The Journal of Clinical Investigation

THE CARDIAC OUTPUT IN MAN: STUDIES WITH THE LOW FREQUENCY, CRITICALLY-DAMPED BALLISTOCARDIOGRAPH, AND THE METHOD OF RIGHT ATRIAL CATHETERIZATION

J. L. Nickerson, … , J. V. Warren, E. S. Brannon

J Clin Invest. 1947;26(1):1-10. https://doi.org/10.1172/JCI101780.

Research Article

THE CARDIAC OUTPUT IN MAN: STUDIES WITH THE LOW FREQUENCY, CRITICALLY-DAMPED BALLISTOCARDIOGRAPH, AND THE METHOD OF RIGHT ATRIAL CATHETERIZATION [1]

By J. L. NICKERSON, J. V. WARREN, and E. S. BRANNON

(From the Department of Physiology, College of Physicians and Surgeons, Columbia University, New York, and the Medical Service of the Grady Hospital and the Department of Medicine, Emory University School of Medicine, Atlanta)

(Received for publication November 13, 1945)

Although the determination of cardiac output from the ballistic recoil of the body with each heart beat has been used repeatedly during the past 40 years, it has not been entirely satisfactory for general clinical use. Recently a survey of the problem has been made by Nickerson and Curtis (1), and as a result of this investigation they have recommended certain conditions to be satisfied in the construction of the ballistic system. Since a simple and reliable clinical method for the determination of cardiac output is of considerable importance, we have undertaken to test the type of ballistocardiograph described by Nickerson and Curtis. Studies have been made measuring the cardiac output by the ballistocardiograph, and by the method of right atrial catheterization utilizing the Fick principle.

APPARATUS

The ballistocardiograph used in this study differs from the instrument described by Starr *et al.* (2) in two main respects: (*1*) the undamped natural frequency of the bed is low; (*2*) the system is critically damped. The frequency of our bed is 1.5 cycles per second, whereas that of Starr was much more rapid. The bed described here is damped so that when it is deflected from its resting position, it returns to the original position with a minimum of overshooting. This is "critical damping" in the terminology of the physicists.

The apparatus used in this study differs from that of Nickerson and Curtis (1) only in that it was constructed for mounting on the fluoroscopic table upon which the right atrial catheterizations were performed. This arrangement permitted the almost simultaneous determination of the cardiac output by the technique of right atrial catheterization and by the ballistic method.

The ballistic bed consisted of a flat wooden table-top mounted on 4 flat strips of spring steel (Figure 1), so that movement in the longitudinal direction only was possible. The weight of the moving parts of the bed was about 75 pounds; the actual amount was not at all important, since variations in it were accounted for in the calibration to be described. Observations of the effect of increasing the weight of the moving part of the bed have led us to believe that it is more important that the bed be rigid than that it be of light weight. The effective length of the 4 springs upon which the bed was mounted was adjustable by means of clamps (Figure 1), so that the undamped frequency of the ballistic system could be brought to the same value (1.5 cycles per second) whatever load was placed on the bed. (The same result could be attained by keeping the spring lengths constant and supplementing the patient's weight by dead weights, thus maintaining the total load and hence the undamped frequency constant.) It should be noted that when calibrating the bed to its proper frequency for various loads, the damping bellows, emptied of oil, should be connected in the system so as to contribute its part to the restoring forces determining the movement of the bed. It is also important that the sylphon bellows be as flexible as possible in order to add but little to the restoring forces. The most satisfactory bellows requires a force of not more than 0.5 pound to compress it about 0.100 inch. The proper position of the clamps for each load was marked on a scale graduated in steps of 5 kgm., so that once calibrated, the setting of the ballistic bed to the nearest 5 kgm. for a subject of any weight was a rapid and simple procedure.

After the frequency calibration had been completed, the damper bellows, tube and reservoir (Figure 1) were filled with oil, care being taken to exclude air bubbles from the system. The position of the damping rod to produce critical damping for each load was then determined. The condition of critical damping can be practically considered as that situation where the bed on release from a displaced position moves back to its resting place with a minimum detectable overshoot. The calibration was made for a wide range of bed loads and over an oil temperature range corresponding to the room temperatures customarily found. When these calibrations were completed it was sufficient to know the oil temperature and the patient's weight in order to set the damping rod at the proper value.

The movements of the bed were recorded optically on

[1] The work described in this paper was done under contracts, recommended by the Committee on Medical Research, between the Office of Scientific Research and Development and Columbia University and also between the Office of Scientific Research and Development and Emory University School of Medicine.

