Suwa, K., and H. H. Bendixen. 1972. Pulmonary gas exchange in a tidally ventilated single alveolus model. J. Appl. Physiol. 32:834-841.

Tenney, S. M., and J. E. Remmers. 1963. Comparative quantitative morphology of the mammalian lung: diffusion area. Nature 197:54-56.

Watson, E. H., and G. H. Lowrey. 1962. Growth and development of children. 4th ed., Year Book Medical Publishers, Inc., Chicago, 384 p.

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MFR PAPER 1046

Ballistocardiography as a Technique for Comparative Physiology

N. TY SMITH and ERIC A. WAHRENBROCK

ABSTRACT

The ultra low-frequency ballistocardiogram was recorded on a young California gray whale. The tracing is remarkably similar to those obtained from man and mouse, both in amplitude and in form. The IJ amplitudes for mouse, man, and whale were 2.6, 4.3, and 4.6 cm/sec². We conclude that greater differences are caused by poor recording technique or by disease than by species differences. The major interspecies differences were seen in the timing of cardiac events, such as preejection or ejection time. These differences could be caused by differences in heart size.

The ballistocardiograph (Bcg) is a device for evaluating the mechanical function of the heart. It has been recorded in an incredible array of animals, ranging from egg embryos to cattle. One of the more interesting facts to arise from these recordings is that the tracings are remarkably similar among species, particularly mammals. This similarity holds both in form and in amplitude. It was therefore an excellent opportunity to extend these observations to Gigi, an animal with an entirely different mass and configuration from other mammals previously used.

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The Bcg records the movements of the body caused by movements of blood in the body. First recorded in 1887, the Bcg has undergone a series of ups and downs in its attempts to become a useful tool for measuring cardiovascular function noninvasively. Not until the 1950's when physicists and engineers entered the field, did the Bcg finally re-emerge as an accurate, relatively simple technique.

Essentially, the Bcg works on the principle that an attempted shift in the center of mass of a floating body is compensated for by a movement of the body in the opposite direction, so that the center of mass remains constant in relation to a fixed point. Thus, if blood moves in one direction after ejection by the left ventricle, the body will move in the opposite direction. These movements are quite small, but the reader has certainly noticed a slight bodily movement as he lies quietly on a bed or a slight movement of the pointer on a weighing scale, each movement synchronous with the heart beat. This minute body movement can be recorded as displacement, velocity, or acceleration. Figure 1 shows examples of normal tracings in man. The important fact to note is that the major components of the Bcg occur during ejection of blood, particularly during the early portion.

METHODS

When the physical scientists entered the field, they laid down certain standards for recording the Bcg, standards which were to convert ballistocardiography from a haphazard technique to a precise one. The first requirement is that a very light bed is necessary, in contrast to the heavy ones formerly used. A ratio of 10:1 for subject:bed is minimal. Second, coupling, or binding, of subject to bed must be as tight as possible. Third, coupling to ground must be minimal, so that ambient vibrations can be attenuated. The Bcg is an extremely sensitive instrument. Peak displacement is about 100μ, peak acceleration, a few millig's, g being the acceleration of gravity. With older instruments, vibrations from a truck outside the building were able to destroy a bal-

