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PROCEDURE TO ASSESS ENERGY EXPENDED DURING A SHORT-PERIOD TASK

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FOREWORD

This study was conducted by the Anthropology Branch and Crew Stations Branch, Human Engineering Division, Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, in support of Project No. 7184, "Human Performance in Advanced Systems," Task Nos. 718408, "Anthropology for Design," and 718405, "Design Criteria for Crew Stations in Advanced Systems." This study covers research performed between May and August, 1964.

The authors acknowledge the invaluable assistance of Major William C. Kaufman, Biothermal Branch, Physiology Division, Biomedical Laboratory, Aerospace Medical Research Laboratories, whose interest and technical advice at critical moments made the entire undertaking possible. Acknowledgement is made also of the assistance of Major E. J. Hatzenbuehler, Cargo Operations Division, Directorate of Flight Test, Deputy for Flight Test, Aeronautical Systems Division, for his conscientiousness in adhering to the strict schedule of the test program and in flying the aircraft maneuvers in accordance with the precise timing required by the test.

The authors are grateful to Mr. Lou Cox, Physical Director of the Dayton Y.M.C.A., for the loan of the rowing machine used during the program and to Captain R. S. Kellogg, Crew Stations Branch, and Dr. C. E. Billings, Ohio State University, for their aid during the initial stages of the program.

This technical report has been reviewed and is approved.

WALTER F. GRETHER, PhD
Technical Director
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ABSTRACT

A procedure was developed to measure the energy expended in a rowing task completed during a 12-second zero-G parabola. The technique was based on completed expired air samples. The subject's expired air was collected under three conditions: (1) 30 seconds of rest, (2) 12 seconds of rowing, and (3) 15 seconds of recovery. The conditions were repeated 10 times, and the subject's expired air was cumulated separately in three bags to obtain, in essence, a 5-minute collection for rest, a 2-minute collection for work, and a 2-1/2 minute collection for recovery. This procedure was replicated in four environments: laboratory, aircraft 1G level flights, aircraft 2G-1G-2G bank maneuvers, and aircraft 2G-0G-2G parabolic maneuvers. The results showed that the body reacted to a change in physical activity and returned to a state of equilibrium much more quickly than previously reported in the literature. The volumes of expired air, oxygen, and carbon dioxide in each condition (rest, work, and recovery) were similar in the four environments, but the specific effects, if any, of the differential gravity levels were negligible and unsystematic.

SECTION I

INTRODUCTION

Determination of man's energy expenditure for tasks of very short duration (a few seconds) has not been necessary for most of the evaluative procedures conducted in the past. Welch et al (ref. 10) report some of the shortest metabolic assessment trials in their 2-minute 45-second tests. The shortest investigated task found in the literature is from Rasch and Burke (ref. 9) who computed the energy expended by a weight-lifter in the performance of a 7-second snatch. One reason for the lack of research in short-duration energy output is that most tasks require minutes to complete, and therefore would naturally fall within the time allowances considered necessary to measure accurately the physiological changes occuring in body functions.

In recent comment, Grodins (ref. 5) shows that some thinking is being applied to the question of how quickly the body reacts physiologically to exercise. Based on data obtained by Dejours, he postulated that:

> "A neural factor must be responsible for the initial increase in ventilation simply because it occurs so rapidly, i.e., well within the shortest relevent circulatory deadtime. A neural factor must operate in the steady state for its abrupt disappearance is the only way to account for the very rapid fall in ventilation when exercise is stopped."

Recently, the subject of man in space has generated interest in the effects that a reduced gravity environment may have on the physiological functions of man in general, and, specifically, on the energy expended during the performance of tasks. For example, Pierson and Rich (ref. 8) studied the oxygen cost of work when man's body weight was not lifted against gravity. Their assessment of energy output was based on exercises totaling 9 minutes in duration. DeBrovner (ref. 3) studied the change in CO_2 output of a subject wearing an inflated pressure suit doing a pullup exercise during 12-second-weightlessness periods, but no traditional energy cost measurements have hitherto been conducted in zero G. Therefore, a test procedure was needed that could evaluate the energy expended during the time period of a zero-gravity parabola. Such a test procedure, involving a rowing task, is described herein.

