SOME OBSERVATIONS ON THE BALLISTOCARDIOGRAPHIC PATTERN, WITH SPECIAL REFERENCE TO THE H AND K WAVES [1]

By JOHN L. NICKERSON

(From the Department of Physiology, College of Physicians and Surgeons, Columbia University, New York City)

(Received for publication July 26, 1948)

The origin of certain portions of the ballistocardiographic pattern has been discussed only briefly in the physiological literature. Starr and his associates (1) have given letter designations to the salient peaks and troughs and have discussed in some degree the origin of the I and J waves. Hamilton and his coworkers (2, 3) have suggested that the pattern may be due in part to the oscillations of the blood mass within the larger portions of the arterial tree. It is the purpose of the work being presented here to consider the results of some simple experiments which help elucidate in broad outline the significance of several parts of the ballistocardiograph pattern.

Two sources of information have been tapped in this study, to wit, model experiments and clinical observations. The ballistocardiograph used in this investigation was not the instrument constructed by the workers mentioned above but was the low frequency, critically damped instrument designed by Nickerson and Curtis (4). The heart model built for the study of the ventricular contribution to the ballistic pattern was a simple one-chamber device. This model ignores the asynchronism which sometimes appears between the ejection of the left and right ventricles (5, 6) and also ignores the auricular contribution to the impacts, a problem which will be dealt with in a different fashion.

The construction of the model heart is demonstrated in Figure 1. It consists of a closed elastic system of bulbs and tubing filled with water. The dimensions of the tubing approximate those of the aortic tree of an adult human. One elastic bulb is contained in a glass pressure bottle so that the force on this bulb may be raised to any suitable level. The tubing used in this system is of rubber and the bulbs are rubber balloons of various thicknesses. This bottle has sufficient volume that the pressure changes in it during ejection are small. In operating this system, water to any desired amount (30–100 cc.) is squeezed back into the bulb in the pressure bottle at a time when the pressure bottle is open to the atmosphere. The exit tube from this bulb is then clamped shut and the pressure in the bottle raised to a measured level (40–120 mm. Hg). If now the quick-acting clamp is suddenly released by burning through a restraining thread the water in the heart bulb will be forced into the outer portions of the circulatory system corresponding to the aortic tree. This movement of fluid produces a reaction equivalent to systolic ejection. By varying the filling of the heart bulb and also the pressure in the bottle it is possible to control both the stroke volume and the force of ejection.

The normal human ballistocardiogram is illustrated in Figure 2 in which the H, I, J, K and L waves of Starr's notation are identified. It is

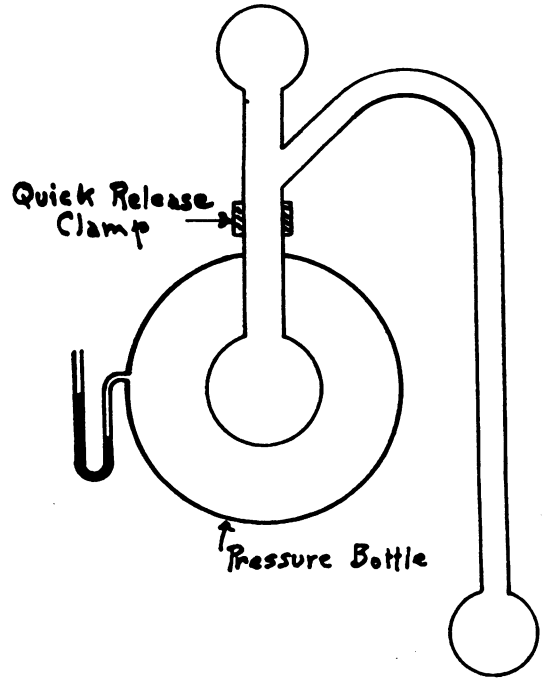

FIG. 1. DIAGRAM OF THE MODEL HEART

[1] This investigation was supported in part by a research grant from the Division of Research Grants and Fellowships of the National Institute of Health, U. S. Public Health Service.

