METHODS

A MODEL APERIODIC BALLISTOCARDIOGRAPH AND A DESCRIPTION OF AN APERIODIC BALLISTOCARDIOGRAM OF A HEALTHY INDIVIDUAL

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Ballistocardiography is a comparatively recent method of physiological investigation which has been extensively applied clinically. The first serious application was in 1905 in a famous experiment by Haldene, Henderson, and other investigators [7] on hills in the Peak District. Henderson used this method for a dynamic study of the stroke volume of the heart during a human sojourn at high altitudes. The device consisted of a wooden platform hung from four rigid supports on long flexible steel wires. Its characteristic frequency was about 0.3 sec. The fundamental principle had been advanced much earlier by Gordon [6]; Henderson was the first to produce a true ballistocardiograph. In order to record the displacement of the human body caused by cardiac contraction and the expulsion of the blood, Henderson took the important step of isolating the body as far as possible from surrounding objects. In this way, the system (human body – apparatus) possessed a high sensitivity; this fact is important because the amplitude of the displacement of the human body does not exceed a few hundred microns. However it was not this apparatus but the high-frequency ballistocardiograph of Skarr [10] which was applied widely in clinical practice. Unfortunately it was found quite rapidly that there was little correspondence between the low precision of the actual changes recorded by means of the high-frequency ballistocardiograph and the clear quantitative principles of classical mechanics which it was natural to apply to the reaction between the system comprising the body and the apparatus on the one hand and the heart and the blood expelled from it on the other. In the design by Dok the real value of ballistocardiography as a quantitative method of investigation was not realized, because a number of side effects occurred which could not be taken into account quantitatively even under the conditions of an acute experiment. Despite some success in diagnosis achieved by means of the ballistocardiograph of Dok, Kazmeier, and Schild [8] it was found that direct ballistocardiography was not an effective means of measurement.

The experience of V. S. Gurfinkel' based on experimental studies of the physical nature of dynamo- and ballistocardiography led to the conviction that the nature of the recorded process and the magnitude of errors ignored of or taken into account depended on the structure of the connections between the interacting parts of the system; heart – blood expelled by it – body – apparatus, and on connections between the system and surrounding objects. Burger [4,5], von Wittern [11], Yu. A. Vlasov [1,2], and R. I. Gismatulin [3] came to the same conclusions. This line of thought led to the creation of the original ballistocardiographic method. We must note that Klensch [9] had already incorporated these principles in the construction of an aperiodic ballistocardiograph, but his instrument suffered from many important defects which restricted its clinical application.

The basic idea of our instrument is to make the connections between the system consisting of the human body and the apparatus rigid, but to make the connections between this system and surrounding objects as weak as possible. The rigid connection within the system results in a minimum interference to the transmission of the impulse from the generator (heart and large blood vessels) to the apparatus, while the weak connection between the system and the surrounding objects enables the apparatus to reproduce precisely the shape and size of the signal. The first condition was realized by insuring a minimal weight to the recording platform (less than 5 kg) and an aperiodic system of operation. The aperiodicity satisfied a second requirement, that the apparatus should be loosely coupled to surrounding objects.

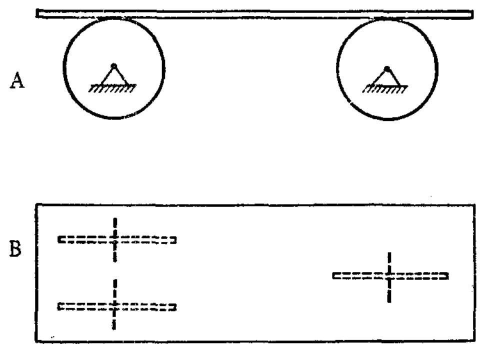

Fig. 1. Explanation in text.

In practice this end was realized by placing a light rigid recording platform on which the subject lay on three light sports-bicycle wheels standing in a vertical plane (Fig. 1).