SECTION II

METHOD

SUBJECT:

Only one subject, 23 years old, was tested because of the requirements which had to be satisfied, i.e., flying orders, complete well-being in zero G, physically healthy, available for six consecutive weeks, and well trained in the test procedures.

EQUIPMENT:

The items used in this test can be classified into two categories:

A. Those used for the collection of air samples (these items are shown in their relative positions in figure 1):

1. Nose clip.

2. Mouthpiece with two 1-way flow valves.

3. Hose, 25.8 inches long, connecting the outlet of the mouthpiece with the inlet to the knife-valve.

4. Knife-valve with 1 inlet and 3 outlets. A high-vacuum silicon sealing substance was used between the plates of the knife-valve to prevent air leaks.

5. Three 200-liter Douglas bags, each with a 2-position petcock — flow into the bag or flow to the outside. The same silicon sealing substance as used in the knife-valve was used in the petcock to prevent air leaks. To collect the subject's expired air, a bag was connected to each outlet on the knife-valve. A fourth bag was used to collect ambient air of the test environment.

6. Rowing machine with two hydraulic oar wells with 35 pounds resistance at each handgrip. The oars were 40.8 inches long, and the oar wells were 46.3 inches from the center line of the seat track. The seat track was 36.0 inches long, and the seat was mounted on coaster wheels on opposing tracks to keep the seat from rising during zero gravity.

7. Restraining straps for the seat and the foot rest.

8. A timer controlled by the experimenter's foot pedal. A second timer controlled by the same foot pedal was mounted on the pilot's instrument panel so that he could precisely time the aircraft maneuvers.

B. Those used in the analysis of the collected air samples:

1. Precision wet-test meter for volume determinations.

2. Lira infrared CO_2 analyzer.

3. Beckman F-3 O_2 analyzer.

4. Vacuum pump.

TRAINING AND RESTRICTIONS:

Initially, the subject acquainted himself with the breathing modifications required by the wearing of the nose clip and mouthpiece. While wearing these items and watching the timer, he practiced the rowing motion such that the rate and intensity of muscular contraction would be as regular as possible. Gordon (ref. 4) emphasizes the importance of the intensity of muscular contraction as a physiological factor in work assessment. This orientation period covered 1 hour of practice a day, 4 days each week for 2 weeks.

