A PHYSIOLOGICAL STUDY OF THE TRANSVERSE BALLISTOCARDIOGRAM

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The ballistocardiogram was developed in 1951 as a method of studying cardiac activity [1], and in recent years there have been extensive theoretical and clinical applications. It is a method of recording the kinetic processes associated with cardiac activity and with the movement of the blood in the main vessels. The receptive element of the apparatus produces an analysis of the forces acting on it, these forces originate in the thoracic cavity of the subject, who lies on a special table. The principal record is that of the projection of the center of gravity of the thoracic cavity on to the receptive plane of the instrument.

It has been shown [2] that a sufficiently complete account of the movement of the center of gravity of the human thoracic cavity may be obtained by means of two leads of the ballistocardiogram, the longitudinal and the transverse. The first of these (BCG-1) records the displacement along the longitudinal body axis. Displacements perpendicular to the longitudinal axis are recorded by the transverse lead, BCG-2.

We here report a study of the changes in the transverse lead.

The longitudinal ballistocardiogram has by now been adequately studied, but little work has been done on the transverse component. The BCG-2 component has been used as an additional recording in vector ballistocardiography [2, 3, 4], and it has also been studied in connection with the work of the heart in patients with hereditary heart disease [6]. In this connection, a physiological analysis of the transverse ballistocardiogram is not only interesting as a method, but it also has practical applications because, as will be shown below, it enables the duration of ventricular systole to be determined clinically in diagnosing various cardiac diseases.

METHOD

The transverse ballistocardiogram is recorded by means of a two-channel addition to a "Biofizpribor" electrocardiograph. The pick-up device responds to the displacement of the center of gravity of the thorax both longitudinally and transversely. For transverse recording, the device is connected so that a displacement of the load from the patient's right to left gives a negative deflection of the oscillograph beam.

Simultaneously, a recording is made of: the electrocardiogram (lead II), heart sounds, longitudinal ballistocardiogram, and the sphygmogram of the carotid artery. All the curves are on the same time scale. The rate of movement of the photographic paper is either 50 or 100 mm/sec. The time marker consists of vertical lines extending across the whole 120 mm width of the paper at 0.02 sec time intervals.

Because the pulse wave reached the carotid artery at an appreciable time after the moment of opening of the semilunar valves, when comparing this curve with the transverse ballistocardiogram we have introduced a time correction for the rate of spread of the pulse wave. For each separate curve this correction was calculated, by Schulz's method,[13], as the time interval between the second sound and the notch on the carotid pulse curve, made on 70 healthy human subjects between 20 and
40 years old.

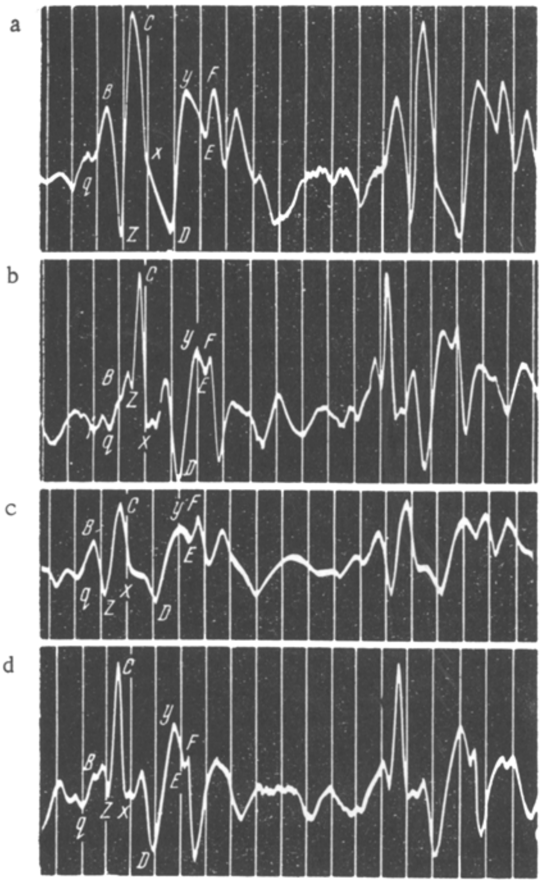

Fig. 1. Variants of the normal transverse ballistocardiogram. The interval q – B corresponds to phase of asynchronous contraction, the interval B – z represents the phase of isometric contraction, the z – y interval corresponds to the expulsion of blood from the ventricles, and the y – E interval represents the protodiastolic period.

In addition to making a physiological analysis of the transverse ballistocardiogram, we also studied the shape of the recording itself.

We here report the results of investigations made on 70 healthy human subjects between 20 and 40 years old.

RESULTS

The transverse ballistocardiogram consists of a curve which repeats at each heart beat, and whose shape shows the same characteristic features in different investigations. The principal waves of the systolic complex have been described by us so as to correspond to those of the longitudinal ballistocardiogram, and are designated q, B, z, C, D, E, and F.