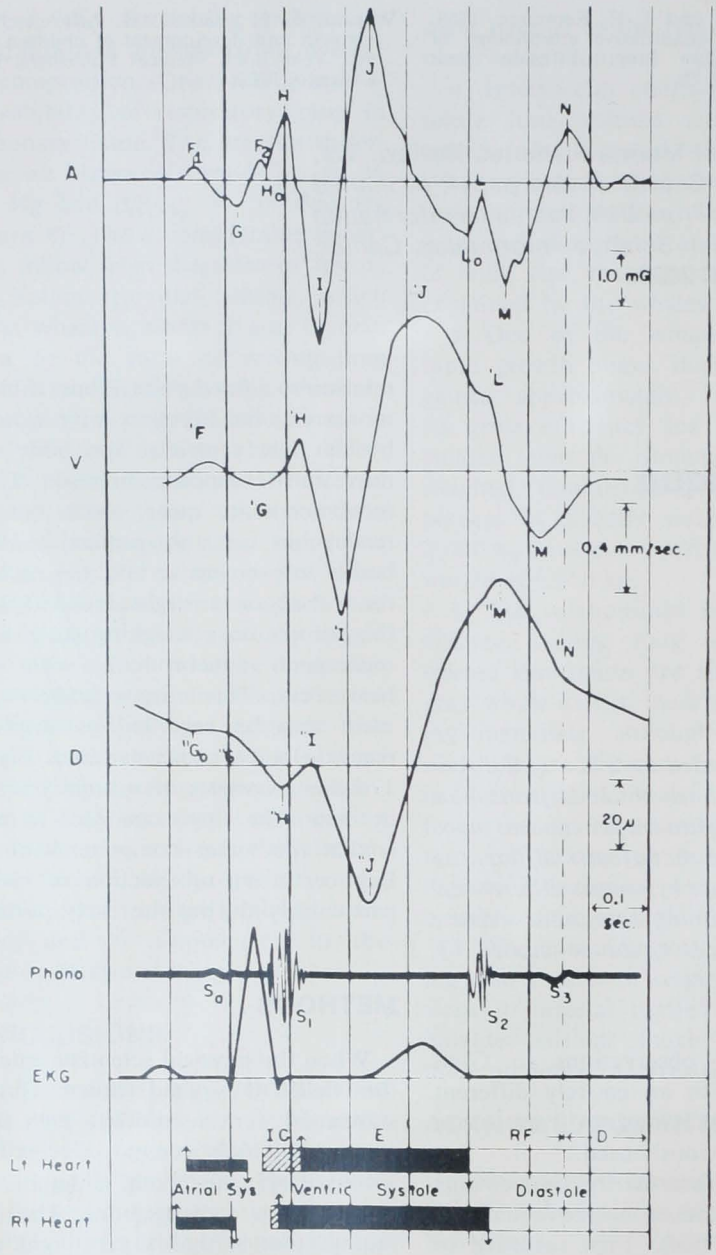

Figure 1. — Examples of normal ballistocardiographic tracings in man. From top to bottom are recorded acceleration (A), velocity (V), and displacement (D). In addition, the EKG and the major events of the cardiac cycle are given as reference points. (From Scarborough et al., Am. J. Cardiol. 2:613-641, 1958.)

listocardiographic recording. Finally, the natural frequency of the entire system should be as low as possible—0.3 Hz or less is mandatory. These four requirements imply that the ideal Bcg system is one in which subject and bed float as a unit in space.

Several ingenious systems, some simple, some complex, have been assembled to accomplish the above requirements. Beds have been constructed from aluminum and canvas, styrofoam, balsa, or aluminum honeycomb, and suspended by wires or floated on mercury or air. The simplest and original bed is based on the pendulum, and was the type used in this study. The Bcg bed was the same stretcher used to weigh Gigi (Figure 2). The stretcher was constructed from canvas and two 20-foot heavy wall, galvanized steel pipes 3 inches in diameter. The total weight of 227 kg may seem large to most ballistocardiographers, but Gigi's weight at the time was 4,500 kg, and the whale: bed ratio of 20:1 was more than adequate. Six ropes supported the poles, four at the ends, each 13 feet in length, and two in the middle. A board inserted between the two middle ropes prevented injury to the animal. The six ropes were suspended by a single cable from a crane. During the recording the cable was 7½ meters from pulley to hook, giving a natural frequency of about 0.18 Hz. The crane was part of a truck hoist, which was ideal for isolation from ground because of the pneumatic lift and the rubber tires.

Most of the water was drained from Gigi's tank to reduce her mobility and to enhance our own. She was reluctant to lie on the bed, and had to be coaxed. The coaxing process took 45 minutes. Once on the bed, she became surprisingly quiet, which was fortunate, since she could easily have demolished our fragile accelerometer. One readjustment of the relative position of whale and bed was required to level the bed.

Acceleration was transduced in the head-foot direction with an Endevco[1] piezo-resistive accelerometer clamped to one of the steel poles with a large C clamp. The accelerometer was calibrated with a pendulum, according to the method of Moss (1961). Lead two of the ECG was recorded using 4 inch 18 g spinal needles. All electrical cables were supported by a rope stretched across the tank. A 60 Hz passive notch filter and a 50 Hz low pass Butterworth filter were used on both the ECG and Bcg to eliminate unwanted noise and at the same time preserve timing relations. Data were recorded on a Hewlett-Packard oscilloscope and an Ampex FM tape recorder.

[1]Use of trade names in this publication does not imply endorsement of commercial products by the National Marine Fisheries Service.