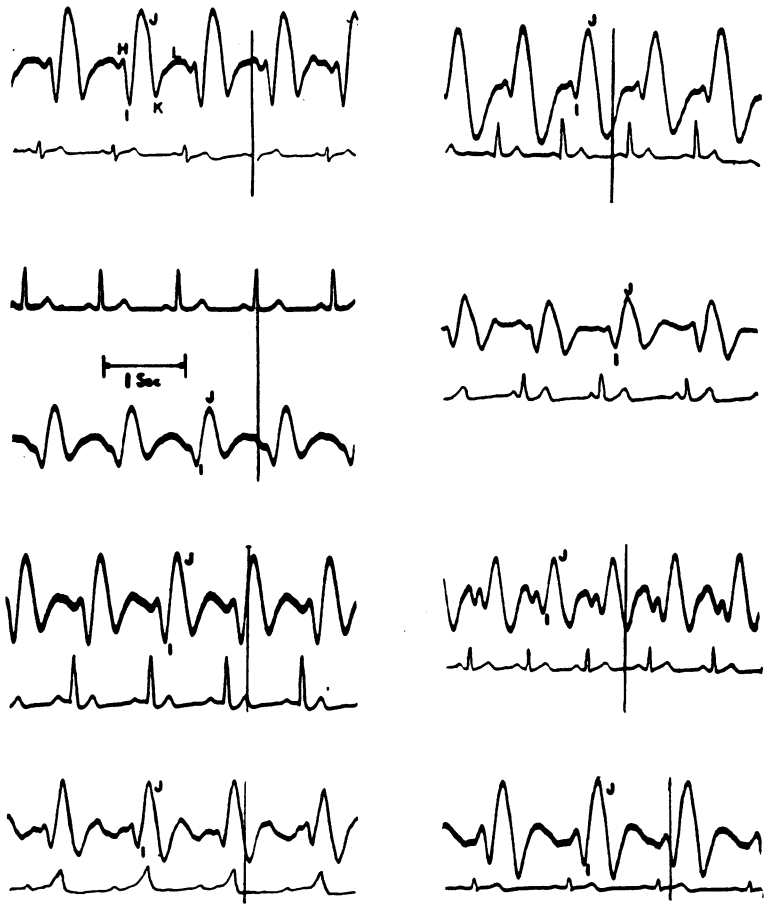

FIG. 2. BALLISTOCARDIOGRAMS ON NORMAL SUBJECTS

the general view that the I-wave is produced by the footward recoil of the body and ballistic bed as a result of the headward movement of the blood at the time of its ejection from the left and right ventricles during systole. After the commencement of this footward movement, the blood, which is travelling headward, begins to fill up the aortic tree, and so slows in its course. At the same time some portion of the blood actually reverses its direction by passage around the aortic arch. These occurrences result in a large headward recoil which is sufficient to neutralize and reverse the footward movement, thus driving the ballistic system headward to produce the J-wave. Following this impact the system reaches its maximum headward deflection and since it is critically damped might be expected to return to the baseline position without overshooting. However, the blood rushing down the descending aorta does not continue with undiminished speed but in the lower abdominal region is slowed in its footward rush, thus producing a footward thrust. This thrust is on most occasions so timed that it drives the ballistic system footward across the baseline, thus generating the K-wave. Following the K-wave there is frequently a return to the baseline. However, in many cases a subsequent headward wave, the L-wave, appears which is likely due to a reflected wave of blood travelling first up and then down the long column of the descending aorta.

That this normal pattern can be reproduced by the model heart's ejection is shown by Figure 3. Records 1 and 2 were produced by essentially the same stroke volume and ejection pressure and differ only in the greater length of the descending aorta in Record 1. The slope of the I–J line in both records is the same. Hence the stroke

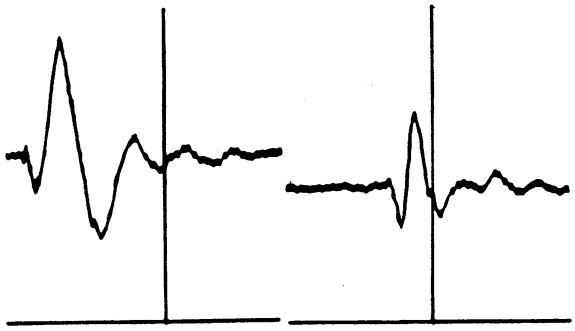

FIG. 3. BALLISTOCARDIOGRAMS FROM THE MODEL HEART DEMONSTRATING VARIATION IN THE K-WAVE

In part 1 the descending aorta is long while in part 2 it is short.

volumes are equal. However, the relative depths of the K-waves are quite different. Further observation has shown that variation in the length of the descending aorta is singularly effective in changing the K-wave and appears to be one of the chief factors determining the depth of this wave in the normal human ballistocardiogram.