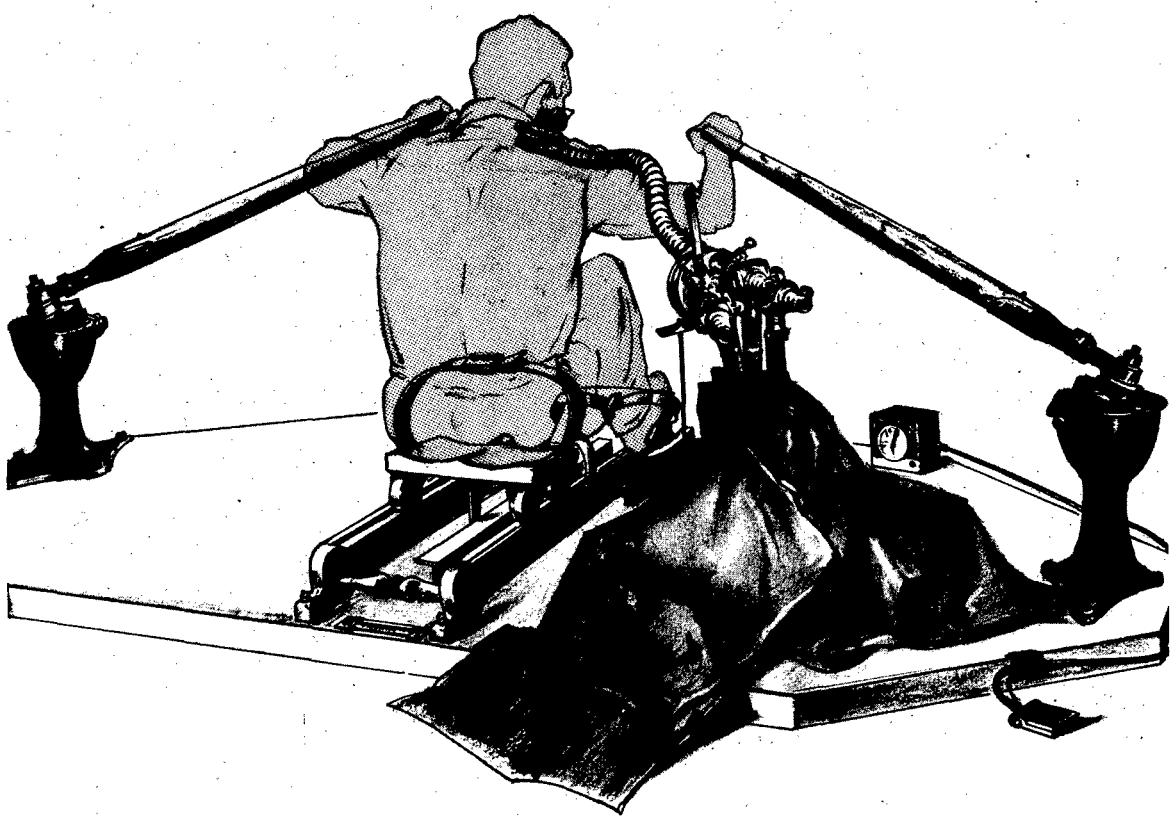

Figure 1. Apparatus Used for Collection of Air Samples.

Secondly, the subject was instructed not to change his then existing level of exercise.

Finally, the subject agreed that during the 6 weeks (2 weeks of orientation and 4 weeks of testing) he would refrain from the use of alcohol and tobacco (he was a nonsmoker), would retire every night before 11:00, and, in general, would maintain a regular regimen. The only dietary requirement was that breakfast consist of only one can of Nutrament approximately 1 hour prior to the test.

PROCEDURE

The subject's expired air was collected during three conditions: (1) 30-second rest condition; (2) 12-second work conditions (rowing at a rate of 30 strokes per minute); and (3) 15-second recovery condition. Preceding each series of these three conditions was a 3-minute period of inactivity for the subject.

The subject sat on the rowing machine seat, the seat belt and footrest strap secured. The oars were forward and up, so that the first stroke would begin in the pull position. Three minutes then were allowed to elapse during which the subject sat in a relaxed manner and made no movements. In the last 30 seconds of these 3 minutes, the subject put on his nose clip, inserted the mouthpiece into his mouth,

and resumed his relaxed posture. At this point in the test procedure, the petcocks on the Douglas bags were still in a flow-through position so that the evacuated bags remained sealed. The inlet opening on the knife-valve was aligned with the outlet opening to which the first bag was attached (see figure 2).

When the 3 minutes had elapsed, the monitor opened the petcock on the first bag and activated the timer(s) by depressing the foot pedal. During the ensuing 30 seconds, the subject's expired air was collected in the first bag, which was referred to as the "resting collection." During this time, the monitor turned the petcock on the second bag, thereby opening the petcock to the knife-valve plate (figure 2).

When the 30 seconds had elapsed, completing the resting condition, the subject immediately reached for the oars and performed six complete rowing motions within the next 12 seconds. As the subject reached for the oars, the monitor turned the knife-valve so that the inlet-opening aligned with the outlet-opening to which the second bag was attached. The subject's expired air was collected in this second bag which was referred to as the "working collection." While the subject was rowing and expiring into the second bag, the monitor turned the petcock on the third bag and reset the petcock on the first bag.