RESULTS

Figure 3 shows the Bcg recorded from Gigi. In amplitude and form, it is similar to that seen in man. Figure 4 demonstrates that the influence of ventilation on the tracing is profound. In fact, during expiration and inspiration reading the Bcg is impossible.

Figure 5 displays the Bcg's of three animals—a mouse, a man, and a whale. Their similarities are more striking than their differences. This similarity holds in spite of differences in body mass and form, amount and distribution of fat, and natural environment.

Table 1 lists some measurements derived from the Bcg's of the mouse, man, and a whale. It also gives some fundamental values which are helpful in comparing the species.

The Bcg has been used to estimate cardiac output and stroke volume in several species. By using the Starr formula (Starr and Noordergraaf, 1967, p.177-180) we estimated Gigi's stroke volume to be 7.2 l, and the cardiac output as 308 l/min (Table 1).

DISCUSSION

One of the major postulated objections to the Bcg is that the amount and distribution of body fat can considerably alter the recording. This did not seem to be the case in Gigi, in spite of a 3½ inch layer of blubber. It is true that the old direct-body Bcg used in the 1950's was subject to influence by body fat. However, the ultra low-frequency bed, by virtue of its light weight and strong coupling between subject and bed, has eliminated most of this inaccuracy. The fundamental natural frequency of the body ("bowl of jelly" phenomenon alluded to by some in reference to the Bcg) does not depend on body mass, amount of fat, or age (Burger, Noordergraaf, and Verhagen, 1953; Burger and Noordergraaf, 1956; Talbot and Harrison, 1955; Tannenbaum, Vessell, and Schack, 1956; Weissback, 1960a, 1960b; Tischenko, 1963). Some of the higher mode frequencies may depend on the amount and distribution of body fat.