The apparatus must be set out so as to ensure an accurately horizontal position for the recording platform which rests upon the wheels. It is only when this condition is observed that the device will operate aperiodically, and that the platform will always be in a state of equilibrium. Because the system is aperiodic, the damping which has to be observed in all other ballistocardiographs working on a periodic system is not necessary. The large radius of the wheels leads to a considerable turning moment, therefore there is considerable reduction in the rolling friction of the solid wheel along the firm surface of the platform, and of the rolling friction of the wheel bearings which remain practically motionless. This design leads to reduction in energy losses of the ballistocardiographic impulse expended in friction at the points of support; the increase of radius of the wheel and the reduction of friction at the points of support is brought about by use of the principle of the Atwood machine, and use of material of corresponding hardness and weight for the support and for the wheels. The whole platform together with the three wheels weighs 7.5 kg. We used three wheels instead of four, because it is only with three that a plane can be maintained truly horizontal. By contrast with our apparatus, in the aperiodic ballistocardiograph of Klensch [9] the sensitivity cannot be increased or the frictional losses reduced because increase of radius of the basic working element – the sphere – leads to an increase of its mass proportional to the cube of the radius, whereas increase of the radius of a disc (in our apparatus a wheel) leads to an increase of mass proportional only to the square of the radius. Furthermore a rigid sphere of larger radius can be made only of hard materials such as corundum or of special high-tensile steels, which causes a disproportionate increase in their mass, whereas a disc of larger radius and of minimal weight may be made sufficiently rigid in a very simple way, for example by use of a bicycle wheel. In our apparatus the displacement was recorded by means of strain gauges supplying a signal to a strain-gauge amplifier UTM-4. From the output of the amplifier the signal was taken to the input of a 2-channel in-writing electrocardiograph.

The aperiodic displacement ballistocardiogram which we obtained consists of an oscillation showing a striking resemblance to the volume pulse of the thigh and lower leg (Fig. 2). The cycle of the aperiodic ballistocardiogram corresponding to one cardiac contraction (in the example taken lasting for 0.82 sec) begins with a small rise starting 0.02 sec after the end of the S wave of the ECG (the end of the S wave occurs immediately before the onset of ventricular contraction); the apex of the ballistocardiogram occurs 0.05 sec after the end of the S wave. This rise constitutes the first oscillation which is not always well shown. This wave is shown in Fig. 2 by number 1 and corresponds in time to the J wave on the acceleration ballistocardiogram. The first wave of the aperiodic displacement ballistocardiogram changes over in its descending portion into a negatively inclined oscillation. This second wave (2) corresponds in time to the apex of the J wave on the acceleration ballistocardiogram. The apex of this wave occurs

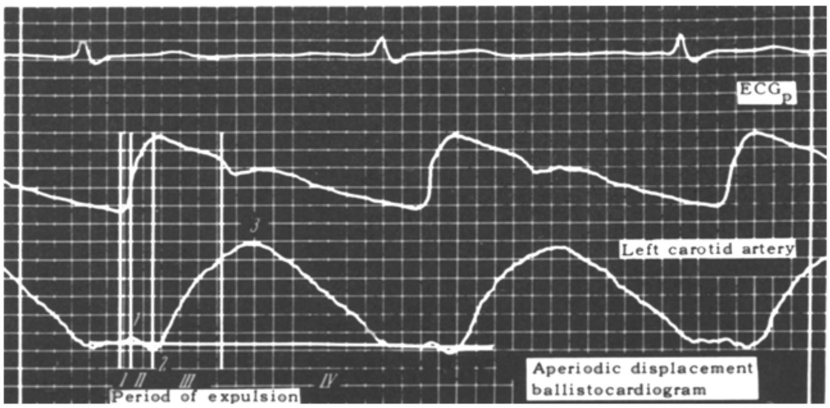

Fig. 2. Explanation in text.

0.095 sec after the end of the S wave of the ECG. The second oscillation, having reached the equilibrium point of the system on its ascending portion becomes transformed into a mainly positive-going oscillation of greatest amplitude (3); the apex of this oscillation corresponds to the diastolic wave M on the acceleration ballistocardiogram. The apex of the main wave of the aperiodic displacement ballistocardiogram occurs 0.305 sec after the end of the S wave of the ECG.

