THE CIRCULATORY REACTION TO GRADUATED WORK AS A TEST OF THE HEART'S FUNCTIONAL CAPACITY *

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The valuable aid to diagnosis, prognosis, and treatment which an accurate test of the heart's functional capacity would afford has made it the object of much clinical research, and although a number of tests have been devised, the validity of each has been seriously questioned and no one has met with general acceptance.

As a preliminary to a new form of exercise treatment for cardiac insufficiency which we have described elsewhere, we investigated several of these tests, more particularly one described by Graüpnér. The essential features of his test are the deductions made from the form of the curve of the systolic blood-pressure after measured amounts of work. Although we were unable to confirm his most important results, we believe that the method of making frequent readings of the pulse rate and systolic pressure after measured amounts of work furnishes the key to this problem of determining the heart's efficiency.

Our work may be divided into two parts. The first consists in experiments on twenty-three normal persons. In three persons the graduated work was performed by means of a bicycle ergometer of the type described by Krogh and Lindhard,¹ and in twenty persons by means of dumb-bell and bar movements.

The second part comprised experiments on thirty-two patients suffering from cardiac insufficiency. The ergometer was used in two patients, and dumb-bell work in the remaining thirty.

EXPERIMENTS ON NORMAL PEOPLE WITH ERGOMETER

Charts 1 and 2 represent experiments done on a man aged 22 with a normal heart. During work the systolic blood pressure and pulse rate increased and the increase was proportionate to the amount of work done. After work the blood pressure and pulse rate fell rapidly to the original figures, except in the last experiment. In this 2,472 kilogrammeters of work were done in two minutes while the subject

* Submitted for publication Nov. 3, 1915.

* An abstract of this article was read before the Society for Experimental Biology and Medicine, Dec. 15, 1917.

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1. Krogh and Lindhard: *Skandinavisches Arch. f. Physiol.*, 1913, xxx, 378.

Chart 1.—Circulatory reactions in a normal man to increasing amounts of work performed on the bicycle ergometer. The upper continuous lines represent the systolic blood pressure, the lower dotted lines the pulse rate and the spaces between the heavy perpendicular lines the periods of work in each experiment.

Chart 2.—See Chart 1.

was panting and perspiration was running from his face. Immediately after the work stopped the systolic pressure was 168, and one minute later had risen to 178 at which time the pulse had dropped from 172 to 148. This delayed rise of the systolic blood pressure after heavy work is of much significance and we direct particular attention to it.

Experiments were carried out on two other people with normal hearts with the same results as above, an increase in pulse rate and blood pressure during work and a delayed rise of the systolic pressure following very heavy work.

Chart 3.—Circulatory reactions in a normal man to increasing amounts of work performed by means of dumb-bells. The white perpendicular spaces represent the work periods in each experiment during which blood pressure and pulse rate could not be measured.

EXPERIMENTS ON NORMAL PEOPLE WITH DUMB-BELL AND BAR WORK

Various movements with heavy dumb-bells and a steel bar weighing 25 pounds, which will be described later, were carried out in a way which permitted an approximate estimation of the foot-pounds of work performed. Naturally the pulse rate and blood pressure could not be taken during the work, but they were taken before and every minute or half minute after work.

Chart 3 represents the type of reaction we obtained in several hundred experiments on twenty normal persons. The delayed rise in systolic blood pressure was obtained after large amounts of work which varied according to the subject's physique and condition of muscular training.

EXPERIMENTS ON PATIENTS WITH CARDIAC INSUFFICIENCY USING
THE ERGOMETER

Ten experiments were carried out on two patients who rode the bicycle ergometer for periods of two and one-half minutes with successively increasing loads. Seven experiments were made with the same patients turning the bicycle pedals by hand instead of by the feet. This was done to see if approximately the same amount of work would be followed by a delayed rise in systolic pressure, whether performed by the legs or the arms.

Chart 4.—Circulatory reactions in patient C. G. suffering from cardiac insufficiency to increasing amounts of work performed with the legs on the bicycle ergometer.