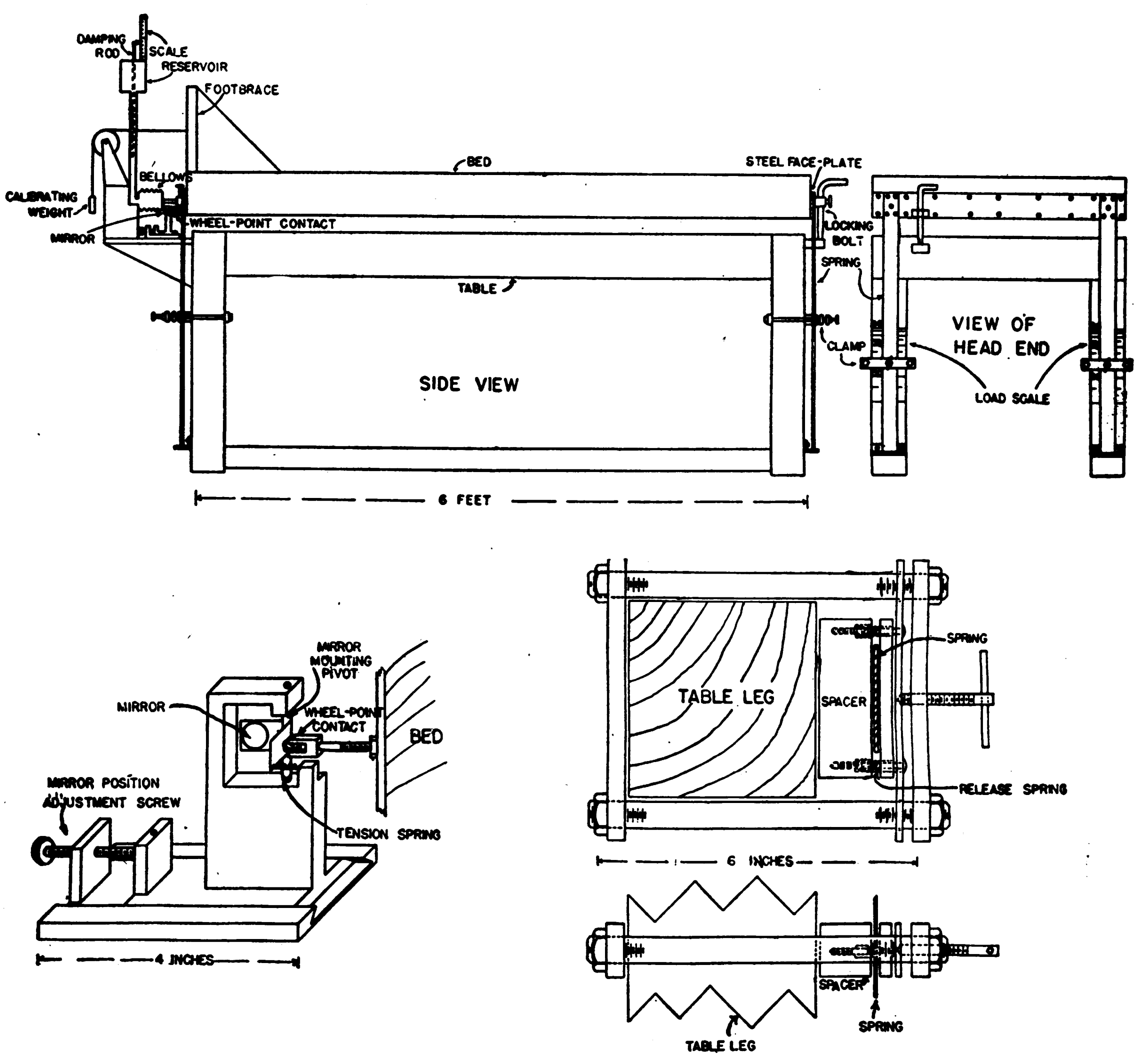

FIG. 1. DETAILS OF THE CONSTRUCTION OF THE BALLISTIC BED AS MOUNTED ON A TABLE

The figure shows the flat springs on which the bed is supported, the spring clamps, the locking bolt, the damping system, the pickup mirror mounting, and wheel-point contact. The spring clamp and mirror system are shown in considerable detail.

photographic paper. A light beam was reflected from a small pivoted concave mirror, which was held by means of a small spring against a frictionless wheel point moving with the ballistic bed (Figure 1). The movements of the reflected light were recorded by a camera similar to that used in an electrocardiographic apparatus.

METHOD

The subject was placed on his back on the ballistocardiograph with the soles of the feet tight against the upright foot-board, and the breath held in mid-position while the tracing was being taken. Figure 2 shows a typical tracing, with the headward deflections recorded in the upward direction, and the footward deflections in the downward direction. The initial major footward deflection (I) resulting from the recoil due largely to the ejection of blood by the heart, and the initial major head-

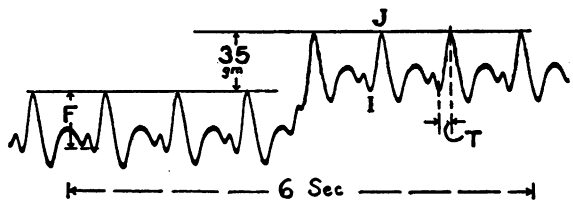

FIG. 2. A CHARACTERISTIC BALLISTOCARDIOGRAPH RECORD

This figure demonstrates the method of calibration, and indicates the measurements to be taken from the tracing.

ward deflection (J), resulting in the main from the slowing of blood in its headward course and from its turning around the aortic arch, are the most important landmarks in the tracing. A force of 35 grams was applied to the system during a portion of the tracing by weights attached to the foot of the ballistic bed and hanging over a light frictionless pulley. This offered a means of calibrating the bed while it was under the actual conditions of use, by showing how far the base line was displaced by a standard force. Knowing the displacement caused by the standard force, the displacement of the major deflection can be converted to the force involved (F) by measuring the distance between the peak of the first major footward deflection (I) and the peak of the first major headward deflection (J) and making a simple proportionality calculation. Two other measurements were required from the tracing: (*1*) the heart rate, and (*2*) the time interval in seconds (T) between the peak of the first major footward movement (I) and the peak of the first major headward movement (J).

The formula used for computing the cardiac output is slightly modified from the basic equations discussed in an earlier paper (3). The stroke volume is given by:

$$SV = \frac{5.02\ F\ P}{T\ L}\ \text{ml.},$$

and the cardiac output equals the stroke volume multiplied by the heart rate, where F and T have been defined above and, along with the heart rate, are obtained from the ballistic record. The quantity L is the height of the subject in centimeters, and 5.02 is a constant determined to adjust the ballistic results to a best fit with the catheter data. The factor P over most of the range of blood pressures, equals the square root of the arithmetic mean of the systolic and the diastolic pressures. However, at low pressures the results computed using $\sqrt{P_a}$ in the formula were somewhat too large, since with the correspondingly small stroke volumes, the momentum of the center of gravity of the heart muscle provided an appreciable part of the impact. For this reason, a table of P values (Table I) has been provided which gives a better fit for the data on normal subjects. As seen in Table I, the values of P differed only from $\sqrt{P_a}$ at low pressures.