At the end of the 12-second work condition, the monitor turned the knife-valve so that the inlet-opening aligned with the outlet-opening attached to the third bag. During the next 15 seconds, the subject, assuming the same relaxed position as in the rest condition, expired into the third bag, which was referred to as the "recovery collection." During this time, the petcock on the second bag was reset. At the end of this recovery period, the monitor stopped the timer(s), reset the petcock on the third bag, and instructed the subject that the first run was completed.

This sequence of 3 minutes of inactivity for the subject, then a 30-second rest collection, 12-second work collection, and 15-second recovery collection was repeated 9 more times resulting in 10 expired air samples. Thus, for each condition, the 10 air samples were accumulated in its respective bag. This series of 10 runs was repeated during 4 consecutive days for each of four different environments: (1) laboratory, (2) aircraft 1G level flight, (3) aircraft 2G-1G-2G bank maneuvers, and (4) aircraft 2G-0G-2G parabolic maneuvers.[1] Table I shows the test grid of the conditions by the four environments.

A fourth Douglas bag was used to collect ambient air samples during each test period to check the O_2-CO_2 content of the ambient air in the four environments. Each day prior to testing, the 4 Douglas bags (3 for expired air and 1 for ambient air collections) were evacuated by means of a house vacuum line.

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[1] The aircraft 2G-1G-2G bank maneuvers and 2G-0G-2G parabolic maneuvers were flown so that 3 minutes elapsed between each maneuver and that the initial 2G was 30 seconds in duration, the 1G and 0G were 12 seconds in duration, and the final 2G was 15 seconds in duration.