Charts 4, 5, and 6 show a typical group of experiments on one of these patients, suffering from mitral regurgitation and cardiac insufficiency. The blood pressure could not of course be measured during the arm work. It will be noticed that 732 kilogrammeters performed with the legs is followed by a marked delayed rise, and 729 kilogrammeters performed with the arms shows an equally marked delay.

The subjects of these experiments both had badly damaged hearts, and histories of two or more attacks of cardiac insufficiency extending over several years.

These experiments present several striking features and some marked contrasts to the experiments on normal persons. The amounts of work necessary to produce the delayed rise in systolic blood pressure were far less than in the normal subjects. Again the pressure *during* work, instead of rising decidedly as in normal subjects, rose but slightly or fell below the pre-exercise level.

Chart 5.—A continuation of the experiments pictured in Chart 4 on the same patient a few minutes later, the work being performed on the bicycle ergometer with the arms instead of the legs. The white perpendicular spaces represent the work periods in each experiment during which blood pressure and pulse rate could not be measured.

Chart 6.—See legend of Chart 5.

EXPERIMENTS ON PATIENTS WITH CARDIAC INSUFFICIENCY USING
DUMB-BELL WORK

Several hundred experiments were carried out on thirty different patients. The pulse rate and blood pressure could not be taken during the performance of the dumb-bell work, but were measured every thirty or sixty seconds after work.

The following examples are selected because they represent the different types of reactions following work.

R. S., a delicate girl aged 23, with a history of chorea and tonsillitis followed by endocarditis. This resulted in a mitral stenosis and regurgitation and, five months previous to the test below described, cardiac decompensation from which she slowly recovered under rest and digitalis.

Time	Pulse Rate	Systolic Blood Pressure
10:05	92	108
10:08	96	104
200 foot-pounds in 30 seconds (5 lb. bell pushed 20 times)		
10:10	114	122
10:10½	108	120
10:11½	92	106
10:16	90	106
400 foot-pounds in 30 seconds (10 lb. bell pushed 20 times)		
10:18	120	110
10:18½	108	110
10:19½	98	106
10:30	96	110
480 foot-pounds in 32 seconds (10 lb. bell pushed 24 times)		
10:31	120	114
10:32	102	122
10:33	90	110
10:34	90	110

C. G., a man aged 31, with a history of four attacks of rheumatic fever, and symptoms of cardiac involvement for four years. June 8, 1915, he was recovering from a six months' attack of acute articular rheumatism. His heart was much enlarged and showed a mitral regurgitation and regular rhythm. He was dyspneic, his legs were edematous, and the edge of the liver could be felt 5 inches below the free border of the ribs in the nipple line. He was put to bed and given digitalis. June 21, the following test was made:

Time	Pulse Rate	Systolic Blood Pressure
10:55	100	136
10:58	88	130
11:00	100	126
250 foot-pounds in 20 seconds (10 lb. bell flexed 10 times)		
11:02	108	138
:03	108	136
:04	96	132
:05	92	126
:06	90	128
11:22	96	128

500 foot-pounds in 35 seconds
(10 lb. bell flexed 20 times)

11:23½	106	140
11:24	102	130
11:25	96	136
11:26	92	130
11:28	100	128
11:34½	96	122

750 foot-pounds in 45 seconds
(10 lb. bell flexed 30 times)

11:37	114	146
11:38	102	136
11:39	102	136
11:42	96	136
11:44	100	122

1,000 foot-pounds in 40 seconds
(15 lb. bell flexed 27 times)

11:47	126	{ 136 142 138 134
11:48	114 Delayed rise	
11:49	108	
11:50	108	
11:51	96	138
11:52	96	124

These show the ordinary types of reaction to increasing work.

The same patient several months later showed a type of reaction occasionally encountered.