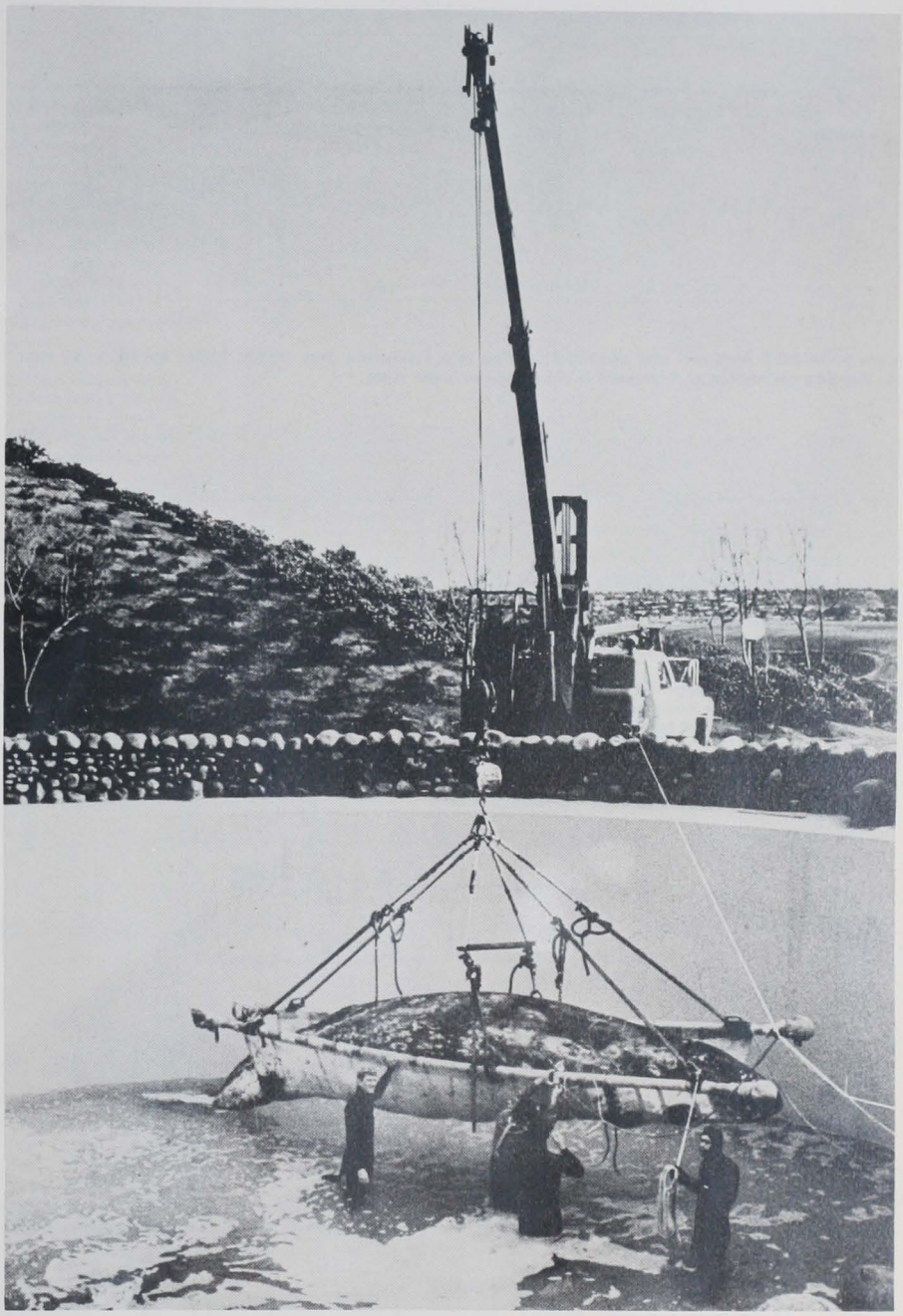

Figure 2. — Gigi, Bcg bed, man, and hoist. The accelerometer is being attached to the right side of the proximal pole. The truck was jammed against the retaining wall of the tank. A white rope strung across the tank supports the cables.

A crucial factor in ballistocardiography is the orientation of the aorta in relation to the body. This is so because usually complexities have forced ballistocardiographers to record the Bcg in one dimension, the head-foot direction, instead of the possible three dimensions and six degrees of freedom. Thus if the direction of ejection and runoff is different in different species, the comparison would be difficult. The orientation of the aorta seems to be no

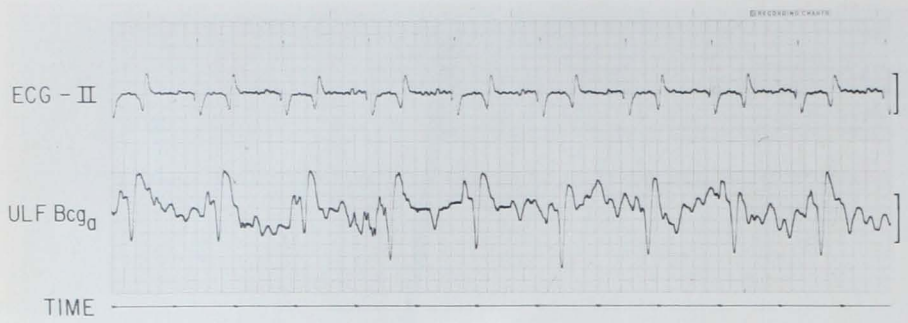

Figure 3. — ECG lead two and acceleration Bcg in a California gray whale. Paper speed = 50 mm/sec. The Bcg calibration of 3 cm/sec^2 is shown in the lower right.

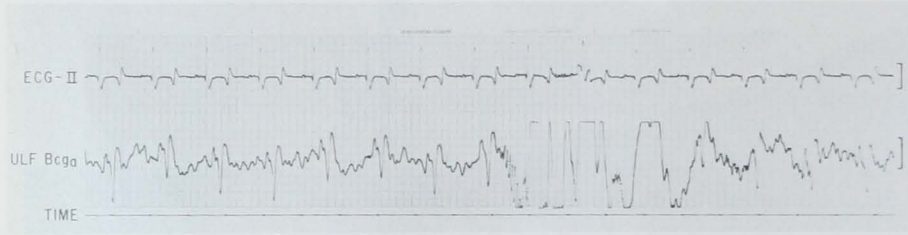

Figure 4. — The Bcg with Gigi during one breath. Paper speed = 25 mm/sec. The respiratory influence on the Bcg is considerably greater in the whale than other species. This is probably due to the necessarily rapid and large tidal exchange.