Further shortening of the descending aorta or constriction of this vessel so that the blood following this course does not have a clear path below the aortic arch produces complete disappearance of the K-wave. This type of pattern is demonstrated in Figure 4A by an actual coarctation of the aorta and in Figure 4B by a coarctation at the arch of the aorta in the model experiment. Similarly in all cases of coarctation of the aorta in which it has been possible to obtain low frequency, critically damped ballistocardiograms, diminution or disappearance of the K-wave is found. It is to be noted that this absence of the K-wave is not observed when a conventional high frequency ballistocardiograph is used (see Figure 5). It is proper to state at this point that although all patterns of coarctations observed with

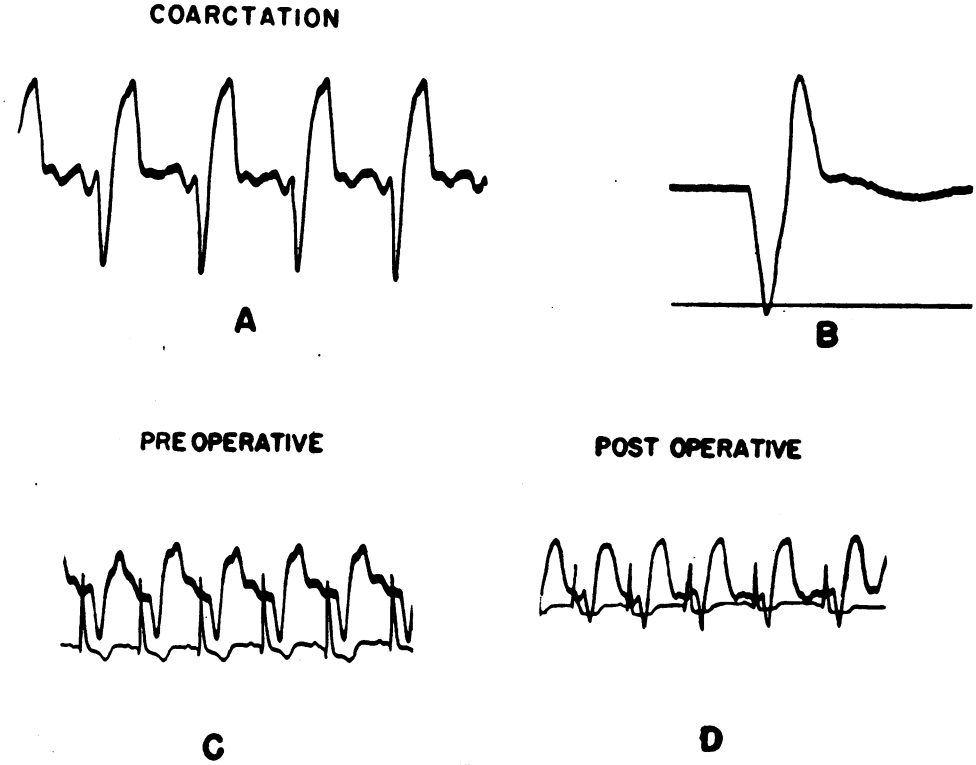

FIG. 4

A. Coarctation of the aorta in a patient.
B. Coarctation of the aorta in the model at the beginning of the descending aorta.
C and D. Pre- and post-operative records on a patient with coarctation of the aorta. The surgical procedure was the anastomosis of the subclavian artery to the descending aorta.

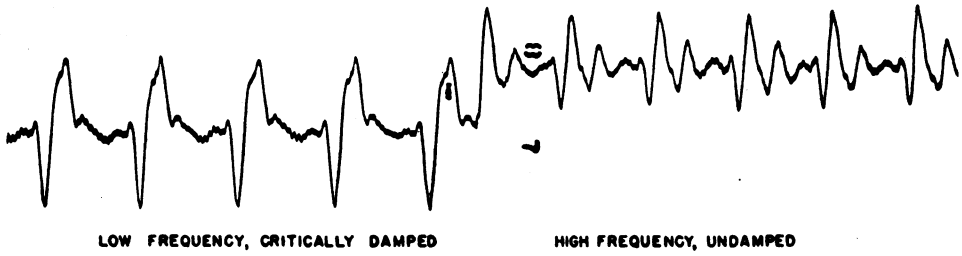

FIG. 5. RECORD ON A PATIENT WITH COARCTATION OF THE AORTA TAKEN WITH A LOW FREQUENCY, CRITICALLY DAMPED BALLISTOCARDIOGRAPH AND WITH A HIGH FREQUENCY, UNDAMPED BALLISTOCARDIOGRAPH

the low frequency, critically damped ballistocardiograph show this reduction of the K-wave, nevertheless a few records are seen where the K-wave is diminished without aortic coarctation being present. From analogy with the model experiments it is believed that this result appears when the effective free lengths of the major portions of the headward regions of the aortic tree and the descending aorta are essentially equal. To date only one patient with coarctation of the aorta on whom surgical treatment has been performed has had pre- and post-operative ballistic records taken. The results obtained are shown in Figures 4C and 4D. In this case the anastomosis accomplished was of the subclavian to the aorta, a procedure by which the circulation to the extremities was improved. As a result of this particular anastomosis the momentum of the blood in the descending aorta was still impeded in a region high in the thorax rather than low in the abdominal cavity as is normal. For this reason, although the movements producing the K-wave post-operatively are more accentuated than in the pre-operative pattern, the results, however, are not as completely normal as would be expected had the anastomosis been of the aorta on itself.