Time	Pulse Rate	Systolic Blood Pressure
10:05	92	124

462 foot-pounds in 35 seconds
(15 lb. bell flexed 15 times)

10:07	102	140
10:07½		134
10:08	100	134
10:15	92	126

750 foot-pounds in 35 seconds
(20 lb. bell flexed 15 times)

10:17	108	140
10:17½		136
10:18	84	126
10:20	88	132

1,000 foot-pounds in 45 seconds
(20 lb. bell flexed 20 times)

10:22	108	134
10:22½	96	130
10:23		128
10:23½	90	128
10:29	92	122

1,250 foot-pounds in 60 seconds
(20 lb. bell flexed 25 times)

10:31	108	{ 126 128 126 126
10:31½	102 Delayed rise?	
10:32	90	
10:39	92	

1,500 foot-pounds in 60 seconds (20 lb. bell flexed 30 times)			
10:43	114	Delayed rise	{ 124
10:43½			{ 126
10:44	92		{ 124
10:44½	90		{ 128
10:45	84		{ 120
10:46	84		{ 124
10:47	84		122

The blood pressure reactions to work became less and less marked as the work increased, although the pulse became more and more rapid. Finally in the fourth experiment we got apparently a slight delayed rise in systolic pressure, and, when the work was still more increased (fifth experiment) the pressure immediately after work was lower than it was before, although the pulse-rate had risen to 114.

One more example of the last type may be given.

D. C., aged 23, suffering from disease of all the valves except the pulmonary, and cardiac insufficiency, died Jan. 1, 1915. December 9 he showed the following:

Time	Pulse Rate	Systolic Blood Pressure	
12:25	84	100	
150 foot-pounds in 20 seconds			
12:26	108	102	
:27	96	102	
:28	90	102	
:30	80	100	
12:40	84	98	
200 foot-pounds in 20 seconds			
12:41	104	Delayed rise	{ 100
:42	96		{ 108
:43	88		{ 106
:48	90		{ 102
1:05	84		106
350 foot-pounds in 25 seconds			
1:06	108	Delayed rise	{ 98
:07	102		{ 106
:08	96		{ 110
:09	90		{ 110
:13	90		{ 100

EXPERIMENTS DEMONSTRATING THAT THE AMOUNT OF WORK
NECESSARY TO PRODUCE A DELAYED RISE IN SYSTOLIC
BLOOD PRESSURE IS THE SAME WHATEVER GROUP
OF MUSCLES IS EMPLOYED

This is the first time as far as we can ascertain that this law of circulatory physiology has been demonstrated. Proof of the invariability of this phenomenon was afforded, as previously stated, by three experiments on two patients with cardiac insufficiency, using the ergometer, and also by many other clinical experiments. A few of the latter will be given for this law plays an important part in establishing the validity of our test of the heart's functional capacity.

The patient on whom the following experiments were performed was aged 58 years, had a normal heart and suffered from occasional attacks of moderate hypertension. On each of the five days preceding the experiments described below this patient had been able to do between 1,500 and 1,800 foot-pounds of work before delayed rises were produced.

Time	Pulse Rate	Systolic Blood Pressure
10:45	96	146
1,500 foot-pounds (approximate) in 35 seconds (Work performed with right arm by swinging 20 lb. bell 8 times)		
10:47	108	164
:48	100	160
:49	96	152
:50	92	148
1,800 foot-pounds (approximate) in 40 seconds (Work performed with right arm by swinging 20 lb. bell 10 times)		
11:17	114	Delayed rise {
:18	96	
:19	90	
:20	90	
:24	84	
1,800 foot-pounds (approximate) in 40 seconds (Work performed with left arm by swinging 20 lb. bell 10 times)		
11:26	120	Delayed rise {
:27	96	
:28	96	
:29	90	
:30	90	
:32	84	140
11:40	9	140
11:45	92	140
1,800 foot-pounds (approximate) in 40 seconds (Work performed with both arms by swinging two 10 lb. bells 10 times)		
11:47	108	Delayed rise {
:48	96	
:49	90	
:50	90	
:51	84	
:52	80	138
11:53	84	136

It will be seen that it makes no difference whether one or both arms are used to do the work, as far as concerns the production of the delayed rise.