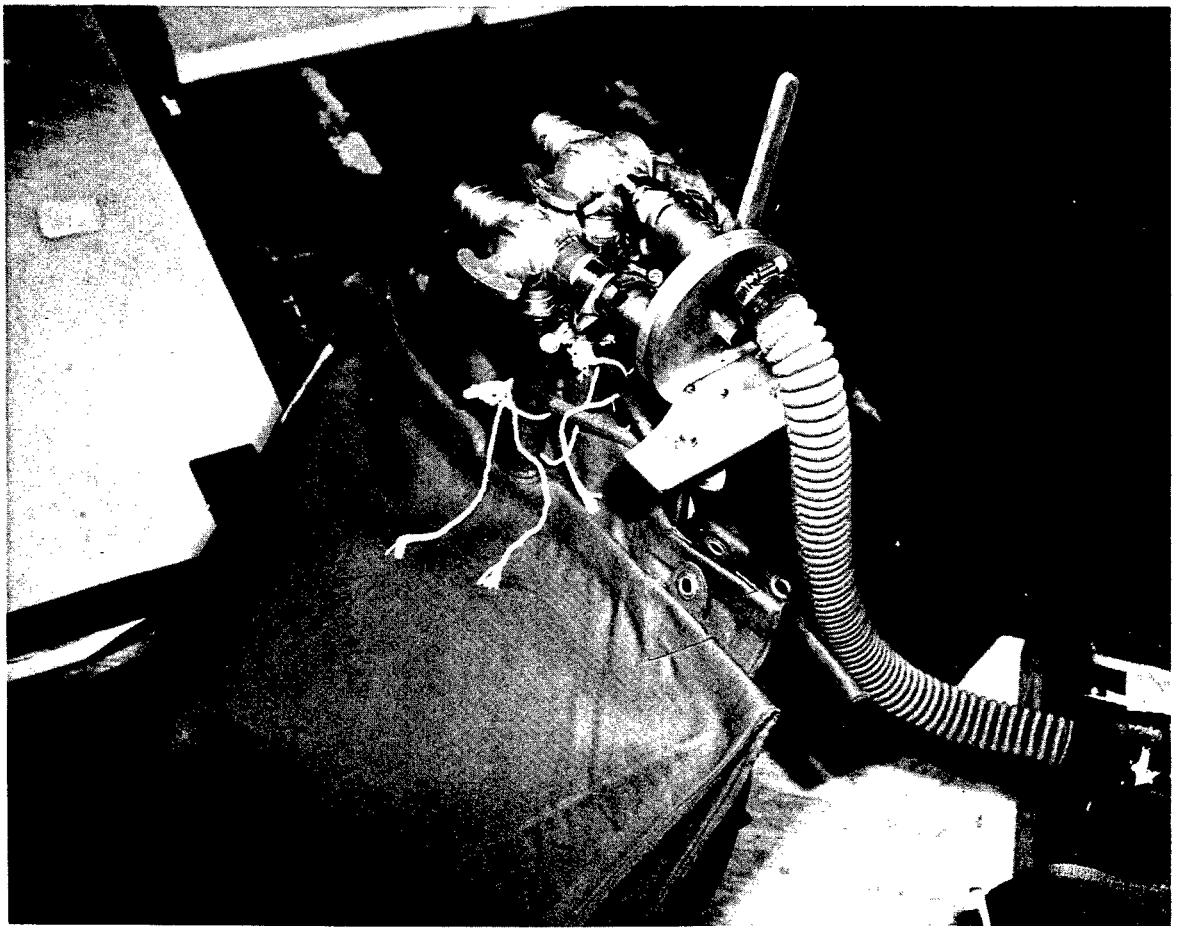

Figure 2. Douglas Bags in Position.

TABLE I

TEST GRID OF THREE CONDITIONS BY FOUR ENVIRONMENTS

	Three Test Conditions			
Environments	Resting No Collection 3 Minutes	Resting Collection* 30 Seconds	Work Collection* 12 Seconds	Recovery Collection* 12 Seconds
1	Laboratory 1G	Laboratory 1G	Laboratory 1G	Laboratory 1G
2	Aircraft 1G	Aircraft 1G	Aircraft 1G	Aircraft 1G
3	Aircraft 1G	Aircraft 2G	Aircraft 1G	Aircraft 2G
4	Aircraft 1G	Aircraft 2G	Aircraft 0G	Aircraft 2G

*10 expired air samples are cumulated so that the total cumulated times for the resting, work, and recovery conditions are 300 seconds, 120 seconds, and 150 seconds, respectively.

The Lira-CO_2 and the Beckman-O_2 analyzers were each calibrated with known concentrations of N, O_2, and CO_2 before each day's collected air samples were subjected to analysis. The analyzers and the wet-test meter were connected in-line, and the air samples were drawn out of each Douglas bag through the analyzers and wet-test meter by a vacuum pump with a flow rate predetermined by the analyzers. The wet-test meter was reset to zero before each air sample was passed through it to alleviate volume error readings caused by subtracting previous amounts.

The concentration readings indicated by the analyzers and the volume readings from the wet-test meter were recorded directly, and the corrections for 1 minute and BTPS* were applied by means of a computer program utilizing the formula by Consolazio (ref. 2):

$$\text{Vol. (BTPS)} = \text{Vol. obs.} \times \frac{273 + 37\,°\text{C}}{273 + \text{temp. obs.}} \times \frac{\text{bar. press} - P_{H_2O} \text{ at temp. obs.}}{\text{bar. press} - P_{H_2O} \text{ at } 37\,°\text{C}}$$

SECTION III

RESULTS AND CONCLUSIONS

Table II presents the individual data for each of the three conditions for the four days in each of the four environments. Each score represents 10 collections.

Table III presents the summary data for each of the three conditions for the four environments. These same data are presented graphically in figure 3. Each score in Table III and in figure 3 represents 40 collections, i.e., the accumulation of the 4 days of collections.

The similarity among the conditions of the four environments are shown in the tables and in figure 3. Part of the reason for this is that the rowing task was hydraulic and therefore was not weight oriented, i.e., the amount of force required on the oars was the same regardless of the environment (gravity level). The specific effects of the environments upon the energy expended are not clear, and it is not within the scope of this report to analyze the interactions critically.

The gross differences of the volume of air, oxygen, and carbon dioxide exchanged in condition 1 (rest) as compared to condition 2 (work) clearly shows that the body reacts more quickly to a change in physical activity than was previously reported (see ref. 1). This difference in expired air samples is also true between condition 2 (work) and condition 3 (recovery). This shows that the body begins to return to a state of equilibrium quickly.