Another point of evidence for the development of the K-wave arises in the change of pattern on the production of a reactive hyperemia of the lower extremities. This reaction appears if the circulation to the lower limbs is occluded by pressure cuffs applied to the thighs with pressures above the systolic level for a period of 15 minutes and then released. The resulting increased oxygen demands of the tissues result in an increased blood flow to the affected parts. The changes in the ballistocardiogram are shown in Figure 6. There are two chief changes, first, an increase in the slope of the I to J movement, thus indicating an increase in stroke volume (7, 8), and second, a decrease in the relative depth of the K-wave. This diminution of the K-wave occurs since the retardation of the blood velocity at the lower end of the descending aorta is not so great as normal, more of the blood flowing directly into the wider open vascular bed of the lower extremities. Thus the impulse producing the K-wave is less than before.

The effect of reducing the stroke volume in the model heart produces some variations in the size of the pattern. These are shown in Figure 7 where are illustrated the types of pattern found in a patient in shock. These general variations were found in all our shock cases. In this particular case the first record was made before treatment while the second and third records were made after treatment with albumin and with saline respectively. The values of the stroke volumes from the Fick data were successively 26, 37, and

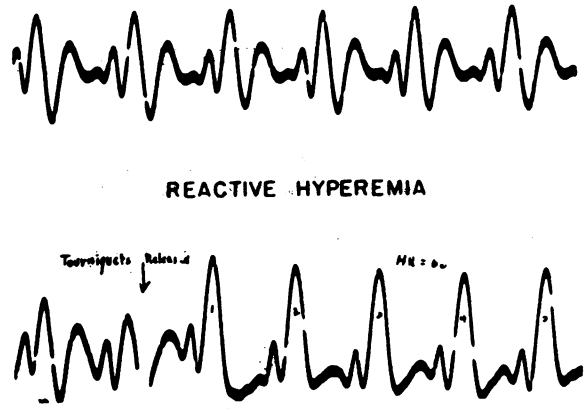

FIG. 6. CHANGE IN THE FORM OF THE PATTERN ON THE OCCURRENCE OF A REACTIVE HYPEREMIA OF THE LOWER LIMBS

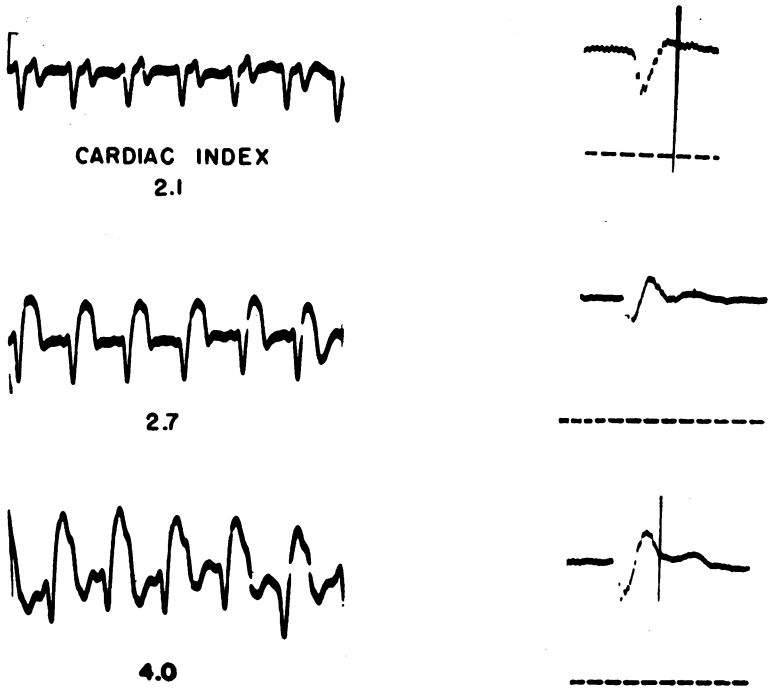

FIG. 7. SUCCESSIVE BALLISTOCARDIOGRAMS ON A PATIENT IN SHOCK (CARDIAC INDEX BY THE FICK = 2.1), AFTER TREATMENT WITH ALBUMIN (INDEX = 2.7) AND AFTER FURTHER TREATMENT WITH SALINE (INDEX = 4.0)

The accompanying records are of the model heart with increasing stroke volume.