The methods used in the cardiac output determination by the catheter technique have been described elsewhere (4). Samples of mixed venous blood were obtained by passing a flexible radiopaque catheter through the venous system into the right side of the heart. Arterial blood was obtained from an inlying needle in the femoral artery. Oxygen consumption was measured by collecting a 2- or 3-minute sample of expired air and analyzing its contents. From these data, utilizing the Fick principle, the cardiac output was calculated as follows:

$$\text{cardiac output} = \frac{\text{oxygen consumption}}{\text{arteriovenous difference}}.$$

Because the output of the heart varies with body size, we have facilitated comparison between individuals by expressing the output in terms of cardiac index. This is the cardiac output in liters per minute per square meter of body surface.

TABLE I

P_a	$\sqrt{P_a}$	P	P_a	$\sqrt{P_a}$	P
50	7.1	5.0	100	10.0	10.0
52	7.2	5.3	102	10.1	10.1
54	7.3	5.6	104	10.2	10.2
56	7.5	5.8	106	10.3	10.3
58	7.6	6.1	108	10.4	10.4
60	7.7	6.4	110	10.5	10.5
62	7.9	6.7	112	10.6	10.6
64	8.0	7.0	114	10.7	10.7
66	8.1	7.2	116	10.8	10.8
68	8.2	7.5	118	10.9	10.9
70	8.4	7.8	120	11.0	11.0
72	8.5	8.1	122	11.0	11.0
74	8.6	8.3	124	11.1	11.1
76	8.7	8.5	126	11.2	11.2
78	8.8	8.7	128	11.3	11.3
80	8.9	8.9	130	11.4	11.4
82	9.1	9.1	132	11.5	11.5
84	9.2	9.2	134	11.6	11.6
86	9.3	9.3	136	11.7	11.7
88	9.4	9.4	138	11.7	11.7
90	9.5	9.5	140	11.8	11.8
92	9.6	9.6	142	11.9	11.9
94	9.7	9.7	144	12.0	12.0
96	9.8	9.8			
98	9.9	9.9			

In obtaining the data reported here, all subjects, except the patients in shock, were studied in the morning 15 hours after the last meal. The catheter was passed and the arterial needle inserted. After a variable period of time, during which the subject was able to relax and reach a relatively stable state, the observations were made. At first, ballistic tracings were obtained both before and after the samples were taken for the Fick output. Later, because these tracings varied so little, they were obtained only either immediately before or after the Fick output determinations.

RESULTS

Eighty-one cardiac output determinations by the catheter technique and almost simultaneous ballistic tracings were made on 58 individuals. The data obtained on the first 50 of these determinations on subjects without heart disease or myxedema were used to evaluate empirically the constants in the stroke volume equation. The stroke volume constant 5.02, and the values of the pressure factor P given in Table I are the results of these determinations. Once determined, these constants, which gave the best fit of the ballistic and the catheter data, were used throughout this study. This method of computing the cardiac output from the ballistic records does not invalidate a comparative study of the results of the 2 methods. Actually, it tests the success of the formula in fitting the ballistic data to that obtained by the application of the Fick principle. It should be remembered, however, that because of the empirical adjustment, the cardiac output by the ballistic method is dependent on the values obtained by the