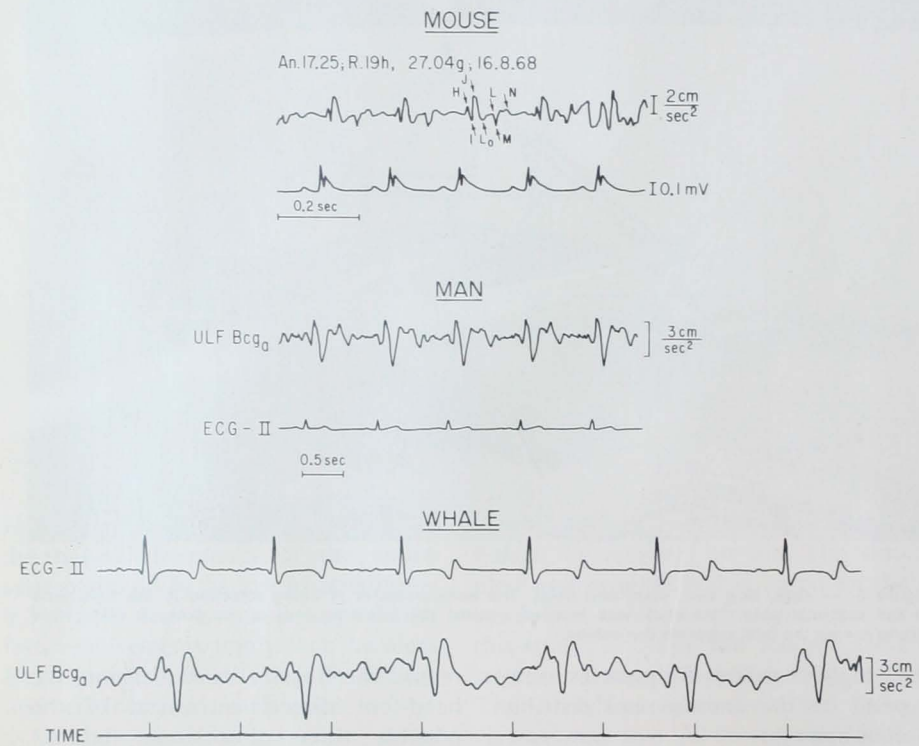

Figure 5. — The ultra low-frequency acceleration Bcg's in a 27-gm mouse (top record), a 73,000-gm man (middle record), and a 4,500,000-gm whale (lower record). The ECG's are also shown. Note the more rapid paper speed in the mouse Bcg. Considering the 167,000-fold difference in body mass, as well as the differences in body shape, amount and distribution of fat, and instrumentation, the records are remarkably similar. The mouse Bcg is from Južnič, G., Bibl. Cardiol. 26:281-291, 1970. The human Bcg is courtesy of Dr. Aaron G. Dinaburg.

different in the whale from other mammals. Green (1971) describes the course and relations thus: "Leaving the left ventricle, the aorta makes the characteristic left arch before passing superficially and caudally to lie just under the center of the thoracic cavity to pass through the diaphragm."

Body acceleration, which is closely related to blood acceleration, is a constant factor among various mammalian species. A peak-to-peak body acceleration of 2.5-5 cm/sec^2 (about 2.5-5 millig) seems to be optimum. If the acceleration is greater, as with severe aortic insufficiency, the slight motion now becomes quite noticeable. If the whale's body acceleration were proportionately large in relation to its mass, the motion could become uncomfortable. Why a smaller normal acceleration would not be feasible, or indeed why an initial ventricular impulse is necessary at all, is difficult to guess.

Other constants occur among mammals. For example, with rare exceptions such as the giraffe, arterial blood pressure is very similar in different species (Altman and Dittmer, 1971, p. 405-408). One could speculate why these values are so appropriate. If normal arterial pressure were higher, either the vessel walls would have to be of considerably stiffer material, or they would have to be so thick that the ratio of wall thickness to lumen would be impractical. If normal pressure were lower, perfusion through the necessarily small capillary vessels would be difficult. Perhaps even more pertinent a constant involves the relative masses of the heart and body in different mammals (Table 1). Apparently there is more variation within species than among species.

The general form of Gigi's Bcg is very similar to that given for normal man by Scarborough et al. (1958). One can certainly recognize an HIJ complex and an LMN complex. It seems that greater differences in amplitude and form are caused by faulty technique, such as a heavy bed and poor

coupling, or by disease states, than by differences in species. Figure 6 gives an example of this. It compares a virtually normal Bcg in a dog with the Bcg in a dog at the terminal stages of rejection. The latter tracing is obviously grossly abnormal and demonstrates the extreme in Bcg abnormality. Other conditions which can cause a greater ballistocardiographic variation within than among species include anginal attacks, severe coronary artery disease, hyperthyroidism, aortic valvular insufficiency, and congestive heart failure (Starr and Noordergraaf, 1967). Even a program of physical conditioning over several months can alter an individual's Bcg to as great an extent as the differences seen among species (Elsbach et al., 1970, Holloszy et al., 1964).