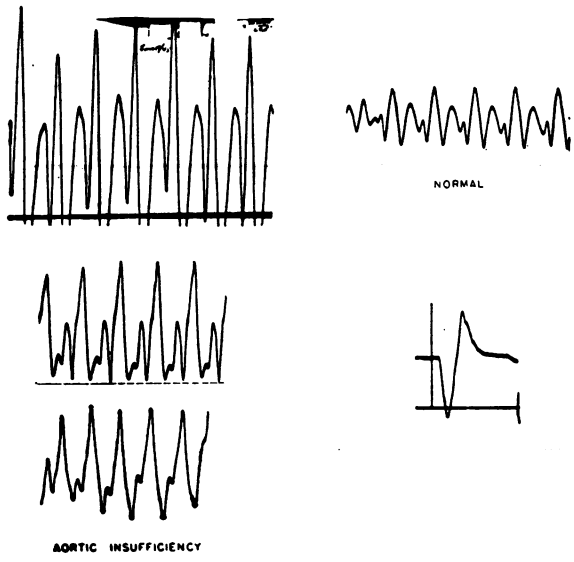

FIG. 8. BALLISTOCARDIOGRAMS ON THREE PATIENTS WITH AORTIC INSUFFICIENCY, ON A NORMAL SUBJECT AND ON THE MODEL HEART IN A SITUATION WHERE A LARGE STROKE IS EJECTED INTO A FLACCID AORTIC TREE

55 ml. The most significant parallelism from the patient's records and from the records of the model heart is the manner in which the J-wave increases more markedly than the I-wave as the stroke volume returns toward normal. The low J-wave may possibly be a distinguishing mark of a stroke volume below normal.

The other extreme of an unusually large cardiac stroke volume produces also a characteristic pattern, Figure 8. The situation demonstrated is that of aortic insufficiency where the excessively large stroke volume is partly returned to the heart through the faulty aortic valve during diastole. The most striking features of these records are their unusual size (*i.e.*, the I–J slope is extremely steep) under basal conditions as compared with normal records, and the appearance in many records of a slurring in the rising limb of the J-wave. The latter feature was reproducible in the model heart as is also shown in Figure 8. This particular pattern occurs when

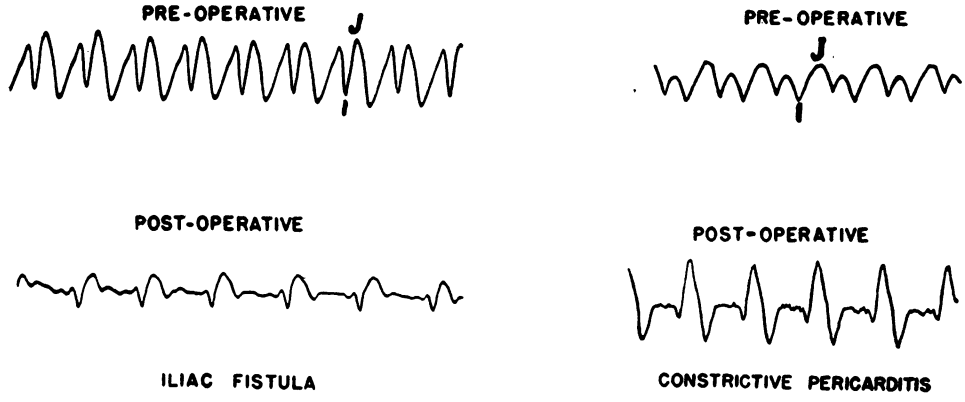

FIG. 9

the stroke volume of the model is large and the bulb at the head end of the model is of unusually stretchable rubber.

In Figure 9 are shown several patterns which are dramatically abnormal. The first is a pre-operative iliac arteriovenous fistula in which the fistula carried a large flow of blood. The pattern presents a sequence of footward and headward movements of almost equal size. A possible explanation of this pattern may be that it is the result of a series of impacts due successively to the footward thrust of the ventricular ejection, the headward thrust at the turn of the arch of the aorta, etc., the large footward impact caused by blood changing its direction in passing through the iliac fistula and finally the return to the base-line in time for the cycle to begin again. The post-operative pattern after removal of the fistula shows a slowing of the heart, a decrease in the stroke volume and a restoration of the pattern to a more normal form. In particular the influence of the fistula upon the K-wave should be noted. The second illustration in this figure is a case of constrictive pericarditis. The pre-operative pattern shows a small I–J slope which indicates a stroke volume well below the normal basal value. The post-operative pattern is remarkably improved toward normal and has a normal value of the basal cardiac index.