TABLE II

Subject	Sex	Age	Ht.	Wt.	S.A.	Fick CI	Pressure		F.	T.	HR	BCG CI
							P_s	P_d				
		yrs.		*lb.*	*sq. m.*	*l. per min. per sq. m.*	*mm. Hg*		*grams*	*sec.*	*per min.*	*l. per min. per sq. m.*
L.A.	M	15	5′7″	131	1.68	2.3	89	58	26.0	.128	81	2.4
L.A.	M	15	5′7″	131	1.68	3.5	107	61	35.0	.124	75	3.4
L.A.	M	15	5′7″	131	1.68	4.3	124	65	45.0	.126	75	4.6
E.J.	F	30	4′11″	90	1.31	2.1	103	59	11.6	.140	103	2.0
E.J.	F	30	4′11″	90	1.31	2.7	111	59	19.8	.134	97	3.4
E.J.	F	30	4′11″	90	1.31	4.0	116	62	26.6	.140	97	4.4
S.M.	M	39	6′2″	150	1.91	2.3	82	49	32.0	.124	107	2.8
S.M.	M	39	6′2″	150	1.91	4.0	93	49	45.0	.128	94	3.7
S.M.	M	39	6′2″	150	1.91	5.6	102	49	65.0	.124	90	5.6
S.M.	M	39	6′2″	150	1.91	5.9	102	50	77.0	.128	90	6.4
W.T.	M	52	5′7″	167	1.87	1.5	71	42	40.3	.148	70	1.8
W.T.	M	52	5′7″	167	1.87	2.9	122	63	34.1	.154	82	2.8
M.Z.	F	22	5′1″	110	1.46	2.2	86	47	22.3	.123	100	3.0
M.Z.	F	22	5′1″	110	1.46	4.8	130	75	34.0	.130	96	5.6
P.D.	M	34	5′7″	130	1.67	3.1	76	46	45.0	.168	78	2.5
N.A.	M	33	5′10″	135	1.75	2.9	112*	60*	36.0	.138	62	2.4
N.A.	M	33	5′10″	135	1.75	2.7	120*	63*	47.0	.138	54	2.8
N.A.	M	33	5′10″	135	1.75	2.6	120*	63*	47.0	.135	57	3.1
J.B.	M	30	5′11″	189	2.04	3.3	133	75	55.0	.144	60	3.2
J.B.	M	30	5′11″	189	2.04	2.8	155	86	48.0	.133	62	3.3
J.B.	M	36	5′9″	189	2.00	3.6	125	75	40.0	.137	78	3.3
J.B.	M	36	5′9″	189	2.00	4.4	155	79	60.0	.141	60	4.0
L.L.	M	16	5′8″	139	1.73	2.5	119	68	46.5	.137	51	2.8
L.L.	M	16	5′8″	139	1.73	3.3	142	78	35.0	.124	60	3.0
L.L.	M	16	5′8″	139	1.73	3.1	142	75	37.0	.129	52	2.6
A.R.	M	40	6′1″	146	1.87	3.6	179	106	35.9	.162	71	2.7
A.R.	M	40	6′1″	146	1.87	3.4	179	106	32.8	.158	81	2.9
J.S.	M	30	5′8″	142	1.75	2.6	117	65	47.0	.161	54	2.5
J.S.	M	30	5′8″	142	1.75	3.6	123	71	47.0	.147	60	3.1
W.W.	M	57	5′6″	145	1.73	3.1	163	86	33.0	.120	64	3.4
W.W.	M	57	5′6″	145	1.73	5.1	166	84	42.0	.120	65	4.4
W.W.	M	57	5′6″	145	1.73	5.2	150	77	40.0	.120	60	3.7
Y.A.	M	16	5′5″	116	1.56	2.5	110	60	43.2	.166	65	3.0
W.B.	M	17	5′4″	105	1.48	4.3	152	84	32.0	.120	78	4.7
O.F.	M	31	5′11″	155	1.87	3.0	115	66	50.3	.146	62	3.0
E.G.	M	29	5′6″	121	1.60	3.1	121	63	31.0	.148	60	2.3
M.J.	F	21	5′4″	104	1.46	4.6	110	61	32.0	.120	78	4.1
V.M.	M	18	5′6″	153	1.77	4.5	127	64	70.0	.176	65	4.3
J.W.	M	42	5′6″	135	1.68	2.8	114	58	34.0	.168	75	2.5
C.C.	M	36	6′1″	166	1.97	3.7	170	94	63.0	.142	73	5.1
J.E.	M	48	5′11″	148	1.84	4.6	163	83	34.6	.133	98	4.3
B.E.	F	22	5′4″	129	1.61	5.5	152	68	52.0	.131	75	6.0
R.C.	M	50	5′3″	126	1.62	4.6	133	57	45.8	.117	71	5.3
R.C.	M	50	5′3″	126	1.62	3.0	137	60	28.4	.118	43	2.0
I.M.	F	22	5′4″	94	1.41	7.8	120	64	44.0	.154	103	6.2
A.C.	F	27	5′2″	127	1.57	3.5	85	47	39.0	.145	70	2.7
A.C.	F	27	5′2″	127	1.57	3.5	109	69	28.0	.126	84	3.6
J.C.	M	35	5′7″	133	1.70	6.0	148	88	35.0	.143	90	4.2
A.G.	F	30	5′4″	108	1.49	3.6	83	33	33.0	.142	72	2.2
H.M.	M	34	5′4″	172	1.82	3.5	120	80	43.0	.153	63	3.0
M.S.	F	30	5′1″	111	1.47	2.8	134	75	29.0	.132	60	3.0
C.L.	F	26	5′10″	258	2.23	2.3	115*	70*	33.0	.140	79	2.3
C.L.	F	26	5′10″	258	2.23	2.4	115*	70*	32.0	.140	70	2.0
B.H.	M	29	5′9″	168	1.91	2.7	120*	72*	49.5	.152	66	3.2

* By cuff.

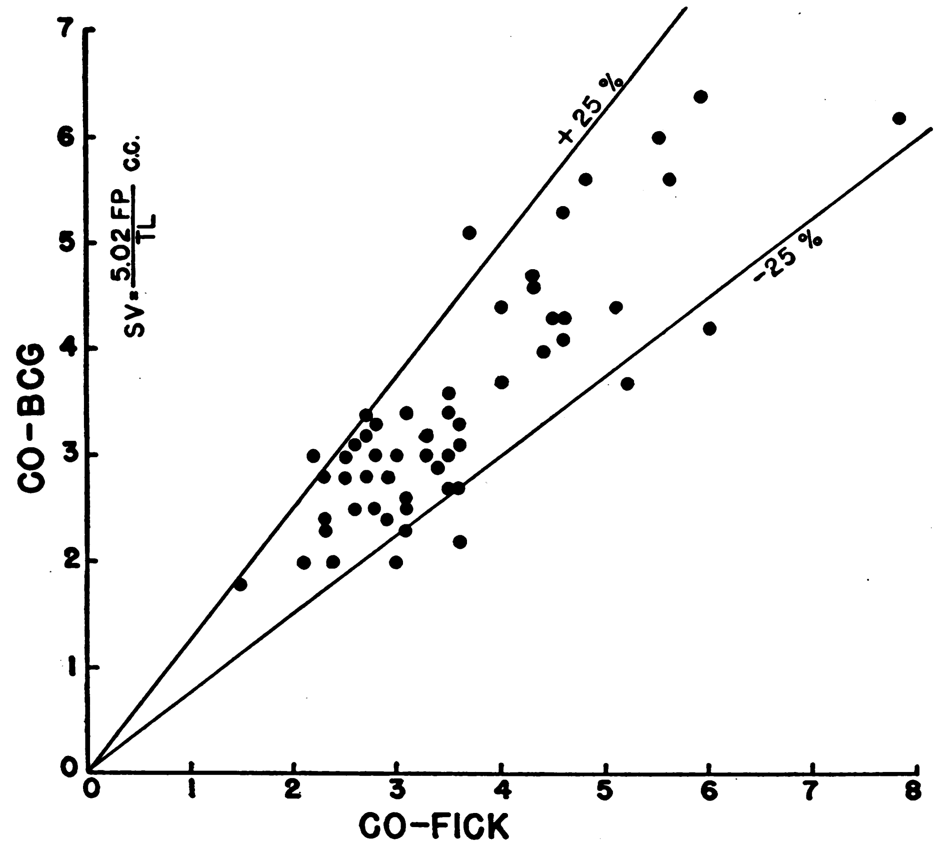

FIG. 3. CARDIAC INDICES COMPUTED FROM THE BALLISTIC TRACING PLOTTED AGAINST THE VALUES DETERMINED FROM THE CATHETER METHOD FOR PATIENTS IN WHOM THERE IS NO CLINICAL EVIDENCE OF CARDIAC DISEASE

The limits of ± 25 per cent deviation from the catheter values are shown.

catheter technique and is subject, therefore, to any fundamental errors in that method.