The major difference among the Bcg's of various mammals seems to be one of timing of the systolic wave forms. As body size increases, the onset of the systolic complex is delayed (QH interval) and the complex spreads out (HJ and HL intervals, Table 1). If we consider the tip of the H wave as the onset of ejection, we shall at worst slightly underestimate the cardiac pre-ejection period. Certainly the relative values among species can be estimated by the QH interval. Similarly, ejection time can be estimated by the HL interval. This interval did not seem to be so relatively prolonged in Gigi as the QH. The contribution of prolonged conduction time in hearts of different sizes to the interspecies differences in systolic time intervals is probably considerable, as is shown by the PR and QRS intervals in Table 1.

In general, heart rate and ejection time are inversely related. Thus part of the differences in systolic time intervals is due to heart rate differences. But heart rate cannot explain all of the differences. Gigi's heart rate of 43 beats/min was not as slow as expected and occurred presumably because she was excited. An athlete with a heart rate of 40-45 beats/min does not show the prolonged pre-

Table 1.—Some comparative values among mouse, man, and whale.

	Mouse	Man	Whale	Ratio Whale/Mouse
Weight (gm)	27	73,000	4,500,000	167,000
Length (cm)	6.5-9.5 (12.5-20) + [1]	180	760	38-117
Heart/body mass (gm/100 gm)	0.41-0.51 [2]	0.44-0.57 [3]	0.32-0.50 [4]	0.78-0.98
Heart rate (beats/min)	300-700 [5]	60-80	43	0.13
Bcg IJ amplitude (cm/sec²)	2.6 [6]	4.3 [6]	4.8	1.8
Bcg IJ amplitude (corrected, cm/sec²)	3.4*	4.7*	5.0*	1.5
Bcg IJ amplitude (dynes)	73.0	250 × 10³ [7,8]	2.27 × 10⁷	311,000
Cardiac output (l/min)	—	5.0-8.0	308	—
Cardiac index (Ml/min/kg)	—	70-90 [9,10]	68.4	—
Stroke volume (ml)	—	70-90 [9,10]	7150	—
Stroke index (ml/kg)	—	0.9-1.2 [9,10]	1.6	—
PR interval (msec)	42 [11]	180-200	294# (320) [11]	7.0
QRS interval (msec)	22 [11]	80-100	103# (90-120) [11]	12.9
QH interval (msec) "Pre-ejection period"	27	90-110 [7,8]	320	11.9
HJ interval (msec)	43	140 [7,8]	205	4.8
HL interval (msec) "Ejection time"	64	320 [7,8]	490	7.7

\+ With tail
* Corrected for mass of bed: $IJ\left(\frac{\text{Total Mass}}{\text{Body Mass}}\right)$
\# Measured in Gigi
1 Walker, et al., 1968.
2 Altman and Dittmer, 1971, p. 240.
3 Altman and Dittmer, 1971, p. 236-7.
4 Altman and Dittmer, 1971, p. 239.
5 Altman and Dittmer, 1971, p. 340.
6 Južnič, 1970.
7 Starr and Noordergraaf, 1967.
8 Moss, 1961.
9 Cullen, et al., 1970.
10 Altman and Dittmer, 1971, p. 323-4.
11 Altman and Dittmer, 1971, p. 278.

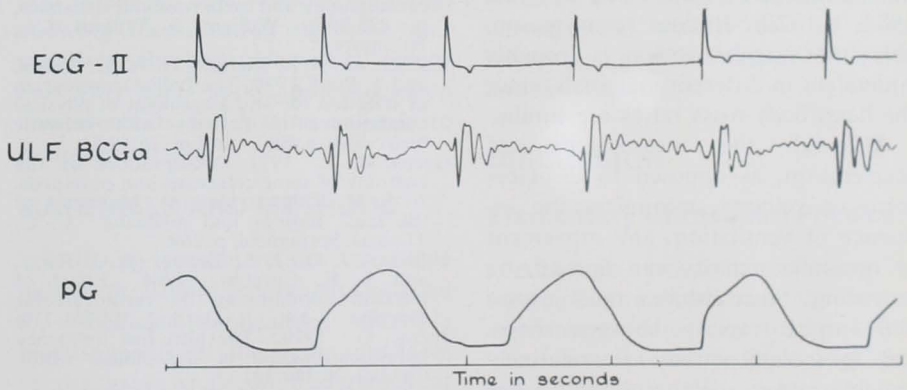

Figure 6a. — These two tracings are from a conscious dog after cardiac autotransplantation. The Bcg is essentially normal. PG = Pneumogram (Whitney gauge).