Figure 10 illustrates changes in the pattern which appear as a result of irregular rhythms of the heart. Part 10 A presents the pattern observed in sinus arrhythmia and shows that the variations are largely in the size of the pattern, the longer filling period being followed by a steeper I–J slope indicating a larger stroke volume, and the shorter intervals between beats being followed by smaller patterns and therefore

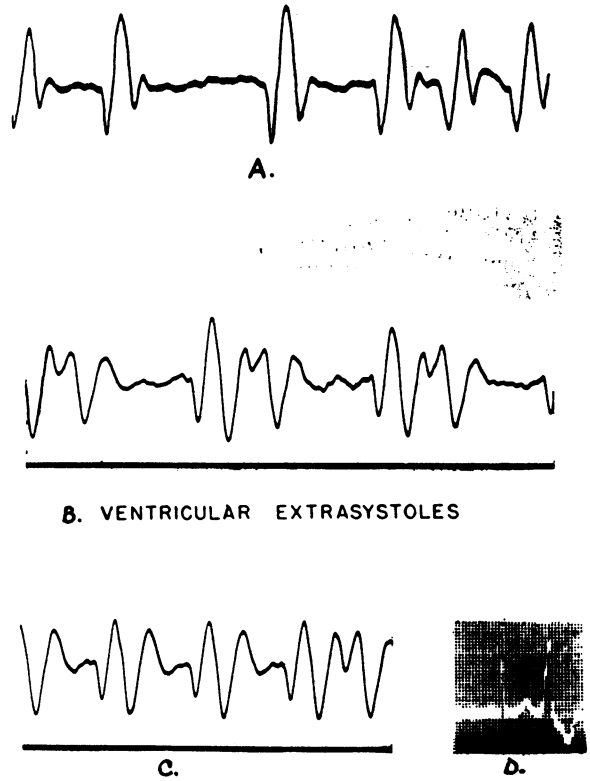

FIG. 10

A. Irregular beats originating in the sinus node.
B. Extrasystoles of ventricular origin.
C. Same patient (B) when extrasystoles are not occurring.
D. ECG on patient in B and C showing normal and abnormal ventricular patterns.

smaller stroke volumes. Part 10 B illustrates the result of a close succession of beats. The pattern of the premature beat begins before the termination of the pattern of the preceding normal beat and permits only a short filling time. Since this premature beat is not observable in the radial pulse, it is quite possible that the ballistic movement accompanying this beat is not the result of the impact caused by an ejection of blood but is rather an indication of the contribution of the movement of the heart mass to the pattern. Part 10 C shows the ballistic pattern on the same subject at a time when these premature beats are not occurring.

So far in this discussion the presence of the H-wave has been ignored and the movements of the ballistic system considered as beginning with a footward excursion starting at the peak of the H-wave. However, as pointed out by other workers (3), this is probably not correct. For example, the time interval from the beginning of the QRS complex of the electrocardiogram to the peak of the H-wave is about 0.100 second whereas the time from the QRS complex to the beginning of the ventricular ejection is about 0.0700–0.0800 second (9). Because of this discrepancy, it has been suggested that the I-wave of the ballistocardiogram does not follow the ventricular ejection but rather is associated with some other circulatory event. Of course the possibility exists that the ballistic movements of the