Fifty-four of the observations reported here were made on 32 subjects without clinical evidence of heart disease. The data on this group are given in Table II. These subjects represent a cross-section of the hospital population. They include members of the staff, convalescent patients, patients with anemia, thyrotoxicosis and shock, and normal subjects given albumin and saline intravenously. If the subjects were cooperative, and if the technical procedures were satisfactory, the data were used, regardless of whether or not the subject showed evidence of anxiety or apprehension. We are primarily interested in determining the relation of the ballistic tracings to the cardiac output as measured by the catheter technique under a variety of conditions, rather than in establishing basal values for the cardiac output. The comparison of the cardiac indices as measured by the 2 methods is shown for this group of subjects in Figure 3. Eighty-seven per cent of the values obtained by the ballistic method fall within 25 per cent of those by the catheter method. The correlation coefficient relating the data from the 2 methods has a value of 0.83.

Twenty-seven almost simultaneous measurements were made on a group of 26 patients with heart disease or myxedema. The data on these patients, with diagnosis, are given in Table III. The cardiac output as measured by the 2 methods did not agree as closely in this group as in the group without heart disease. Excepting those patients having aortic insufficiency, 60 per cent of the ballistic values of the patients in this group fell within 25 per cent of the catheter values (Figure

4). As one might expect on theoretical grounds, the patients with aortic insufficiency failed to show good correlation between the 2 methods. While the ballistic outputs were large, the catheter outputs were small, the difference between the ballistic and the catheter results giving some indication of the quantity of blood regurgitated during each cardiac cycle.

With the exception of those patients with aortic insufficiency, the cardiac output as calculated from the ballistic record fell within 25 per cent of that obtained by the catheter method in 80 per cent of the cases for the entire group studied.

Serial measurements were made at various stages in the treatment of 5 patients in shock (Figure 5). In Figure 6 portions of 4 successive ballistic records taken on one such patient are shown. All patients had distinct clinical evidence of shock. Two (W.T. and M.Z.) were patients with hemorrhagic shock from superficial stab wounds, one (L.A.) with a penetrating stab wound of the chest, one (E.J.) following an operative procedure for tuberculous infection of the kidney, and one (S.M.) with shock resulting from hemorrhage after drainage of a periurethral abscess. All, except one whose arterial pressure was 103/59, had systolic blood pressures below 100 mm. Hg at the time the initial measurements were made. The increase in cardiac output after treatment with saline and albumin was shown by both methods of measurement, and the agreement between the methods was good. In fact it appears that changes

TABLE III

Subject	Sex	Age	Ht.	Wt.	S.A.	Fick CI	Pressure		F.	T.	HR	BCG CI	Diagnosis
							P_s	P_d					
		yrs.		lb.	sq. m.	l. per min. per sq. m.	mm. Hg		grams	sec.	per min.	l. per min. per sq. m.	
P.B.	F	25	4′10″	108	1.30	3.0	155	82	16.0	.148	64	2.0	Treated myxedema, dilated heart
L.W.	F	42	5′4″	137	1.66	1.9	100*	70*	24.0	.140	65	1.9	Myxedema
A.D.	F	70	5′7″	108	1.55	5.2	175	72	28.0	.133	124	5.5	Thyrotoxicosis—auricular fibrillation
M.W.	F	45	5′4″	105	1.48	4.3	176	83	13.2	.129	86	2.1	Cardiac enlargement—? cause
A.F.	F	15	5′2″	90	1.35	6.0	123	57	39.0	.138	62	3.9	Sickle cell anemia with cardiac enlargement
M.H.	F	39	5′9″	168	1.91	2.7	129	60	40.0	.149	63	2.5	Rheumatoid arthritis—cardiac enlargement—? cause
I.H.	F	33	5′7″	137	1.71	3.9	116*	66*	41.0	.116	106	6.2	Rheumatic heart disease with mitral stenosis—5 mo. pregnant
C.H.	M	29	5′11″	168	1.94	2.7	152	87	42.0	.136	57	2.8	Cardiac enlargement—? cause
M.W.	F	57	5′5″	150	1.75	1.7	139	87	18.5	.198	88	1.5	Rheumatic heart disease with mitral stenosis
J.S.	M	34	5′10″	138	1.76	3.1	106	45	61.0	.179	58	2.7	Rheumatic heart disease with mitral stenosis
T.E.	M	53	5′7″	137	1.71	1.9	160*	65*	53.0	.255	63	2.4	Coarctation of the aorta
D.M.	M	62	6′	119	1.70	1.8	125	76	36.0	.166	65	2.3	Cor pulmonale—emphysema
J.M.	M	38	5′2″	123	1.54	3.5	105*	70*	30.0	.140	73	3.0	Cor pulmonale
T.S.	M	54	5′8″	133	1.71	2.9	133	72	33.0	.148	60	2.3	Rheumatic heart disease with mitral stenosis—auricular fibrillation
J.M.	F	42	5′2″	105	1.45	2.7	140	106	12.5	.132	182	4.2	Paroxysmal auricular tachycardia
J.W.	M	30	5′3″	115	1.52	2.6	127	60	39.0	.146	54	2.9	Rheumatic heart disease with mitral insufficiency
M.D.	M	14	5′4″	104	1.48	6.3	113	54	55.6	.154	77	5.3	Arteriovenous fistula
J.C.	M	32	6′1″	176	2.00	1.9	135	60	128.0	.168	88	9.0	Aortic insufficiency with failure
J.C.	M	32	6′1″	176	2.00	1.7	131	56	96.0	.191	78	5.2	Aortic insufficiency with failure
J.E.	M	34	5′11″	162	1.91	2.9	165	58	55.4	.162	56	3.0	Aortic insufficiency
W.F.	M	48	5′11″	144	1.82	1.9	168	78	54.0	.215	92	3.9	Aortic insufficiency with failure
L.F.	F	36	5′4″	108	1.50	2.3	182	35	53.7	.270	75	3.2	Aortic insufficiency with failure
G.H.	M	57	5′8″	119	1.64	4.0	148	44	48.4	.156	92	4.9	Aortic insufficiency
A.H.	F	62	5′4″	117	1.55	2.4	174	64	20.0	.160	88	2.4	Aortic insufficiency—well compensated
D.T.	F	27	5′7″	130	1.68	2.0	210	63	66.4	.149	76	7.0	Aortic insufficiency
A.W.	M	52	6′	153	1.89	3.0	175	43	123.0	.160	73	8.5	Aortic insufficiency with failure
H.Y.	M	72	5′7″	159	1.83	2.8	181	56	37.7	.166	80	3.2	Aortic insufficiency

