Brit. Heart J., 1967, **29**, 285.

Ballistocardiography

D. C. DEUCHAR

From Guy's Hospital, London, S.E.1

The concept of body movements occurring in relation to the heart beat is an old one, arising from clinical observations in such conditions as severe aortic incompetence and hyperthyroidism; several attempts were made in the sixty years before the last World War to detect and record such movements. The initiation of the modern study of these motions and the christening of the technique as ballistocardiography must be credited to Isaac Starr. The first report from his department in this field appeared in 1938 (Starr, Rawson, and Schroeder), and he has continued to contribute to it ever since.

Starr's original technique used a heavy, rigid platform, supported by stiff springs, upon which the subjects lay. Because of its physical properties this system became known later, when other techniques were developed, as the high-frequency system. Experimental and theoretical analysis of the mechanics of ballistocardiography, expecially in the Netherlands (Burger, Noordergraaf, and Verhagen, 1953; Burger *et al.*, 1956; Burger and Noordergraaf, 1956) and in the United States (von Wittern, 1953; Talbot and Harrison, 1955), has since established that the use of a very light, freely suspended platform yields more accurate representations of the body's movements; this is the so-called ultra-low frequency system. Physical principles dictate that recordings of the displacement of the high-frequency platform and of the acceleration of the low-frequency platform will both reflect the forces acting on the body as a result of the beating of the heart and the movement of the blood (Starr and Noordergraaf, 1962). Other techniques have been devised to obtain ballistocardiograms but most have fallen by the wayside; amongst these is the "direct-body" method introduced by Dock and Taubman (1949). This ingeniously simple device did much to popularize the office use of ballistocardiography in the U.S.A. in the early 1950's. At that time the technique was in a relatively undeveloped state and the limitations of the direct-body records were not appreciated; the ensuing disenchantment with the ballistocardiogram amongst clinicians is only now just beginning to be overcome.

The established methods of recording also have their limitations, but these are less serious and have now been well defined. Perhaps the biggest of these, which still awaits an adequate solution, is that of multidimensional recording. It is relatively easy to obtain records of movement along the head-foot axis, but difficult along other axes; fortunately the head-foot motion is clearly the most important, but the potential ancillary significance of, for example, the lateral motion, is tantalizingly uncertain. Instruments have been designed to detect these other motions but all have important technical limitations and most are suited for research purposes only, not for routine clinical use.

Now that the physicists have succeeded in analysing many of the complexities of the mechanical behaviour of the supine body resting on a platform and impelled by its internal cardiovascular system, it is possible to construct recording systems which will predictably yield technically satisfactory head-foot force records; the minuteness of the motions involved, however, still renders this a far from simple task.

Noordergraaf and his colleagues have carried the mechanical analysis further, to explore the generation of the forces concerned within the body. Their first attempt in this direction was an extraordinarily laborious, mathematical analysis of the human arterial tree which, for this purpose, was divided into 115 segments. The shifts of blood in all these segments at 20 msec. intervals were calculated, summated, and a predicted ballistocardiogram derived therefrom. The result was gratifyingly close to the observed "normal" pattern (Noodergraaf and Heynekamp, 1958; Noodergraaf, 1961). This encouraging initial result was followed by the construction of a complex analogue computer which reproduced the original mathematical model and made it possible readily to obtain predicted ballistocardiograms with a number of variations in the properties of the arterial tree and the ventricular ejection patterns applied to it (Noodergraaf, Verdouw, and Boom, 1963). The patterns, both normal and abnormal so derived, have accorded well with those

U

found in clinical studies and by physiological experiment. This analogue computer has proved a most flexible tool for analysing the behaviour of the circulation, particularly in helping to unravel the complexities of pulsatile blood flow in the arteries. In the ballistocardiographic field it has predicted clear relationships between the left ventricular ejection pattern, arterial elasticity, etc., and the amplitude and form of the record.

When Starr began his clinical studies it very quickly became clear that all young, apparently healthy, people yield head-foot force records conforming closely to a single pattern. It was to the waves of this pattern that Starr attached the arbitrary letters H,I,J,K,L,M, and N. This pattern is that of the generally accepted "normal" record. It was also soon shown that people with cardiovascular disease and many older, apparently healthy, people had records which differed, sometimes greatly, from the "normal" standard. In the case of apparently healthy people this was difficult to understand, but considerable excitement was created when Starr (1947) published an early follow-up series which suggested that an abnormal ballistocardiogram could be predictive of impending cardiac disease. It was the premature attempt to exploit this by means of the direct-body instrument that led to much disillusionment with the whole technique.