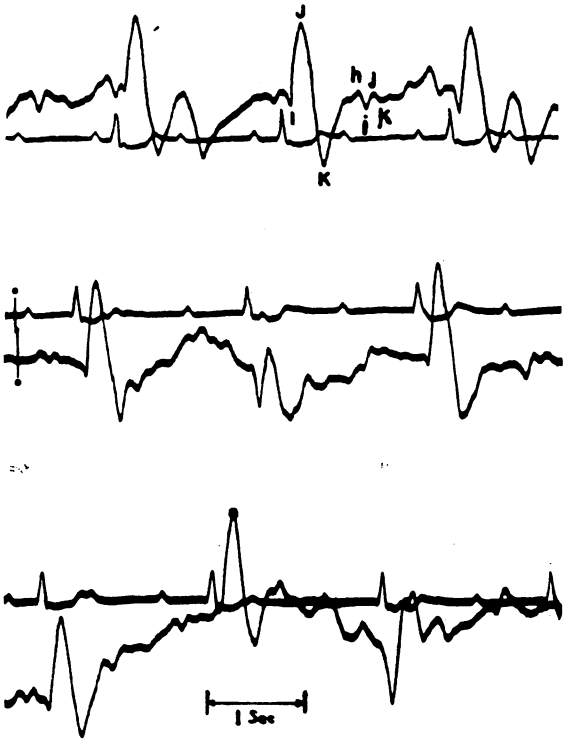

FIG. 11. BALLISTOCARDIOGRAM OF A PATIENT WITH COMPLETE HEART BLOCK

The auricular complex h, i, j, k is shown as well as the purely ventricular complex I, J, K, . . . Where overlapping of the two complexes occurs, the usual H-wave of the ballistocardiogram appears.

TABLE I

No.	Ph	Pi	Pj	Pk	PR	QH	QI	QJ
1	0.11	0.15	0.24	0.31				
2	0.11	0.15	0.24	0.31	0.20	0.09	0.13	0.23
3	0.11	0.15	0.25	0.33				
4		0.13	0.25	0.29	0.31	0.07	0.14	0.24
5					0.35	0.07	0.13	0.24
6	0.11	0.15	0.25	0.31	0.40	0.07	0.13	0.24
7	0.11	0.16	0.23	0.31	0.54	0.065	0.14	0.23
8	0.12	0.17	0.23	0.35	0.51	0.065	0.14	0.25
9	0.15	0.20	0.27	0.37	0.40	0.07	0.15	0.26
10	0.14	0.19	0.27	0.37	0.64	0.07	0.16	0.25
11					0.20	0.10	0.19	0.25
12	0.11	0.17	0.23	0.31	0.73	0.08		
13	0.09	0.16	0.25	0.35	0.27	0.08	0.13	0.26
14					0.36	0.07	0.13	0.25
15	0.09	0.16	0.24	0.30	0.49	0.07	0.13	0.24
16		0.16	0.24	0.29	0.60	0.065	0.14	0.25
17					0.23	0.085	0.14	0.25
18		0.13	0.23	0.30	0.34	0.08	0.13	0.24
19		0.15	0.24	0.31	0.51	0.08	0.13	0.25
20					0.67	0.07	0.12	0.25
21	0.08	0.13	0.23		0.21	0.08	0.13	0.24
22					0.065	0.07	0.14	0.25
23					0.19	0.09	0.14	0.26
24		0.14	0.23	0.30	0.32	0.08	0.13	0.24
25		0.15	0.24	0.31				
26					0.07	0.07	0.13	0.25
27					0.13	0.09	0.14	0.26
28	0.07	0.16	0.24	0.29	0.41	0.07	0.13	0.24
29	0.08	0.15	0.24	0.29	0.70	0.065	0.13	0.26
30	0.09	0.15	0.24	0.31	0.40	0.075	0.14	0.23
31	0.09	0.15	0.24	0.31				
mean	0.104	0.155	0.242	0.315			0.137	0.247

P = beginning of P wave of the electrocardiogram.
Q = beginning of the QRS complex of the electrocardiogram.
h, i, j, k are successive peaks in the auricular complex of the ballistocardiogram.
H, I, J are successive peaks in the normal ballistocardiogram.
PR = the usual interval defined as the time from the beginning of the P wave to the beginning of the QRS complex of the electrocardiogram.
The table above lists the time in seconds between the points so defined.

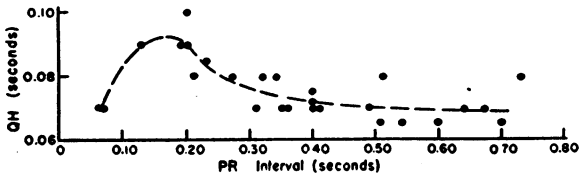

FIG. 12

QH, the time from the beginning of the QRS complex to the beginning of the footward movement producing the I-wave, is plotted against the PR interval, which is taken as an index of the amount of overlapping of the auricular and ventricular ballistic complexes, in a patient with complete heart block.