The individual features concern essentially the depth of the z wave and the height of the C wave. In some cases the B wave is toothed (Fig. 1).

As is shown in Fig. 2a, all the waves of the BCG-1 and BCG-2 are strictly synchronous (except for the D wave). At the same time, on the transverse ballistocardiogram there are always two waves (the x and y waves) for which in some cases there is no corresponding wave on the BCG-1. The values for the duration of the BCG-2 waves are given in Table 1. Individual variations in the duration of the intervals indicate features of the cardiac contraction, and are also associated with variations in the cardiac rhythm in the different studies.

In 80% of the cases a comparison of the transverse ballistocardiogram and the electrocardiogram showed that the break in the curve q (Fig. 2b) corresponds to the beginning of electrical systole (Q wave). In other cases, the onset of depolarization of the ventricles is not indicated on the BCG-2, evidently because of the small mechanical effect of the asynchronous contraction.

When the transverse ballistocardiogram is compared with the phonocardiogram, it is seen that the beginning of the high frequency oscillations of the first sound corresponds precisely to the point B of the transverse ballistocardiogram, and the onset of the second sound occurred at the same time as the point E (see Fig. 2b).

In the carotid pulse curve produced as described above, the beginning of the anacrotic notch corresponds to the apex z on the BCG-2, and the lowest point of the notch on the pulse curve corresponds to the point E on the BCG-2. In all cases the point y on the BCG-2 corresponds clearly with the point at which the catacrotism changes into the notch (Fig. 2b).

The relationship between the transverse ballistocardiogram and the electrocardiogram, phonocardiogram, carotid pulse curve, and longitudinal ballistocardiogram is summarized in Fig. 3.

The comparison enables a physiological evaluation of some of the waves of the systolic complex of the transverse ballistocardiogram to be made. The first of these, the q wave, evidently represents the phase of what Holldack has called the phase of change of shape of the ventricles, or, as we call it, the phase of asynchronous contraction. This is the time of occurrence of the successive contraction of the different parts of the ventricular myocardium, which causes them to change shape without increasing the intraventricular pressure.

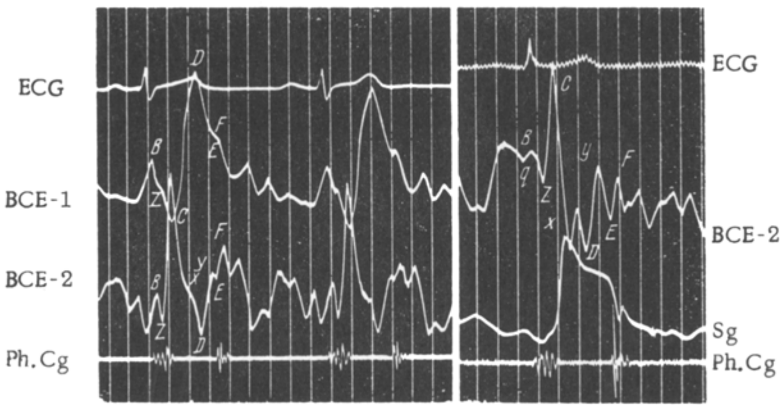

Fig. 2. Simultaneous records of the transverse ballistocardiogram (BCG-2) and the electrocardiogram (ECG), phonocardiogram (FCG), sphygmogram of the carotid artery (SG), and the longitudinal ballistocardiogram (BCG-1). Description in text.

TABLE 1

Values of the Time Intervals of the Transverse Ballistocardiogram

Interval	Limits over which duration varies (in seconds)
q – B	0.04 – 0.07
B – z	0.02 – 0.05
z – C	0.03 – 0.06
C – x	0.03 – 0.06
x – D	0.08 – 0.12
D – y	0.06 – 0.10
y – E	0.02 – 0.05
E – F	0.01 – 0.04

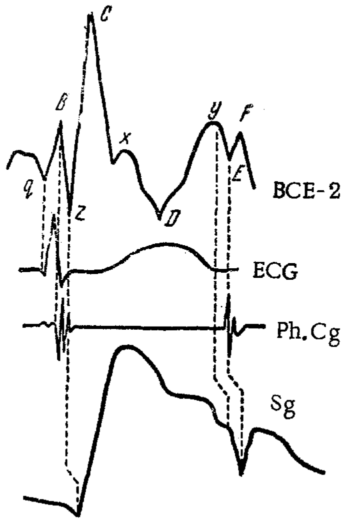

Fig. 3. Diagram comparing the transverse ballistocardiogram with curves recorded by other methods (indications as in Fig. 2).

The B wave of the transverse ballistocardiogram occurs at the moment of closure of the atrioventricular valves, as is shown by the fact that it coincides with the onset of the high frequency oscillations of the first sound. Holldack [11] and others after him [8, 12] have used this phonocardiographic criterion to determine the onset of the phase of increased intraventricular pressure or the phase of isometric contraction. Consequently, the point B of the transverse ballistocardiogram represents the commencement of mechanical systole of the ventricles.

