameter, the lower disk having a concave surface with a 24-foot radius ground into it while the upper disk had a mating convex surface. The lower disk was provided with multiple small orifices through which air was forced between the two disks. Because of the slight concavity of the lower disk, the beds are very slightly center-seeking, and no additional lateral or anterior position stabilization is necessary. The small bed designed for infants and children weighing up to 35 pounds (fig. 5) consisted of two 9-inch disks and a lighter platform, but was otherwise identical to the larger one.

Both systems have a pendulous frequency of 0.186 cycles per second, because of the slight concavity of the lower disk, but can be considered from a practical standpoint to be aperi-

\[ \text{Figure 6} \]

The classification of the ballistocardiograms used in the study. See text for explanation.

\[ \text{Figure 7} \]

Peak transaortic valvular pressure gradients plotted against ballistocardiogram classification.

\[ \text{Figure 8} \]

Preoperative and postoperative ballistocardiograms of a child with a preoperative transvalvular pressure gradient of 65 mm Hg and a postoperative gradient of 5 mm Hg.

\[ \text{Pre-op} \]

\[ \text{Post-op} \]

odic, since they show no electrical output as a result of this pendulous swing. Extensive tests have shown the frequency response of these beds to be essentially flat from 0 to 60 cycles per second. Two accelerometers were used, a Statham accelerometer on the large bed and a Donner accelerometer on the small bed. Tracings made with these instruments alternately were almost identical. All recordings were made on an Electronics for Medicine* photographic recorder.

No artificial coupling was used to couple the patient to the table, but the bed weight was

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*Electronics for Medicine, Inc., White Plains, New York.
kept as low as possible by the use of two systems, each designed for a specific weight group. The infant bed, including accelerometer, weighed 0.9 kg and that for the older children 3.2 kg. Each record was calibrated by adjusting the recorder to give a 1.5-cm deflection, with an acceleration of $3 \times 10^{-3}$ g. Simultaneous electrocardiograms and phonocardiograms were obtained for timing purposes.

After the ballistocardiograms were obtained, all patients underwent transseptal left heart catheterization under mild preoperative sedation, with sodium pentothal being used when necessary as a supplement while the atrial septum was being punctured. After the catheter was introduced into the left ventricle, the patient was allowed to react until the A-V Qs difference became normal and cardiac output as optimal as it would become under the circumstances. Simultaneous left ventricular and arterial pressures were then obtained with matched P23Db Statham transducers. The arterial pressure usually consisted of a central aortic pressure obtained when possible by means of a cardiac catheter introduced into the femoral artery, but in several of the smaller children and infants either a brachial or femoral artery pressure, measured through a no. 20 thin-wall needle, was accepted.

The ballistocardiographic records were divided without knowledge of the patient's age, name, or diagnosis into four categories: normal, borderline, abnormal, and grossly abnormal (fig. 6). The tracings were considered normal if they showed an H-I wave of less than 0.06 second's duration and a high, smooth J wave. Slight notching of the J wave was accepted as normal if it occurred on an occasional complex, but the over-all J waves were peaked and smooth and returned to base line well before aortic valvular closure.

A tracing was considered borderline if the J wave was of diminished amplitude, quite blunted, and obviously and consistently notched. Very few such tracings are seen in normal children, although low amplitude and notching become more common in the third and fourth decades of life, representing probably the earliest sign of an impaired myocardium.

The tracings were considered abnormal when the J wave was markedly degenerated, splintered (often consisting of two or more peaks), definitely and consistently notched and invariably of a low amplitude. Quite often the J segment on these tracings did not return to base line until aortic valvular closure.

A tracing was considered very abnormal when the location of the systolic waves could not be determined without the use of the electrocardiogram as a timing device.

After the tracings were divided into the various categories, they were plotted against the transvalvar systolic pressure difference obtained at left heart catheterization. The results are seen in figure 7.

As can be seen from figure 7, no patient with a systolic gradient of over 35 mm of mercury had a ballistocardiogram that could be considered either normal or borderline, although it must be noted that patients with gradients of under 30 mm of mercury had abnormal tracings.

**Discussion**

The acceleration ballistocardiogram is an easily obtained, sensitive index of cardiac function. It is probably the earliest parameter of cardiac function to become abnormal in patients with myocardial disease, coronary disease, or aging, and it is also obviously changed in many types of congenital and acquired heart disease. It is remarkably constant in children and adolescents, and deviations from normal in healthy young individuals are seldom, if ever, seen. Conversely, in young patients known to have aortic valvular disease, abnormal tracings are frequent, the changes being due to interference with the acceleration of the mass of blood during systole as it passes through the stenotic valve into the ascending aorta. Although we have not yet seen a child with a transaortic systolic gradient of over 35 mm of mercury without striking and easily defined changes in his acceleration ballistocardiogram, definite ballistocardiographic changes may occasionally be present in children with clinically unimportant pressure gradients across this valve. Consequently, an abnormal ballistocardiogram is not absolute evidence of a significantly stenosed valve.

We believe the evidence to indicate quite strongly that any child with findings of aortic stenosis and an abnormal ballistocardiogram should have left heart catheterization prior to being allowed to engage in competitive or strenuous activities, whereas, if the ballistocardiogram is normal, a great deal of thought should be given prior to subjecting such a child to this potentially dangerous procedure.
It should be noted (fig. 8) that after successful aortic valvotomy, the ballistocardiogram usually returns to normal and is consequently useful in evaluating surgical results. It may also prove of value in the long-term follow-up of congenital aortic stenosis by allowing insight into the rate of stiffening and calcification of the valve as the lesion advances with age.

References
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