Starr's early clinical studies and theoretical analyses of the generation of the ballistocardiogram soon led him to believe that the left ventricular ejection pattern was an important factor in determining the ballistocardiogram. This hypothesis he put to the test in a remarkable series of experiments in which ballistocardiograms were recorded from fresh human cadavers in whom ventricular ejection was simulated by the use of syringes inserted into the aortic and pulmonary roots (Starr, 1958). Surprisingly large forces were required to achieve anything approaching the normal left ventricular ejection, but when this was done ballistocardiograms approximating to the normal in pattern and amplitude were obtained. When the left ventricular ejection was more sluggish the records more closely resembled those Starr found in some of his older subjects and in those with heart disease.

Many groups have worked with experimental animals, expecially dogs, to study the relation of the circulatory events to the ballistocardiograms. There are many difficulties in the design and performance of such experiments. Generally speaking the smaller the animal the more difficult it is to construct a ballistocardiograph capable of yielding a satisfactory record; animal experiments nearly always necessitate anæsthesia, and this itself may affect the circulation and grossly alter the ballistocardiogram (Scarborough, 1957); the circulation is such a closely integrated system that most manœuvres designed to alter it in any way are followed by a number of secondary adjustments which may well obscure the response of the ballistocardiogram to the initial interference. Much of the work in this field has therefore been disappointingly inconclusive though repeated observations have been made, which are consistent with the view that it is movement of the blood in the systemic arterial system that produces most of the ballistocardiographic signal and that stroke volume, peripheral resistance and, above all, peak accelerations of blood in the aorta are the important factors determining the amplitude and pattern of the record. Very recently some intricate studies in conscious dogs have established, fairly conclusively, direct relationships between myocardial contractility, the peak acceleration of blood from the left ventricle, and the amplitude of the early systolic waves of the ballistocardiogram (Noble, Trenchard, and Guz, 1966; Winter *et al.*, 1967).

Several clinical studies have shown the poor early systolic deflections of the records from patients with severe aortic stenosis, in whom slowing of the early systolic ejection of blood is well known (Deuchar, 1962; Elsbach, 1956; Moss and Gottori, 1966). Large deflections have been noted in patients with aortic valve regurgitation and with hypertrophic cardiomyopathy, in whom there is an increase in the vigour of early systolic ejection (Deuchar, 1962; Moss and Gottori, 1966).

Computer analysis, human cadaver experiments, animal experiments, and clinical studies all indicate that the early systolic, head-foot, force ballistocardiogram provides an index of the peak aortic acceleration of blood from the left ventricle, and hence of myocardial contractility.

The pieces of information gained by research into ballistocardiography, studies of ventricular muscle dynamics, left ventricular function, and instantaneous aortic blood flow now begin to fit together like a jigsaw puzzle (Starr, 1965). The picture that is developing is that of a very rapid and powerful shortening of the active contractile elements of the myocardium, at the onset of ventricular systole, which pulls and stretches elastic structures in series. The later, slower shortening of the whole myocardial fibres is due to these passive elastic elements. The active shortening provides the force for the very rapid attainment of a high peak acceleration of blood from the ventricle. The peak is sharp and acceleration dies away quite quickly so that the peak flow of blood is also reached early in systole. When acceleration out of the ventricle is replaced toward mid-systole by acceleration towards the ventricle, i.e. a slowing of the flow from the heart, the ventricle is no longer pumping but blood is now moving out by its own inertia. The whole of the force of the contractile element of the myocardium, i.e. the "myocardial contractility", is developed and expressed in the initial, very early acceleration of blood into the aorta. This acceleration, which produces the initial upstroke of the normal aortic pressure pulse, leads to a rapidly changing distribution of the mass of blood around the aortic arch. This, in turn, shifts the centre of gravity in the body and produces the ballistocardiographic motion.

The major problem of applying this knowledge of the genesis of the ballistocardiogram in a direct quantitative fashion to any particular patient is the considerable influence of other uncontrollable factors; amongst these, the subject's size and build, the stroke volume, the state of the arterial tree, and the effect of respiration, are all well known. The contribution of these factors is always difficult and often impossible to determine in any individual case.