In the phases of the cardiac cycle the onset of wave 1 corresponds precisely with the start of expulsion of the blood from the left ventricle into the aorta (onset of sharp rise of the curve of the central pulse); the apex of this wave corresponds in time with the anacrotic notch of the central pulse when the rapid flow changes into a slower one. The apex of wave 2 corresponds precisely with the highest point of the curve of the central pulse, after which there is a delay in the expulsion of blood from the left ventricle and a fall in this part of the curve (catacrotic notch). At the moment of the change over from the anacrotic to the catacrotic portion of the curve, in most cases a rise of the anacrotic volume pulse of the thigh occurs. This means that over this interval of time (from the onset of expulsion of blood into the aorta until the start of the anacrotic rise in the thigh pulse) the pulse wave spreads along all branches of the aorta. On the aperiodic displacement ballistocardiogram this interval corresponds to the interval between the onset of wave 1 and the apex of wave 2, and occupies altogether 9.2% of the time of one cardiac cycle. This interval is indicated in Fig. 2 by I - II.

The next interval on the curve corresponds to the growth of the main oscillation of the aperiod displacement ballistocardiogram from its lowest point (apex of the second negative wave) to the highest point, and is indicated by the figure III. On the central pulse the catacrotic section from the apex of the curve to the end of systole (or, what is the same thing, from the point at which the blood expelled from the left ventricle into the aorta is slowed down until the end of expulsion) corresponds to this interval. It is true that the apex of the main oscillation of the aperiodic ballistocardiogram almost coincides with the apex of the dicrotic wave, but because interval III consists mainly of the period at which the blood is slowed down this boundary does not run through the apex of the ballistocardiogram but occurs at the end of mechanical cardiac systole. This period on the volume curve of the pulse corresponds to the anacrotic rise almost to the surface. Thus the rise of the main oscillation of the ballistocardiogram is temporarily related to the slowing down of the expelled blood from the left ventricle and to the synchronous rise in pressure in the peripheral arteries.

We must note that the apices of the curves of the volume pulse of the thigh and of the aperiodic ballistocardiogram occur at almost the same instant. In the period of the cardiac cycle which we are describing there is a spread of the pressure wave along the arteries to the arterioles, and in the time which follows this interval the kinetic energy of the blood expelled by the left ventricle is transformed into potential energy in the form of extension of the aortic and arterial walls. In our example, interval III of the ballistocardiogram occupies 22.5% of the cardiac cycle, and 62% of the period of expulsion, whereas the interval I - II occupied only 38% of the period of expulsion.

Immediately after the end of the expulsion period which corresponds approximately to the apex of the ballistocardiogram, a drop begins which terminates at the onset of the next displacement, and therefore the duration of this period(IV) is equal to that of diastole. In this period there is a reversed exchange of potential energy of the extended aortic and arterial walls into the kinetic energy of the moving blood. The representation of this interval both on the sphygmogram of the central pulse and of the displacement ballistocardiogram are very similar, and both occupy 68.3% of the cardiac cycle, the same proportion which is occupied by diastole in the cardiac cycle of corresponding duration, as in our example. Altogether intervals I - II and III of the displacement ballistocardiogram correspond to the period of expulsion of blood from the left ventricle into the aorta, while period IV corresponds to the diastolic period.

It is as well to point out here that the interval I - II which occupies 9.2% of the cardiac cycle and 38% of the period of expulsion corresponds to the period of expulsion of blood with maximum velocity when two-thirds of the stroke volume are expelled into the aorta, but the amplitude of oscillation at this period is very small, although it is at this time that most of the work is performed by the left ventricle. On the other hand, interval III which occupies 22.5% of the cardiac cycle and 62% of the period of expulsion corresponds to the period of slowing down of the expulsion of the blood when the velocity of the expulsion continuously falls, a period when only one-third of the stroke volume is displaced into the aorta. The amplitude of oscillation during this interval is the greatest; it is at this time that the main oscillation of the displacement ballistocardiogram falls.

SUMMARY

An analysis of blood shifts in an aperiodic ballistocardiogram during the different phases of cardiac contraction showed intervals corresponding precisely to the phases of the discharge of blood from the left ventricle into the aorta.

Interval I -II were the phases of rapid discharge, interval III was the phase of delayed discharge during which the pressure wave was distributed along the arterial bed, and period IV was the period of diastole. The use of an aperiodic ballistocardiograph makes it possible to record curves which may be analysed quantitatively and interpreted physiologically.

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