* By cuff.

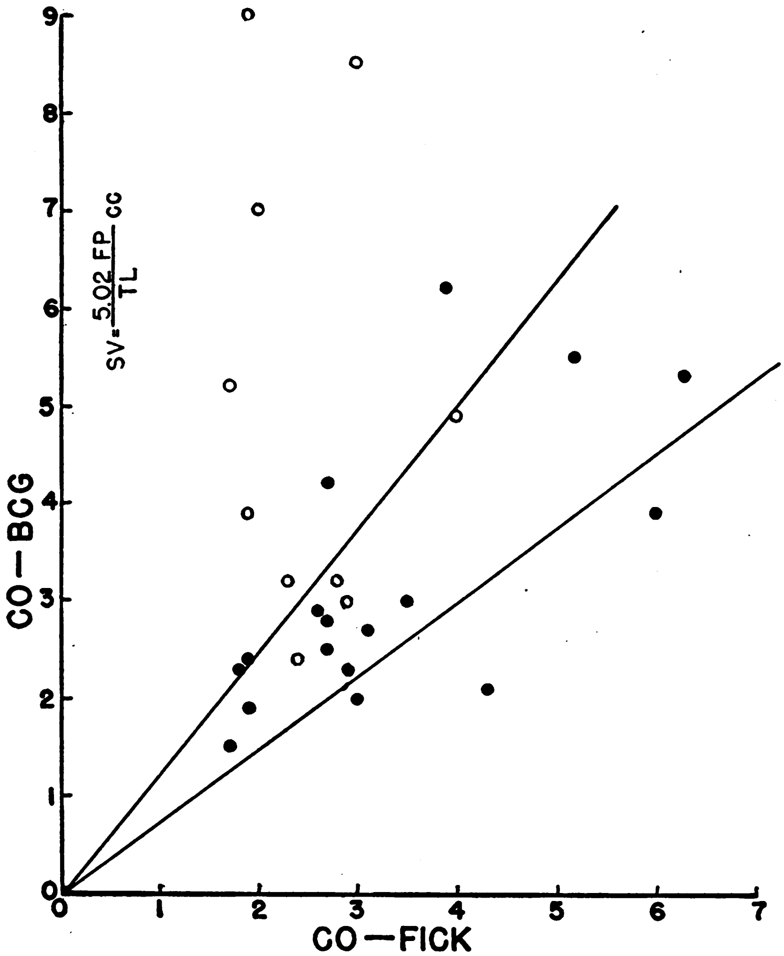

FIG. 4. THE CARDIAC INDICES FROM THE BALLISTIC TRACINGS PLOTTED AGAINST THE CATHETER VALUES FOR ALL SUBJECTS DIAGNOSED AS HAVING CARDIAC DISEASE OR MYXEDEMA

Those patients having aortic insufficiency are specifically designated by open circles. The limits of ± 25 per cent deviation from the catheter values are shown.

in cardiac output for any individual subject were measured with considerable accuracy by the ballistocardiograph.

Variations in arterial pressure, heart rate and age appear to cause no significant variation in the relationship between the cardiac index as measured by the ballistic method and as determined by the catheter method. This is demonstrated in Figure 7 where the ratios of the ballistocardiograph values to the catheter values are plotted against blood pressure, heart rate, and age. This figure includes the patients without heart disease (solid dots) and the patients with heart disease (open dots), except those patients having aortic insufficiency.

DISCUSSION

In comparing the ballistocardiographic determinations of the cardiac output with the method which involves right atrial catheterization and the application of the Fick principle, it must be remembered that the latter method is a procedure subject to considerable error. Although it does not afford an ideal standard for comparative studies, it does, however, appear to offer the best means available.. Its limitations have been evaluated in other