The accurate correspondence of the point z of the transverse ballistocardiogram with the beginning of the anacrotic notch on the sphygmogram of the carotid artery indicates that the point z represents the beginning of the phase of expulsion of blood from the ventricules, or, what is the same thing, the end of the phase of isometric contraction.

Further comparison of the ballistocardiogram and carotid pulse curve enables the physiological significance of the y and E waves to be elucidated. The correspondence of the former with the beginning of the notch, and of the latter with the lowest part on the curve indicates that the point y on the transverse ballistocardiogram represents the beginning, and the point E the end of the protodiastolic period.

The protodiastolic period as defined by Wiggers [14] follows after the phase of expulsion of the blood from

TABLE 2

Mean Duration of the Phases of Cardiac Contraction in Healthy Subjects (in seconds)

Author	Phase of asynchronous contraction	Phase of isometric contraction	Expulsion phase	Mechanical systole	Protodiastole	Method of investigation
Holldack [11].	0.051	0.037	0.290*	0.327	–	Polycardiography
Nassi and others [12] . . .	0.050	0.032	0.289*	0.321	–	The same
E. B. Babskii and V. L. Karpman [5] . . .	0.053	0.030	0.284*	0.314	–	" "
E. B. Babskii and V. L. Karpman [5] . . .	0.052	0.029	0.287*	0.316	–	BCG-1
Our own results.	0.053	0.032	0.280	0.312	0.035	BCG-2

* The duration of the protodiastolic period is included in the expulsion phase.

the ventricles and represents the time expended in closing the semilunar valves. The onset of the protodiastolic period (end of the expulsion phase) is determined from the beginning of the notch on the pressure curve of the great vessels [14]. Broemser [9] has shown that this moment may be determined also from the carotid pulse curve, the beginning of the notch on it corresponding to the end of the phase of expulsion of the blood from the ventricles. However, the end of the protodiastolic period (the time at which the closure of the semilunar valves is completed) corresponds to the lowest point of the notch on the carotid pulse curve and to the beginning of the second heart sound.

The results obtained show that many of the waves of the transverse ballistocardiogram are associated with mechanical processes which represent the beginning or end of the different phases of contraction of the ventricles. It is clear that the duration of the different systolic phases may be determined from the interval between the relevant waves on the BCG-2. Thus, the q – B interval represents the duration of the phase of asynchronous contraction (the time from the beginning of electrical depolarization of the ventricles to the time of closure of the auriculoventricular valves). The B – z interval corresponds to the phase of isometric contraction (the period during which the valves are closed). The duration of both intervals corresponds to Blumberger's phase of tension [7].

The next, systolic, or expulsion phase, was previously considered as the part of the cardiac cycle during which the semilunar valves were open. However, after the work of Wiggers [14] it became clear that actually the time during which blood is expelled from the ventricles is somewhat shorter, because the closure of the semilunar valves takes place during the relaxation of the myocardium, and therefore cannot be included in the expulsion phase. This fact is revealed in many works on the analysis of the phases of cardiac contraction [10, 15]. Nevertheless certain authors [7, 11, 12] continue to include the protodiastolic period in the expulsion phase. Evidently, in that case, the duration of this phase will be relatively increased.

As has been pointed out previously, in the transverse ballistocardiogram it is possible to distinguish the protodiastolic period (y – E interval) and, consequently, to determine the duration of the actual expulsion phase (interval z – y).

Because the duration of mechanical systole includes the times of isometric and of isotonic contractions, it may be determined from the B – y interval of the transverse ballistocardiogram.

Table 2 shows the durations of the different phases of ventricular systole as revealed by the transverse ballistocardiogram in the healthy human subjects whom we studied, as well as the results previously published by other authors who used different methods.

It can be seen from Table 2 that the phasic analysis of cardiac contraction from the ballistocardiogram is quite precise, so that it can be used for physiological and clinical investigations.

Finally we may note that the analysis of the phases of cardiac contraction which we have made by means of the ballistocardiogram has some advantages when compared with the corresponding information revealed by longitudinal ballistocardiography, as some of the waves are more clearly shown. Also, no reliable determination has been made of the significance of the point y on the BCG-1. However, the B wave on the BCG-1 is often more clearly shown than on the BCG-2. For an analysis of the different phases, it is therefore advantageous to use both the ballistocardiograms.

SUMMARY

For the first time a physiological analysis has been made of the transverse ballistocardiogram. The curve was found to indicate the different phases of the cardiac cycle. It was shown that in man under normal conditions the phase of asynchronous contraction lasts 0.053 seconds, the phase of isometric contraction for 0.032 seconds, the ejection phase for 0.280 seconds, mechanical for 0.312 seconds, and the protodiastolic period for 0.035 seconds. An accurate analysis of the different phases of the different cardiac contractions by means of ballistocardiography can be made by recording the longitudinal and transverse ballistocardiograms simultaneously. The transverse ballistocardiogram shows a considerable degree of consistency in different healthy individuals.

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