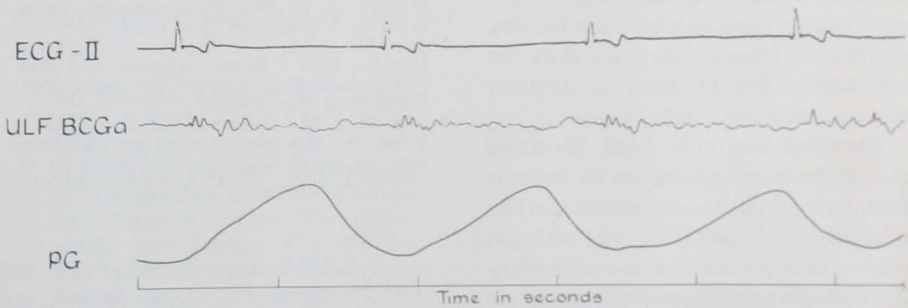

Figure 6b. — These tracings are from a dog in the terminal stages of rejection after cardiac allotransplantation. The difference between the ballistocardiographic records from the two dogs is obviously greater than that between the tracings from a whale and mouse (Figure 5).

ejection period and ejection time that Gigi does (Weissler et al., 1960; Leighton et al., 1971).

We said that the Bcg is used to estimate cardiac function. This is possible because of the close relationship between the acceleration Bcg and the acceleration of blood out of the left ventricle into the aorta (Winter et al., 1966, 1967; Smith, Van Citters, and Verdouw, 1970; Deuchar, 1966). The latter is a proven sensitive indicator of cardiac function (Noble, Trenchard, and Guz, 1966; Noble, Gabe, and Trenchard, 1967; Rushmer, 1964, 1970).

Gigi's stroke index of 1.6 ml/kg is somewhat greater than that of man, about 1 ml/kg. However, since the heart rate was slower in Gigi, the cardiac index was closer to that of man (Table 1). Again, in comparing several species, we note that when cardiac output is plotted against body weight on a log-log scale, a straight line is obtained (Altman and Dittmer, 1971, p. 320). It does seem reasonable that stroke index is roughly equivalent in different mammals, since the heart/body mass ratios are similar.

Although the measurement of acceleration, as opposed to displacement or velocity, minimizes the influence of ventilation, any movement or muscular activity can disturb the recording. Since whales must expire and inspire rapidly between dives, the muscular activity is relatively violent. As Wahrenbrock has measured, Gigi's peak instantaneous flow rate was 285 l/sec. Thus ventilation demolished Gigi's Bcg recording. Fortunately, ventilatory rate was extremely slow so that the Bcg had sufficient time to recover between breaths.

The Bcg has now been recorded in a wider range of masses in animals than any other physiologic test. The mass ratio is 1:6,000,000, egg embryo: whale. This points out the versatility of the Bcg and suggests its importance as a technique for comparative physiological and pharmacological studies.

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LITERATURE CITED

Altman, P. L., and D. S. Dittmer (editors). 1971. Respiration and circulation. Fed. Am. Soc. Exp. Biol., Betheseda, 930 p.

Burger, H. C., and A. Noordergraaf. 1956. Physical basis of ballistocardiography. II. The quanties that can be measured with different types of ballistocardiographs and their mutual relations. Am. Heart J. 51:127-139.

Burger, H. C., A. Noordergraaf, and A. M. W. Verhagen. 1953. Physical basis of the low-frequency ballistocardiograph. Am. Heart J. 46:71-83.

Cullen, B. F., E. I. Eger, II, N. T. Smith, D. C. Sawyer, G. A. Gregory, and T. A. Joas. 1970. Cardiovascular effects of fluroxene in man. Anesthesiology 32:218-230.

Deuchar, D. C. 1966. The relations of ballistocardiography to other methods of studying the cardiovascular system in man. *In* A. A. Knoop (editor), Ballistocardiography and cardiovascular dynamics, p. 225-236. William & Wilkins Co., Baltimore.