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*Body Temperature and Pressure, Saturated.

TABLE II

INDIVIDUAL DATA*

	VOLUME OF AIR LITERS				VOLUME OF O_2 LITERS				VOLUME OF CO_2 LITERS				RESPIRATORY QUOTIENT† LITERS			
DAY	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
CONDITIONS‡ (Laboratory)																
1	6.15	6.11	4.72	6.13	0.317	0.312	0.238	0.350	0.277	0.292	0.212	0.294	0.87	0.94	0.89	0.84
2	16.76	18.91	11.22	19.83	0.872	0.964	0.595	1.130	0.783	0.936	0.538	0.972	0.90	0.97	0.91	0.86
3	9.85	8.88	7.01	8.41	0.591	0.497	0.428	0.538	0.493	0.438	0.336	0.412	0.83	0.88	0.79	0.77
CONDITIONS‡ (Aircraft Level Flight)																
1	5.70	5.31	8.38	6.14	0.296	0.260	0.376	0.350	0.257	0.199	0.390	0.289	0.87	0.77	1.04	0.82
2	16.00	13.04	14.00	19.87	0.880	0.613	0.683	1.113	0.741	0.476	0.700	0.954	0.84	0.78	1.02	0.86
3	8.64	7.96	10.87	9.67	0.572	0.426	0.601	0.599	0.432	0.357	0.544	0.469	0.76	0.84	0.90	0.78
CONDITIONS‡ (Aircraft Bank Maneuvers)																
1 (2G)	6.91	6.21	7.55	4.60	0.370	0.329	0.353	0.239	0.304	0.289	0.369	0.197	0.82	0.88	1.04	0.82
2 (1G)	17.61	15.10	18.58	16.49	0.912	0.891	0.948	0.944	0.766	0.740	0.929	0.772	0.84	0.83	0.98	0.82
3 (2G)	10.83	7.90	9.70	5.92	0.720	0.498	0.572	0.345	0.536	0.395	0.485	0.258	0.74	0.79	0.85	0.75
CONDITIONS‡ (Aircraft Parabolic Maneuvers)																
1 (2G)	6.97	6.47	5.07	5.54	0.383	0.333	0.258	0.313	0.320	0.300	0.244	0.266	0.84	0.90	0.95	0.85
2 (0G)	15.18	13.38	17.17	16.04	0.850	0.728	1.013	0.934	0.713	0.656	0.858	0.802	0.84	0.90	0.85	0.86
3 (2G)	9.67	9.10	10.51	7.52	0.658	0.572	0.673	0.489	0.493	0.454	0.526	0.357	0.75	0.79	0.78	0.73

*All Volume figures are corrected to 1-minute collections and for BTPS.

†Respiratory Quotient (RQ) is a function of CO_2/O_2.

‡The numbers 1, 2, 3, refer to the conditions - rest, work, recovery, respectively.

TABLE III

SUMMARY DATA*

	VOL. OF AIR LITERS	VOL. OF O_2 LITERS	VOL. OF CO_2 LITERS	RESPIRATORY QUOTIENT† LITERS
CONDITIONS‡ (Laboratory)				
1	5.78	0.304	0.269	0.88
2	16.68	0.889	0.807	0.91
3	8.54	0.514	0.420	0.82
CONDITIONS‡ (Aircraft Level Flight)				
1	6.38	0.321	0.284	0.88
2	15.73	0.822	0.718	0.88
3	9.28	0.550	0.450	0.82
CONDITIONS‡ (Aircraft Bank Maneuvers)				
1	6.32	0.323	0.290	0.89
2	16.94	0.923	0.802	0.87
3	8.59	0.534	0.418	0.78
CONDITIONS‡ (Aircraft Parabolic Maneuvers)				
1	6.01	0.322	0.282	0.88
2	15.44	0.881	0.757	0.86
3	9.20	0.598	0.458	0.76

*All Volume figures are corrected to 1-minute collections and for BTPS.