The rational basis for the ballistocardiogram, which is now emerging, does, however, offer an explanation of the abnormal records found in some apparently healthy older subjects and of Starr's early observations about the prognostic significance of these. It will obviously be the contractile elements of the myocardium which will be affected by biochemical disturbances induced by such factors as anoxia and electrolyte imbalance (Talbot, Harrison, and Ginn, 1966). If it is the activity of these elements which largely determines the early systolic pattern of the ballistocardiogram, it is not surprising that the records reflect disturbances of this sort before other, cruder methods of examining the heart can detect any abnormality. It could reasonably be expected to show abnormalities in many patients with ischæmic heart disease or other less well-defined senile myocardial disorders; it could not, however, be expected to predict sudden infarction resulting from a fresh coronary arterial occlusion in a vessel sufficiently diseased for this to happen but not previously so much narrowed as to have produced significant myocardial ischæmia.

The long-term studies of Starr and of the unit at the Johns Hopkins Hospital, under the direction of Benjamin Baker, have fulfilled these expectations. Thus, in the first Philadelphia study (Starr and Wood, 1961) a group of apparently healthy persons were examined and then followed for 20 years; to begin with the form of the head-foot force ballistocardiogram was normal in almost everyone, but some had lower amplitudes. With advancing age the amplitudes of the early systolic complexes declined in all subjects. Of those who had small records initially more developed heart disease than did those with the larger records and their mortality was greater even when the data were adjusted for age differences. Another Philadelphia study (Starr, 1964) of patients with heart disease followed for 5 years or more showed a strong correlation between the abnormality of the form of the ballistocardiogram and subsequent mortality.

Early reports from the Johns Hopkins team (Scarborough *et al.*, 1952) showed a much greater incidence of ballistocardiographic abnormality in a large group of patients with known coronary artery disease than in a similar group of apparently healthy people. This difference was particularly obvious below the age of 50 years. The findings in a long follow-up study of the apparently healthy series are now being analysed; the preliminary results suggest that the ballistocardiogram is a better predictive test of later cardiovascular disease than any of the other tests applied (B. M. Baker, 1966, personal communication). The implication is that many of the older subjects judged to be healthy by clinical, radiological, and electrocardiographic criteria already had some abnormality of cardiovascular function detectable at that time by the ballistocardiograph only.

Apart from these main approaches to the assessment of the significance of the ballistocardiogram, there have been many other studies which have produced interesting results. The effect of cigarette smoking is one of these. The Johns Hopkins group have undertaken one of the largest studies of this (Davis *et al.*, 1956); they showed that cigarette smoking produces deterioration in form or amplitude of the head-foot force record in many subjects. This was much commoner in patients with known coronary artery disease than in apparently healthy subjects. Their investigation of the mechanism of this effect fits in well with Oram's study of tobacco angina (Oram and Sowton, 1963). Buchanan (1966) has recently reported a well-controlled study of the effect of smoking in hyperthyroid patients, and has shown that they too, like patients with coronary artery disease, frequently show deterioration of the ballistocardiogram; this effect disappears when they are treated and made euthyroid.

In the above, consideration has been virtually confined to the early systolic (HIJ) deflections of the ballistocardiogram. There are deflections which occur earlier in each cycle (FGH) which appear to be produced by atrial systole; beyond establishing this much, little has been done to investigate their significance either physiologically or clinically. There are also deflections (LMN) in diastole which are probably produced by the movement of blood in the arterial system occurring at the time of the cessation of foward flow in the aortic root and the retrograde movement which occurs in some of the larger arteries. Again the significance of these deflections has been very little studied; they could be of interest in relation particularly to the state of the arterial walls and the pattern of systemic arteriolar constriction.

In summary it seems fair to suggest that while there is much that remains to be unravelled about ballistocardiography, a great deal is now known about its physical and physiological basis. The relative simplicity, safety, and painlessness of the technique taken in relation to the information it may be able to give about a patient's left ventricular ejection pattern and myocardial contractility should perhaps now commend it to clinical cardiologists for further study.

References

Buchanan, J. (1966). Ballistocardiographic smoking tests in thyrotoxicosis. In *Proc. 1st World Congr. Ballistocard. cardiovasc. Dynamics, Amsterdam.* Karger, Basel.

Burger, H. C., and Noordergraaf, A. (1956). Physical basis of ballistocardiography. *Amer. Heart J.*, **51**, 127 and 179.

——, ——, Korsten, J. J. M., and Ullersma, P. (1956). Physical basis of ballistocardiography—IV. *Amer. Heart* J., **52**, 653.