Elsbach, H., F. A. Rodrigo, H. W. H. Weeda, and J. Pool. 1970. The ballistocardiogram in selection for and assessment of physical conditioning in patients with ischemic heart disease. Bibl. Cardiol. 26:49-51.

Green, R. F. 1971. Observations on the anatomy of some cetaceans and pinnipeds. *In* S. H. Ridgway (editor), Mammals of the sea. Biology and medicine. C. C. Thomas, Springfield, p. 269.

Holloszy, J. O., J. S. Skinner, A. J. Barry, and T. K. Cureton. 1964. Effect of physical conditioning on cardiovascular function. Am. J. Cardiol. 14:761-770.

Južnič, G. 1970. The ultra-low frequency ballistocardiogram of the mouse. Bibl. Cardiol. 26:280-291.

Leighton, R. F., A. M. Weissler, P. B. Weinstein, and C. F. Wooley. 1971. Right and left ventricular systolic time intervals. Am. J. Cardiol. 27:66-72.

Moss, A. J. 1961. Ballistocardiographic evaluation of the cardiovascular aging process. Circulation 23:434-451.

Noble, M. I. M., I. T. Gabe, and D. Trenchard. 1967. Blood pressure and flow in the ascending aorta of conscious dogs. Cardiovasc. Res. 1:9-20.

Noble, M. I. M., D. Trenchard, and A. Guz. 1966. Studies of the maximum acceleration of blood in the ascending aorta of conscious dogs. *In* A. A. Knoop (editor), Ballistocardiography and cardiovascular dynamics, p. 243-247. William & Wilkins Co., Baltimore.

Rushmer, R. F. 1964. Initial ventricular impulse. A potential key to cardiac evaluation. Circulation 29:268-283.

_____. 1970. Cardiovascular dynamics. 3rd ed. W. B. Saunders Co., Philadelphia, p. 110.

Scarborough, W. R., E. F. Folk, III, P. M. Smith, and J. H. Condon. 1958. The nature of records from ultra-low frequency ballistocardiographic systems and their relation to circulatory events. Am. J. Cardiol. 2:613-641.

Smith, N. T. In press. Ballistocardiography. *In* A. M. Weissler (editor), Noninvasive methods in cardiac evaluation. Grune and Stratton, New York.

Smith, N. T., R. L. Van Citters, and P. D. Verdouw. 1970. The relation between the ultra-low frequency ballistocardiogram, the acceleration pneumocardiogram, and ascending aortic flow acceleration in the baboon. Bibl. Cardiol. 26:198-205.

Starr, I., and A. Noordergraaf. 1967. Ballistocardiography in cardiovascular research. J. B. Lippincott Co., Phila., 438 p.

Talbot, S. A., and W. K. Harrison, Jr. 1955. Dynamic comparison of current ballistocardiographic methods. Part I: Artefacts in the dynamically simple ballistocardiographic methods. Circulation 12:577-587.

Tannenbaum, O., H. Vessell, and J. A. Schack. 1956. Relationship of the natural body damping and body frequency to the ballistocardiogram. Circulation 13:404-409.

Tischenko, M. I. 1963. The significance of natural vibrations of the human body in shaping the ballistocardiogram. Biophysics 8:311-319.

Walker, E. P. 1968. Mammals of the world. Vol. II. Johns Hopkins Press, Baltimore, p. 921.

Weissbach, G. H.-J. 1960a. Die Rolle der Tischmasse und der Wert einer zusätzlichen Dämpfung beim Elongations-ballistokardiographen. [In Ger.] Pfluegers Arch. ges. Physiol. 270:529-535.

_____. 1960b. Die registriertechnischen Eigenschaften des direkten ballistokardiographen. Z. Kreislaufforsch. 49:626-630.

Weissler, A. M., R. G. Peeler, W. H. Roehll, Jr., and N. C. Durham. 1960. Relationships between left ventricular ejection time, stroke volume, and heart rate in normal individuals and patients with cardiovascular disease. Am. Heart J. 62:367-378.

Winter, P. J., D. C. Deuchar, M. N. Noble, and A. Guz. 1966. The ballistocardiogram and left ventricular ejection in the dog. *In* A. A. Knoop (editor), Ballistocardiography and cardiovascular dynamics, p. 248-254. Williams & Wilkins Co., Baltimore.

Winter, P. J., D. C. Deuchar, N. I. M. Noble, et al. 1967. Relationship between the ballistocardiogram and the movement of blood from the left ventricle in the dog. Cardiovasc. Res. 1:194-200.

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