†Respiratory Quotient (RQ) is a function of CO_2 /O_2.

‡The numbers 1, 2, 3, refer to the conditions - rest, work, recovery, respectively.

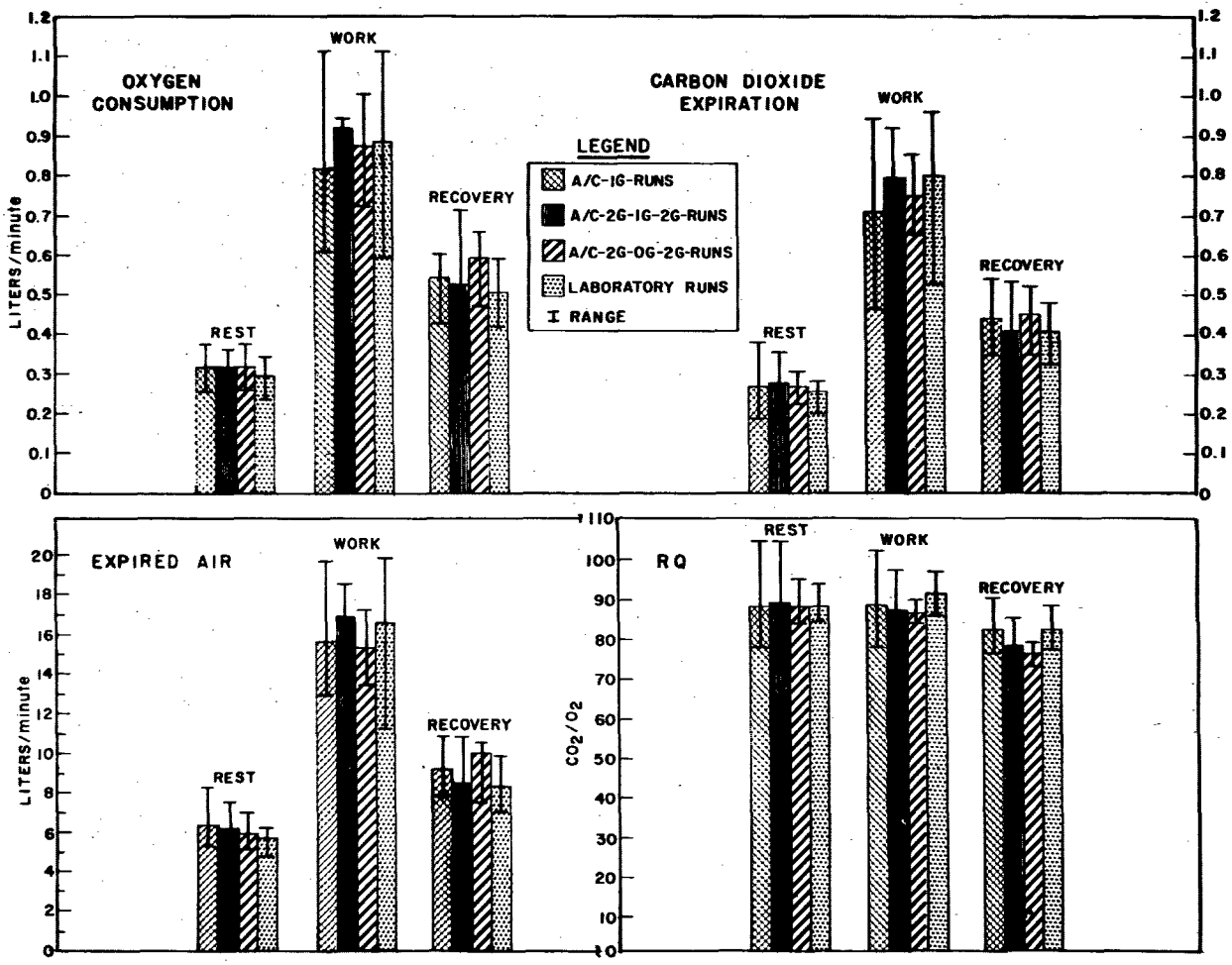

Figure 3. Graphic Summary Data.