E. B., a patient aged 40 years suffering from mitral regurgitation and stenosis and moderate cardiac insufficiency showed the following results:

Time	Pulse Rate	Systolic Blood Pressure
11:28	96	120
400 foot-pounds (12 lb. bell extended 20 times)		
11:29	120	128
:29½	112	126
:30	108	120
:30½	108	116
:31½	104	116
:33	100	116

500 foot-pounds (12 lb. bell extended 25 times)				
11:34	124	Delayed rise	{	120
:34½	120			126
:35	116			122
:35½	104			120
:36½	108			116
:50	104			114
396 foot-pounds (12 lb. bell flexed 18 times)				
11:51	136			138
:51½	112			130
:52	104			128
:52½	108			122
:53	100			122
:58	104			116
440 foot-pounds (12 lb. bell flexed 20 times)				
11:59	140	Delayed rise	{	122
:59½				134
12:00	108			130
:00½	108			122
:01	108			122
:02	104			120

Five hundred foot-pounds of extensor work and 440 foot-pounds of flexor work produced a delayed rise of blood pressure.

As a general rule to which the above experiment is an exception a patient with mitral disease is able to do more flexor work with the arms than extensor work, before a delayed rise is produced. Extensor work apparently produces an obstacle to the pulmonary circulation because it tends to immobilize the thorax, while flexor work does not do so. Graüpnier first called attention to this.

SUMMARY

Our work may be summarized as follows:

Experiments on Three Normal Persons with Ergometer.—During increased amounts of work there was a rise of the systolic blood pressure and an increase of the pulse rate which became very marked with heavy work. After heavy work the delayed rise in systolic blood pressure was noted.

Experiments on Normal People with Dumb-Bell Work.—Several hundred experiments on twenty normal people showed the delayed rise in systolic pressure after heavy work.

Experiments on Two Patients with Cardiac Insufficiency Using the Ergometer.—Ten experiments showed a marked contrast in the course of the blood pressure during work as compared with that in normal persons. In these patients the pressure rose but slightly and as the work increased frequently dropped below the original level. The pulse rate was always quickened. The delayed rise in systolic blood pressure occurred after much smaller amounts of work than in normal persons. Approximately the same amounts of work were followed by a delayed rise whether performed by the arms or legs.

Experiments on Patients with Cardiac Insufficiency Using Dumb-Bell Work.—Several hundred experiments were carried out on thirty patients. The delayed rise in systolic blood pressure was noted in all these patients after comparatively small amounts of work. In patients with marked cardiac insufficiency the pressure immediately after work was occasionally lower than the original level.

THE CIRCULATORY PHYSIOLOGY OF EXERCISE

Certain facts about the circulatory physiology of exercise seem to be fairly well established, and we shall summarize them briefly.² The carbon dioxide content of the blood is increased by muscular work and this stimulates the nervous centers controlling the suprarenal glands. An increase in the adrenin content of the blood is thereby produced, which causes a constriction of vessels in the splanchnic area and a resulting rise in blood pressure. The quickened heart rate accompanying muscular work causes an increase in the quantity of blood discharged by the heart per minute and this also contributes to the rise in blood pressure. Shortly after exercise stops, the carbon dioxide content of the blood falls below normal, the activity of the suprarenal glands decreases and the splanchnic vessels relax.

Nicolai and Zuntz³ have made some important observations on the hearts of a series of normal persons during work on a stationary ergometer by means of the Roentgen ray. If their experiments are confirmed they will have a very direct bearing on the explanation of the delayed rise in systolic blood pressure and its relation to the testing of the heart's functional capacity. They showed that during moderately heavy work the heart increases slightly in size and a few seconds after work suddenly becomes smaller than normal. The increase during work they attribute to the greater quantity of blood pumped into the heart by the muscular and respiratory activity incident to work. They also offered proof that the heart completely empties itself at each systole of this much increased content, whereas the heart of a resting person expels only about one-half of its contents at each systole. The increase in size during work is not to be regarded as a sign of insufficiency because the heart expels its entire content at each systole. Only if a greater quantity of blood than normal remains in the heart after systole does an insufficiency exist. The rapid diminution in size of the heart immediately after work is attributed to the sudden decrease in the quantity of blood pumped into the heart resulting from the stopping of muscular activity.