auricular ejection may act in such a way as to obscure the beginning of the ventricular ejection phase. In order to check this explanation, simultaneous recordings of the ballistocardiogram and the electrocardiogram have been made on several patients having heart block. Figure 11 shows some of the complexes recorded on a patient with complete heart block. The data on the auricular and ventricular complexes are given in Table I. The auricular complex is small and appears to consist successively of a headward (h), a footward (i) and a headward (j) wave of which the average time intervals from the beginning of the P of the electrocardiogram to the peaks of these waves are, respectively, Ph = 0.10 second, Pi = 0.16 second, and Pj = 0.24 second. The purely ventricular complex appears to start directly footward from the baseline with no H-wave in evidence. For this pure ventricular pattern the time from the beginning of the QRS complex to the beginning of the footward movement which produces the I-wave is about 0.070 second, a value which is close to the accepted value for the time from the QRS to the commencement of ventricular ejection. However, this pure ventricular complex is seen only when the PR interval is sufficiently long that the auricular and ventricular complexes do not overlap. This overlap is a function of the PR interval and its effect is illustrated in Figure 12. In this figure the QH interval (H being the point where the ballistic movement first turns footward) is plotted against the PR interval. When the PR interval is long, the QH interval is about 0.070 second. However, when the PR interval lies within normal range, *i.e.*, from 0.10 to 0.20 second, the QH interval is about 0.090 second. This observation suggests that the auricular j-wave is an important factor in producing the H-wave and in delaying the footward movement of the I-wave. Similarly when the PR interval has a value less than normal the QH interval decreases again. In this case it may be that the footward movement is accentuated by the footward i-wave of the auricular complex. This view that the auricular stroke contributes markedly to the H-wave of the ballistocardiogram is supported by the type of ballistic pattern observed in auricular fibrillation. In this case, see Figure 13, the QH interval is relatively short, 0.060–0.70 second. This value would be expected if the auricular beat was ineffective in moving fluid so that the ballistic movement is almost purely ventricular in origin. As a result of these studies it is concluded that in the ballistocardiograms of normal subjects the auricular impact may act to produce the H-wave and in this action mask the onset of the I-wave.

SUMMARY

In this paper have been presented ballistocardiograph records of clinical cases and of the ejection behavior of a simple model heart. Evidence to support the origin of the K-wave is found in records of coarctation of the aorta and of reactive hyperemia. Characteristic patterns of pre- and post-operative cases of coarctation of the aorta, of constrictive pericarditis and of an iliac arteriovenous fistula are also presented here. Further are shown the form of records with extremely large and small stroke volumes as found respectively in the special conditions of aortic insufficiency and of shock.

Data have been presented from the observa-

FIG. 13. BALLISTOCARDIOGRAM ON A PATIENT WITH AURICULAR FIBRILLATION

tions made on cases in heart block. This material illustrates the contribution of the auricular ejection to the ballistocardiogram and shows that in cases with normal PR intervals the auricular beat may produce an apparent delay in the development of the I-wave, a delay attributed by some workers to faulty behavior of the ballistocardiograph.

ACKNOWLEDGMENT

Acknowledgment is made to the Departments of Medicine and Surgery of Columbia University and of Emory University with whom the collaborative work providing some of the clinical records was performed.

BIBLIOGRAPHY

1. Starr, I., Rawson, A. J., Schroeder, H. A., and Joseph, N. R., Studies on the estimation of cardiac output in man, and of abnormalities in cardiac function, from the heart's recoil and the blood's impacts; the ballistocardiogram. Am. J. Physiol., 1939, **127**, 1.
2. Hamilton, W. F., and Dow, P., Cardiac and aortic contributions to the human ballistocardiogram. Am. J. Physiol., 1941, **133**, 313.
3. Hamilton, W. F., Dow, P., and Remington, J. W., The relationship between the cardiac ejection curve and the ballistocardiographic forces. Am. J. Physiol., 1945, **144**, 557.
4. Nickerson, J. L., and Curtis, H. J., The design of the ballistocardiograph. Am. J. Physiol., 1944, **142**, 1.
5. Katz, L. N., The asynchronism of the right and left ventricular contractions and the independent variations in their duration. Am. J. Physiol., 1925, **72**, 655.
6. Hamilton, W. F., Attyah, A. M., Fowell, D. M., Remington, J. W., Wheeler, N. C., and Witham, A. C., Do the human ventricles eject simultaneously? Proc. Soc. Exper. Biol. & Med., 1947, **65**, 266.
7. Nickerson, J. L., The low frequency, critically damped ballistocardiograph. Federation Proc., 1945, **4**, 201.
8. Nickerson, J. L., Warren, J. V., and Brannon, E. S., The cardiac output in man: studies with the low frequency, critically-damped ballistocardiograph and the method of right atrial catheterization. J. Clin. Invest., 1947, **26**, 1.
9. Wiggers, C. J., Circulation in Health and Disease. Lea and Febiger, Philadelphia, 1923, Ed. 2, pp. 102, 267.