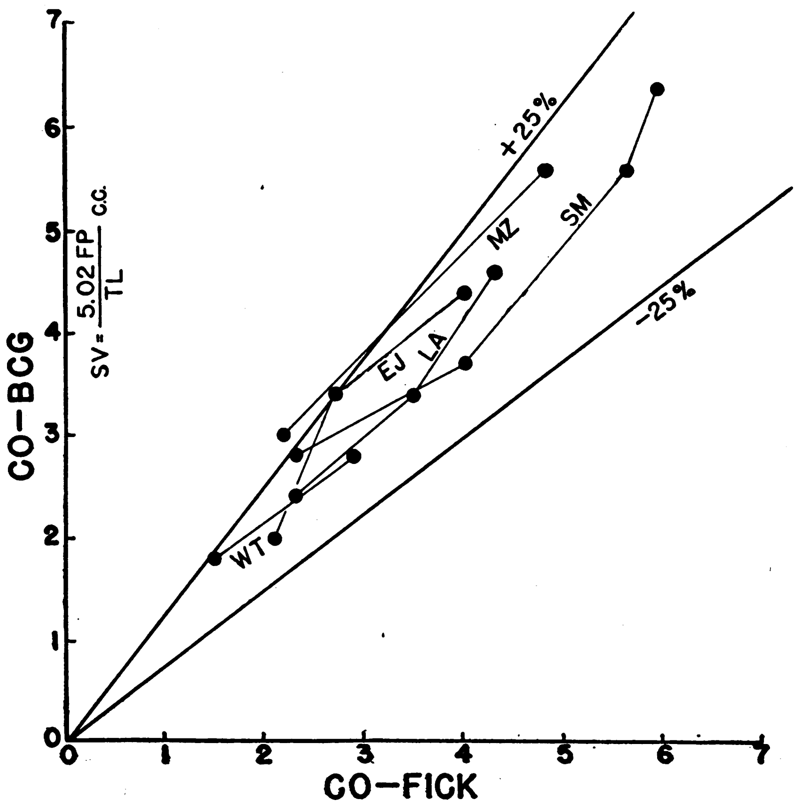

FIG. 5. SERIAL CARDIAC INDEX OBSERVATIONS ON 5 PATIENTS IN SHOCK AND WITH TREATMENT

The limits of ± 25 per cent deviation from the catheter values are shown.

communications from this laboratory (4, 5). Such factors as technical variations in the chemical determinations, inadequate sampling of mixed blood due to the streaming of the blood within the heart, and minute to minute variations of the cardiac output account for unavoidable errors, which may at times rise as high as ± 25 per cent. Moreover, since the computation of the cardiac output depends on the arteriovenous difference, the effect of errors will be larger when this difference is small. These factors should be considered in evaluating this comparative study; and because of these factors even a perfect ballistocardiographic method would fail to give excellent correlation.

The only other reported study comparing the ballistocardiographic method to the catheter technique of cardiac output determination is that of Cournand *et al.* (6). These authors used a high frequency, undamped ballistocardiograph, and found good correlation in relatively normal subjects. We believe that since our patients represent a wider variety of disease conditions, a wider variance of the data is to be expected. In a later publication (7) these authors reported that they were led to discard the high frequency ballistocardiograph for the patients in, or recovering from, shock. This objection to the use of the ballistocardiograph in the study of shock was not found to be applicable to the instrument described in the present paper.

The low frequency, critically-damped ballistocardiograph offers a remarkably simple and rapid method of determining the output of the heart. Rapid changes in output may be followed with ease, thus permitting studies to be made which are not possible by any other method. It is of particular value in following the output changes in an individual subject such as the studies of patients in shock recorded here. The ballistocardiograph, however, is not without disadvantages. As was anticipated, our data demonstrate that the

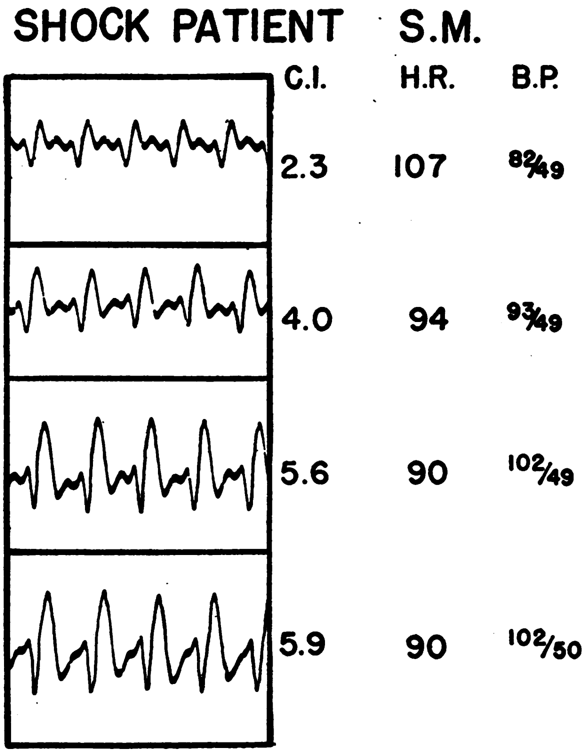

FIG. 6. PORTIONS OF THE SUCCESSIVE BALLISTIC TRACINGS AND SOME OF THE MEASUREMENTS ON THE SHOCK PATIENT S. M. OF FIGURE 5

findings in aortic insufficiency are unrelated to the effective output of the heart. Good results are difficult or impossible to obtain in patients with marked respiratory distress, or those unable to hold their breath for even a few seconds. Extremely irregular heart rhythms and marked tremors might also be mentioned as factors leading to results that are unsatisfactory. Finally, in some patients, particularly those with myocardial disease, we have seen patterns of unusual shape that are quite difficult to interpret.

CONCLUSIONS

The details of the construction of a low frequency, critically-damped ballistocardiograph are presented in this paper, and the procedures for its adjustment to definite physical conditions described. The adjustments enable the reproduction of this type of ballistocardiograph to be made easily, and permit, without the necessity of further calibration by the catheter method, the use of the stroke volume equation tested in this study.

Eighty-one determinations of the cardiac output by the method of right heart catheterization and by almost simultaneous ballistic records with the low frequency, critically-damped ballistocardiograph have been made on a group of 58 normal subjects and hospital patients under a variety of conditions. From the first 50 of these observations on subjects without heart disease, constants were derived for use in determining the cardiac output from the ballistic record. Applying these constants to the entire group of subjects (except patients with aortic insufficiency) the cardiac output computed by the ballistic method fell within 25 per cent of that obtained by the catheter method in 80 per cent of the cases.