2. Cannon: *Am. Jour. Physiol.*, 1914, xxxiii, 356. Von Anrep: *Eng. Jour. Physiol.*, 1913, xlv, 318. Hooker: *Am. Jour. Physiol.*, 1911, xxviii, 235. Schneider and Havens: *Am. Jour. Physiol.*, 1915, xxxvi, 239.

3. Nicolai and Zuntz: *Berl. klin. Wchnschr.*, May 4, 1914, p. 821.

Our own experiments and the facts of circulatory physiology already adduced together with the observations just quoted, give us some insight as to the cause of the delayed rise in systolic blood pressure following work. It may be stated as follows:

In normal people during heavy work the systolic pressure mounts rapidly and the left ventricle finds it more and more difficult to expel its contents against this increasing resistance. At a certain height of aortic pressure the ventricle probably does not empty itself completely and a steadily increasing volume of blood remains in the heart after each systole. In other words, an insufficiency exists. At this moment the Roentgen ray would possibly show a heart decidedly increased in size instead of slightly increased, as found by Nicolai and Zuntz during moderate work. If the work stops the vessels of the splanchnic area begin to relax and the blood pressure falls. Now the heart works more efficiently against the lowered aortic pressure and expels a larger quantity of the increased residual blood at each stroke, until finally it empties itself completely with each systole. The increased quantity of blood which the recovering heart thus throws into the aorta more than compensates for the pressure-lowering effect of the dilating splanchnic vessels and the pressure rises briefly, thereby producing the delayed rise in blood pressure.

The different course of the curve of the blood pressure *during* the work period in patients with cardiac insufficiency implies a difference in circulatory mechanics in these patients as compared with normal persons. This curve showed a slight rise and often a fall with increasing work. The curve *after* work was the same as in normal individuals, except that much smaller amounts of work produced the delayed rise.

The splanchnic vessels in these persons presumably contract during work in the same way as in a normal person. The failure of the blood pressure to rise decidedly during work shows that the heart must propel, if anything, less blood per minute into the aorta than when at rest, even though the rate is much increased; otherwise with a narrowed stream-bed and the same volume discharged per minute the pressure would rise.

Nicolai and Zuntz claim that during work much greater quantities of blood flow into the heart and are ejected at each systole. In our experiments the heart could not have expelled these increased quantities of blood or, as we have already said, the pressure would have risen. Therefore, the blood must have accumulated in the heart and produced a dilatation or insufficiency. The narrowing of the stream-bed caused by the splanchnic constriction incident to work must also play a part in producing this insufficiency.

When the work stops, the stream-bed resumes its normal proportion, possibly more slowly than in a healthy person, the heart acts more efficiently, and expels the increased residual blood, which is sufficient to produce a rise in blood pressure. If the heart is much dilated it probably requires a short time to reach its maximum efficiency and expel its increased content and we have a slowly mounting blood pressure. In other words, our "delayed rise in systolic pressure."

Therefore, if we accept this tentative explanation of the circulatory physiology of exercise, a delayed rise in systolic pressure after work in a normal person or in one with cardiac insufficiency would mean that the preceding work had either made the heart temporarily insufficient or had increased an already existing insufficiency.