——, ——, and Verhagen, A. M. W. (1953). Physical basis of the low-frequency ballistocardiograph. *Amer. Heart J.*, **46**, 71.

Davis, F. W. Scarborough, W. R., Mason, R. E., Singewald, M. L., and Baker, B. M. (1956). The ballistocardiographic cigarette test: further observations. *Amer. Heart J.*, **51**, 165.

Deuchar, D. C. (1962). Some further observations on the ballistocardiogram in aortic valve disease. In *Proc. 3rd Europ. Symp. Ballistocardiography.* Rochet Brussels.

Dock, W., and Taubman, F. (1949). Some technics for recording the ballistocardiogram directly from the body. *Amer. J. Med.*, **7**, 751.

Elsbach, H. (1956). Clinical investigations with the low frequency ballistocardiograph according to the method of Burger. English translation by R. D. Freeman (re-edited by W. R. Scarborough). Johns Hopkins University, Duplication Department, Baltimore.

Moss, A. J., and Gottori, D. (1966). Correlation of the acceleration ballistocardiogram with cardiovascular dynamics in aortic outflow disease. In *Proc. 1st World Congr. Ballistocard. cardiovasc. Dynamics, Amsterdam.* Karger, Basel.

Noble, M. I. M., Trenchard, D., and Guz, A. (1966). Left ventricular ejection in conscious dogs. *Circulat. Res.*, **19**, 139.

Noordergraaf, A. (1961). Further studies on a theory of the ballistocardiogram. *Circulation*, **23**, 413.

——, and Heynekamp, C. E. (1958). Genesis of displacement of the human longitudinal ballistocardiogram from the changing blood distribution. *Amer. J. Cardiol.*, **2**, 748.

——, Verdouw, P. D., and Boom, H. B. K. (1963). The use of an analog computer in a circulation model. *Progr. Cardiovasc. Dis.*, **5**, 419.

Oram, S., and Sowton, E. (1963). Tobacco angina. *Quart. J. Med.*, **32**, 115.

Scarborough, W. R. (1957). Some circulatory effects of morphine—barbiturate anesthesia, artificial respiration, and abdominal compression based on ballistocardiographic observations on dogs. *Amer. Heart. J.*, **54**, 651.

——, Mason, R. E., Davis, F. W., Singewald, M. L., Baker, B. M., and Lore, S. A. (1952). A ballistocardiographic and electrocardiographic study of 328 patients with coronary artery disease. *Amer. Heart J.*, **44**, 645.

Starr, I. (1947). On the later development of heart disease in apparently healthy persons with abnormal ballistocardiograms. Eight-to ten-year after-histories of 90 persons over 40 years of age. *Amer. J. med. Sci.*, **214**, 233.

—— (1958). The relation of the ballistocardiogram to cardiac function. *Amer. J. Cardiol.*, **2**, 737.

—— (1964). Prognostic value of ballistocardiograms. *J. Amer. med. Ass.*, **187**, 511.

—— (1965). Progress towards a physiological cardiology. A second essay on the ballistocardiogram. *Ann. intern. Med.*, **63**, 1079.

——, and Noordergraaf, A. (1962). A comparison between ultralow-frequency ballistocardiograms and those secured by an improved high-frequency technique, with studies to explain remaining differences. *Amer. Heart J.*, **64**, 79.

——, Rawson, A. J., and Schroeder, H. A. (1938). Apparatus for recording the heart's recoil and the blood's impacts in man, (ballistocardiograph). *Amer. J. Physiol.*, **123**, 195.

——, and Wood, F. C. (1961). Twenty-year studies with the ballistocardiogram. *Circulation*, **23**, 714.

Talbot, S. A., and Harrison, W. K. (1955). Dynamic comparison of current ballistocardiographic methods. *Circulation*, **12**, 577, 845, and 1022.

——, ——, and Ginn, W. M. (1966). Features of ULF-BCG pertinent to coronary heart disease. In *Proc. 1st World Congr. Ballistocard. cardiovasc. Dynamics, Amsterdam.* Karger, Basel.

von Wittern, W. W. (1953). Ballistocardiography with elimination of the influence of the vibration properties of the body. *Amer. Heart J.*, **46**, 705.

Winter, P. J., Deuchar, D. C., Noble, M. I. M., Trenchard, D., and Guz, A. (1967). The relationship between the ballistocardiogram and the movement of blood from the left ventricle in the dog. *Cardiovasc. Res.* In the press.