Fifty-four of these determinations were made on subjects without evidence of heart disease, but with a variety of other illnesses. Eighty-seven per cent of the results by the ballistic method lay within 25 per cent of the values by the catheter technique. The other twenty-seven patients studied had clinical evidence of heart disease or myxedema. For 17 patients in this group, *i.e.*, excepting those with aortic insufficiency, the cardiac output by the ballistic method was within 25 per cent of that by the catheter technique in 60 per cent of the cases. Patients with aortic insufficiency showed marked discrepancies between the results from the ballistocardiograph and from the catheter method. As might be expected, the ballistic method gave output results which were considerably higher than those by the other method.

Serial measurements on patients in shock and during recovery showed a good correlation between the cardiac output measurements by the 2 methods. These results suggest that changes in cardiac output in any individual subject may be measured with considerable accuracy by the ballistocardiograph.

It is concluded that the low frequency, critically-damped ballistocardiograph provides a useful and reasonably accurate method of determining cardiac output in normal subjects, and in patients with a variety of disease conditions.

We wish to thank Mr. Herman Just of the Department of Physiology, Columbia University College of Physicians and Surgeons, for his precise work in the construction of the ballistic bed, especially the clamps for adjusting the spring lengths. Mrs. Jane Bailey, Miss Eloise Cavin, Miss Maurine Giese and Miss Lois Jackson gave valuable technical assistance.

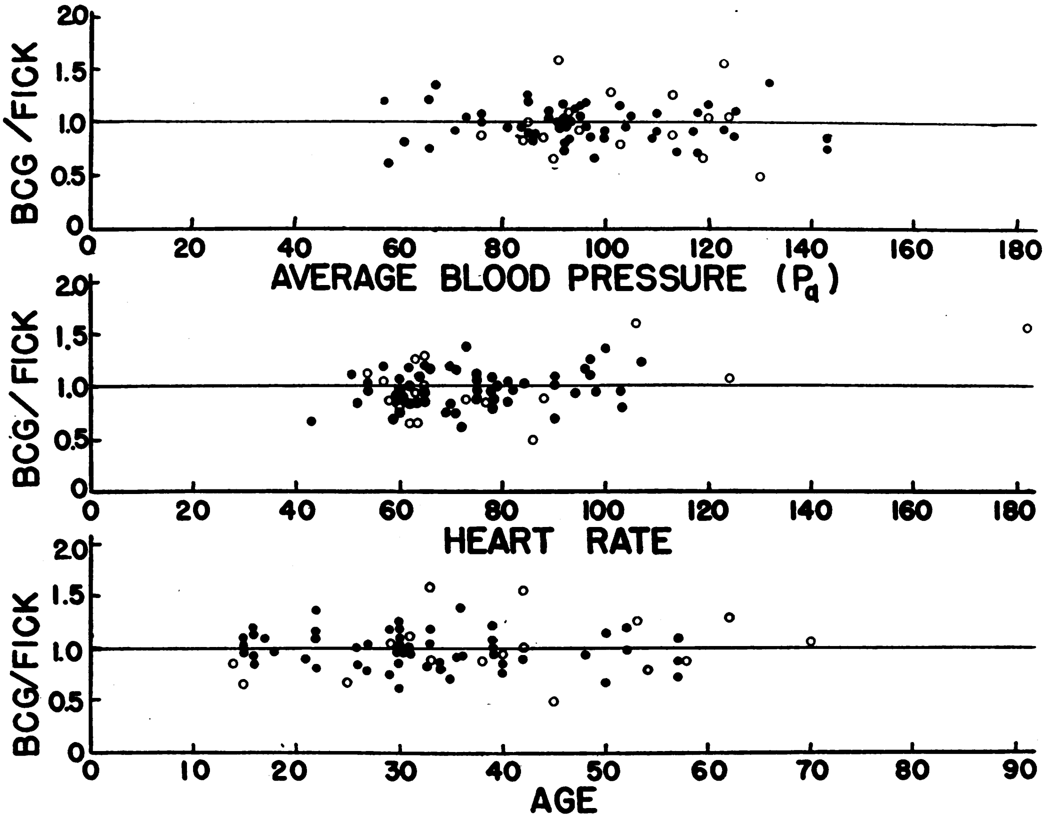

FIG. 7. THE RATIO OF THE BALLISTOCARDIOGRAPH CARDIAC INDEX AND THE FICK CARDIAC INDEX PLOTTED AGAINST THE AVERAGE BLOOD PRESSURE, *Pa*, THE HEART RATE, AND THE AGE OF THE PATIENT

No significant trend with any of these variables is shown.

BIBLIOGRAPHY

1. Nickerson, J. L., and Curtis, H. J., The design of the ballistocardiograph. Am. J. Physiol., 1944, 142, 1.
2. Starr, I., Rawson, A. J., Schroeder, H. A., and Joseph, N. R., Studies on the estimation of the 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.
3. Nickerson, J. L., The low frequency, critically-damped ballistocardiograph. Federation Proc., 1945, 4, 201.
4. Stead, E. A., Jr., Warren, J. V., Merrill, A. J., and Brannon, E. S., The cardiac output in male subjects as measured by the technique of right atrial catheterization. Normal values with observations on the effect of anxiety and tilting. J. Clin. Invest., 1945, 24, 326.
5. Warren, J. V., Stead, E. A., Jr., and Brannon, E. S., The cardiac output in man; A study of some of the errors in the method of right heart catheterization. Am. J. Physiol., 1946, 145, 458.
6. Cournand, A., Ranges, H. A., and Riley, R. L., Comparison of the results of the normal ballistocardiogram and a direct Fick method in measuring cardiac output in man. J. Clin. Invest., 1942, 21, 287.
7. Cournand, A., Riley, R. L., Bradley, W. E., Breed, E. S., Noble, R. P., Lauson, H. D., Gregersen, M. I., and Richards, D. W., Studies on the circulation in clinical shock. Surgery, 1943, 13, 964.