Our *clinical experiments* demonstrate conclusively, we believe, that in the pulse rate and blood pressure reactions to graduated work we possess a valid test of the heart's functional capacity. If the systolic blood pressure reaches its greatest height not immediately after work but from 30 to 120 seconds later, or if the pressure immediately after work is lower than the original level, that work, whatever its amount, has overtaxed the heart's functional capacity, and may be taken as an accurate measure of the heart's efficiency.⁴

Graüpnér⁵ in 1906 carried out a large number of experiments on normal people and persons suffering from cardiac insufficiency, using a Zuntz ergometer and employing the method of frequent blood pressure readings before, during and after work. He reached the following conclusions:

"1. Moderate work in powerful persons causes no change in the systolic blood pressure after work.

"2. An increase in work causes a rise in the systolic blood pressure immediately after work and this returns quickly to normal. Repetition of the work causes the blood pressure to rise less high and to return more quickly to normal.

"3. If the work is still more increased we find directly after work a *sinking* of the blood pressure. Yet the blood pressure then rises quickly above normal and then falls back to normal. This primary fall of the blood pressure and secondary rise above normal is characteristic of 'functional insufficiency' of the heart.

"4. If the blood pressure after work is lower than normal and then slowly returns to normal, but does not rise *above normal*, a primary

4. The determination of delayed rises in patients suffering from auricular fibrillation is difficult and inexact. We have taken the first well-marked beat heard at each reading as a guide. Here the increase in heart-rate is an important aid in deciding if the preceding work has overtaxed the heart.

5. Ztschr. f. exper. Path. u. Therap., 1906, iii, 113; Deutsch. med. Wchnschr., 1906, No. 26.

myocardial weakness exists. This reaction is characteristic of pathological insufficiency."

By the term "normal pressure" Graüpnér presumably meant the pressure when it had reached a constant level just previous to the work. Apparently he did not take the pressure before each experiment. The amounts of work performed in his experiments were about the same as in ours. His blood pressure readings were all made by palpation and he generally made three or four in the course of thirty or forty seconds without letting the air out of the cuff.

We were able to corroborate his first conclusion and the first half of his second conclusion. His fourth conclusion we found true in a very small number of patients with cardiac insufficiency. His remaining conclusions, which constitute the essential features of his test, we were unable to confirm.

Graüpnér's failure to measure the pressure before each experiment explains to a certain extent the divergence of our results, for the pressure may be as much as 20 mm. of mercury lower before the last experiment than before the first. Also the error inherent in the palpatory method of taking blood pressure especially if the arm be compressed for 30 seconds is considerable and may explain some of our differences.

METHOD OF PERFORMING OUR TEST OF THE HEART'S FUNCTIONAL CAPACITY

The apparatus used consists of pairs of 5, 10, 15 and 20 pound dumb-bells, and a steel bar about 40 inches long weighing 25 pounds. Two types of movements are done with the bells.⁶ In the first a pair of dumb-bells is held at the shoulders, one in each hand, and then pushed alternately above the head and toward the median line until the arms are fully extended. As one bell moves up fairly rapidly the other bell returns to the shoulder, the two moving in a sort of see-saw rhythm. In the other movement a bell is held in each hand, the arms hanging by the side of and close to the body, and then each forearm is alternately flexed, raising the bell to the shoulder. The patient stands or sits according to his condition. But one movement is performed with the steel bar. It is picked up from the floor with both hands, raised first to a level with the shoulders, then pushed above the head until the arms are fully extended and then quickly lowered to the floor again with a single rapid motion.

It is possible to calculate approximately the number of foot-pounds of work performed in each of these movements. There is a certain amount of work, however, which we cannot estimate in foot-pounds.

6. These movements were first described by Dr. Jacob Teschner of New York.

When a patient stands with a pair of dumb-bells at his shoulders without moving them, work is done as shown by his circulatory reactions, but we cannot estimate it in foot-pounds. This unknown factor can be ignored, however, for our purpose.

More adults average 2 feet as the distance through which a bell is pushed from the shoulder to full extension of the arm. In the flexion movement, the distance through which the bell is carried from the side of the body to the shoulder averages from 2 feet to 2 feet 6 inches. Now if a 5-pound bell is pushed through 2 feet, 10 foot-pounds of work are done. If the total number of pushes are twenty, 200 foot pounds are done. For the sake of comparison, the time it takes a patient to do any quantity of work should be noted.