A few sources in the literature indicate the possibility of obtaining meaningful energy expenditure data from exercises of less than a minute in duration. Dejours' results quoted in Grodins' article (ref. 5) are presented below in comparison to that of the authors. Grodins asserts that a neural factor is responsible for the quick

Collection Period		Dejours Total Air Expired Liters*	Walk-Sasaki Total Air Expired Liters*
	rest†	7	6
Time	12 sec.†	14	16
	30 sec.†	17	16
	60 sec.	23	20
	120 sec.	30	47

*All figures are corrected to BTPS.

†These data are adjusted to 1 minute

change in expired air noted from the onset of exercise. This could explain some of the similarity in the initial data. The divergence of the 2-minute ventilated air figures in the chart (30 liters for Dejours and 47 liters for Walk-Sasaki) results directly from the difficulty of the respective tasks to the subjects tested.

Dejours' moderate walking experiment rates 4 kcal/min of energy expenditure (ref. 5). Passmore and Durnin (ref. 7) give the range of 3.5 to 4.5 kcal/min for moderate walking (5 km/hr.). Walk-Sasaki obtain a rate of 9 kcal/min (based on a corrected 2-minute collection) for the medium-heavy task of rowing 30 strokes per minute.

Another source of less-than-1-minute energy expenditure evaluation is from Rasch and Burke (ref. 9). Their computed energy expenditure of a 7-second weightlifting snatch is derived by the evaluation of a 1-minute-53-second recovery period required by the subject. These sources, however, do not really develop methods or procedures for universal application to the area of exercise evaluation in general.

We can calculate the amount of physical work done in our experiment

$$W = F \times D \times f$$

where:

W = work

F = force

D = distance

f = frequency in strokes per minute.

Using the following values:

force = 70 lb (35 lb for each of two oars)

distance = 1.5 ft (travel per stroke)

frequency = 30 strokes per minute

we find the physical work to be:

$$W = 70 \times 1.5 \times 30 = 3150 \text{ ft lb.}$$

Applying the formula for mechanical efficiency found in Rasch (ref 9):

$$ME = \frac{W \times 100}{O_2 \times 15{,}000}$$

where:

W = work in ft lb

O_2 = liters of oxygen consumed

15,000 = the calorific equivalent of oxygen in ft lb/liter.

and the following values:

W = 3150 ft lb

O_2 = 0.880 liters consumed per minute

we find the mechanical efficiency to be:

$$ME = \frac{3150 \times 100}{0.880 \times 15{,}000} \quad 23.9\%$$

Since there is no directly comparable yardstick for evaluating the results derived from the rowing test described herein, the authors contend that comparability with accepted values lends validity to the results. Guyton (ref 6) states accepted values of human efficiency as ranging from 20% to 25%, values that compare very favorably with our measured value of 23.9%. Experimentation with groups of subjects will be necessary to prove positively the accuracy of our method for determining energy expenditure for short tasks.

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13. ABSTRACT

A procedure was developed to measure the energy expended in a rowing task completed during a 12-second zero-G parabola. The technique was based on completed expired air samples. The subject's expired air was collected under three conditions: (1) 30 seconds of rest, (2) 12 seconds of rowing, and (3) 15 seconds of recovery. The conditions were repeated 10 times, and the subject's expired air was cumulated separately in three bags to obtain, in essence, a 5-minute collection for rest, a 2-minute collection for work, and a 2-1/2 minute collection for recovery. This procedure was replicated in four environments: laboratory, aircraft 1G level flights, aircraft 2G-1G-2G bank maneuvers, and aircraft 2G-0G-2G parabolic maneuvers. The results showed that the body reacted to a change in physical activity and returned to a state of equilibrium much more quickly than previously reported in the literature. The volumes of expired air, oxygen, and carbon dioxide in each condition (rest, work, and recovery) were similar in the four environments, but the specific effects, if any, of the differential gravity levels were negligible and unsystematic.

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