If the patient whose heart is to be tested has but recently recovered from an attack of cardiac insufficiency, it is well to start with a pair of 5-pound bells, the patient sitting on a stool. Two hundred foot-pounds of work are then given either by flexing or extending the bells. The pulse rate and blood pressure are taken every thirty seconds according to the examples given on a preceding page. After the pressure and pulse have returned to the original, 300 or 400 foot-pounds are done in the same way. The work is increased with each experiment until we reach a delayed rise in blood pressure. *The experiment which has caused a delayed rise should always be repeated after a few minutes' rest, with a slightly increased amount of work, for the purpose of confirmation.* When once the amount of work which will produce a distinct delayed rise in blood pressure is ascertained, it is quite remarkable how little the results vary on a repetition of the experiment with the same or increased work. Yet if our test is valid this should be so.

The following examples illustrate this point:

This patient was 64 years old and suffered from aortic regurgitation and cardiac insufficiency.

Time	Pulse Rate	Systolic Blood Pressure
3:45	80	132
160 foot-pounds (10 lb. bell extended 8 times)		
3:46	88	138
:46½	80	134
:47	80	134
:47½	80	132
:48	80	134
:49	80	134
3:55	80	130
200 foot-pounds (10 lb. bell extended 10 times)		
3:56	88	Delayed rise {
:56½	84	
:57	80	
:57½	76	
:58	76	
:59	80	132
4:03	80	130

240 foot-pounds (10 lb. bell extended 12 times)		
4:04	88	136
:04½	84	142
:05	84	138
:05½	80	144
:06	80	144
:06½	76	138
:07	80	144
:08	76	134
:09	76	128
4:13	76	130

Delayed
rise

As a general rule a patient's cardiac capacity will vary but slightly from day to day. If he improves in general condition his cardiac capacity increases, and if he retrogrades it decreases. Lack of sleep or transient infections have very prompt and decided effects on the cardiac capacity, particularly in persons who already have damaged hearts.

The following examples illustrate this point:

July 7 a patient with a mitral lesion and cardiac insufficiency showed the following reaction (he had been able to do between 600 and 900 foot-pounds each day but not more, during the three weeks previous to this date):

Time	Pulse Rate	Systolic Blood Pressure
11:15	92	120
750 foot-pounds in 40 seconds (15 lb. bell, extended 25 times)		
11:16	116	128
:17	104	130
:18	96	128
:19	96	124
:20	96	124
:22	100	124
:23	92	120
900 foot-pounds in 40 seconds (15 lb. bell flexed 25 times)		
11:26	116	138
:27	108	130
:28	96	126
:29	96	116
:30	96	122

On the afternoon of July 7 the patient became very angry, so much so that he "trembled for three hours afterward." That night he slept but a few hours. On July 8 he showed these reactions:

Time	Pulse Rate	Systolic Blood Pressure
11:37	92	124
375 foot-pounds in 20 seconds (15 lb. bell flexed 10 times)		
11:38	104	136
:39	96	136
:40	92	132
:41	90	126
:42	98	130
:43	96	128
:44	92	126
:45	92	122
:46	96	120

560 foot-pounds in 25 seconds (15 lb. bell flexed 15 times)			
11:47	108		120
:48	104		134
:49	104	Delayed rise	134
:50	104		134
:51	100		130
:52	96		124
12:01	96		120
725 foot-pounds in 30 seconds (15 lb. bell flexed 20 times)			
12:03	108		126
:04	104	Delayed rise	130
:05	96		130
:06	100		132
:07	104		130
:08	96		128
:09	92		124
:10	96		120

July 9 he was again able to do 750 foot-pounds and July 30 he did 1,400 foot-pounds in sixty seconds.

Another patient suffering from renal tuberculosis and a stricture, but with a normal heart, had lost much weight and sleep, being obliged to pass urine every hour.

May 11, 600 foot-pounds of work caused a delayed rise in blood pressure. His stricture was then relieved, he began to sleep normally, his appetite returned and he was able to take daily walks. May 21, 1,500 foot-pounds of work were performed before a delayed reaction ensued.

Rarely we find that our results are not unvarying. We have records of one man with a presumably normal heart who showed a very distinct delayed rise with 640 foot-pounds of work performed in twenty-two seconds, and thirty minutes later did not show a delayed rise until about 1,300 foot-pounds of work in twenty-five seconds had been done.

The Testing of Patients Whose Cardiac Capacity Exceeds an Ability to Perform 1,000 Foot-Pounds of Work in 60-90 Seconds.—People with normal hearts, or patients with well compensated heart lesions, afford a more difficult problem in mechanics when their hearts are functionally tested. These people are able to flex or extend heavy dumb-bells until their arm muscles are exhausted and yet the heart muscle will show no exhaustion. That is, no delayed rise in the systolic blood pressure is obtained. Here it is necessary to use more powerful muscles, capable of doing much greater amounts of work, in order to tire the heart. We use in these people the 25-pound steel bar which is lifted from the floor to the shoulder and above the head until the arms are fully extended. Then it is lowered quickly to the floor and raised again above the head. An adult will raise the bar between 6 and 7 feet, performing thus between 150 and 175 foot-pounds with each raising. In addition to the work arising from the bar movement, the raising of the trunk of the body each time from a

stooping to an erect position is equivalent to a certain number of foot pounds. The exact number is very difficult to estimate, but from some comparative experiments we are now carrying out it apparently lies between 40 and 50 per cent. of the body weight. That is, a man who weighs 150 pounds does between 60 and 75 foot-pounds of work each time that he raises his body from a stooping to an erect position.

The testing of these hearts is necessarily at the present time a comparative matter, and we are unable to obtain absolute values, unless we have a bicycle ergometer at our disposal.

One example of these normal cases will be given:

Male, adult, aged 41, weighing 160 pounds, with a normal heart.

Time	Pulse Rate	Systolic Blood Pressure
8:36	68	112
800 foot-pounds (20 lb. bell pushed 20 times)		
8:35½	84	120
:36	72	122
:37	66	120
:38	66	116
:39	66	118
:43	66	110
1,000 foot-pounds (20 lb. bell pushed 25 times)		
8:45	84	124
:45½	72	120
:46	72	112
:47	72	110
:55	66	112
2,400 foot-pounds (approximate) (25 lb. bar lifted 7 feet 10 times)		
8:56½	108	{ 134
:57	84	Delayed? { 136
:57½	66	116
:58	66	114
:59	66	112
3,360 foot-pounds (approximate) (25 lb. bar lifted 14 times)		
9:01	114	{ 136
:01½	84	Delayed? { 138
:02	72	130
:03	76	126
:04	66	114
4,800 foot-pounds (approximate) (25 lb. bar lifted 20 times)		
9:08	120	{ 136
:08½	90	Marked delay { 146
:09	78	136
:10	72	130

SUMMARY

A large number of experiments have been carried out on normal persons and those suffering from cardiac insufficiency to determine the effect of graduated work on the pulse rate and systolic blood pressure. The work was performed by means of a Krogh bicycle ergometer in a few persons and by dumb-bell exercises in the majority of subjects.

It has been demonstrated that a certain form of the curve of systolic blood pressure determined *after* the completion of work is characteristic of an overtaking of the heart's functional capacity.

A tentative explanation has been given of the circulatory physiology of exercise (work).

A practical test for estimating the heart's functional capacity has been described.

It is a pleasant duty to express our thanks to Dr. Horatio B. Williams of the Department of Physiology of Columbia University for his assistance in supervising the experiments conducted with the bicycle ergometer, and for many valuable suggestions made during the course of the work outlined above. Also we are indebted to Mr. R. McIntosh for much help in the experiments with the ergometer.

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