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During prolonged space missions, man is exposed to a broad spectrum of deleterious factors, among them--weightlessness. In recent years, numerous studies attest to the possibility of considerable physiological changes during weightlessness (1, 2, 3, 4, 5, 6, 7, 8, 9).

Weightlessness can elicit manifold changes in the various functional systems thereby producing definite deviations in metabolism and in thermal balance, both factors affecting proficiency.

In studying the impact of weightlessness on man as well as adaptation and compensation thereto, gas metabolism provides an integral index of the body's functional state. Gas metabolism reflects fully the dynamia of changes occurring within the body. Specifying optimal environments within a space cabin wherein man may be partly dependent upon a closed metabolic, ecological system (1, 11) and in spacesuits during EVA requires knowledge of median and optimal O_2 demand and CO_2 elimination.

Gas metabolism studies are essential for solving many theoretical, practical, and prognostic questions in astronautics.

To date, literature provides insufficient scientifically grounded data to determine the metabolic requirements under zero gravity.

Some researchers (12, 13, 14) cite increased work energy expenditure during weightlessness in performing a given task. Berry (1966) reported that the median energy expenditure of astronauts on "Gemini-9 and 10" ranged from 91.7 to 94.4 kcal/hr. Berry emphasizes that the majority of American astronauts ("Gemini-4, 9, 10, 11") feels that a task performed during EVA is four times more difficult than when performed on Earth in a spacesuit.

Other authors (6, 16, 15) theorize that metabolic changes occurring during weightlessness ranging from several minutes to several hours fall within the physiologic norm.

A. M. Genin et al., in 1965 (17), concluded that space flight effects man's energy expenditure only slightly. These studies were based on postflight analysis of regenerated substances as well as changes in O_2, CO_2, and H_2O concentration in the space cabin. According to their data, the mean energy expenditure per hour in these flights was: for A. G. Nikolayev--85.8 kcal/hr, for P. R. Popovich--97.2 kcal/hr, for V. V. Tereshkova--83.5 kcal/hr, and for V. F. Bykovskiy--84.6 kcal/hr.

These authors hypothesize that prolonged space missions will elicit a decrement in the basic metabolic indices.

In the paper at hand, data are presented (1963-1966) concerning the functional state of pulmonary ventilation, gas metabolism, and energy expenditure during brief Keplerian trajectory flights to simulate zero-gravity. During such flights, recordings were made of respiratory rate, tidal air volume, and pulmonary ventilation. Grab samples of expired air were taken. Analyses were conducted along the lines of the generally accepted Douglas-Haldane method and with the aid of the miniature spiro-anemometers "Rezeda-2 and 3". These devices have a feature facilitating grab sampling of expired air with subsequent analysis thereof in a Haldane apparatus. Gas metabolism volumetric computations were made at STPD, and for pulmonary ventilation--at BTPS. In three series of experiments, 58 flights were performed involving 55 test subjects ranging from 22 to 46 years of age.

In the first series of experiments (7 flights), the test subjects were required to remain seated for the entire flight. The results showed that all test subjects experienced stepped-up gas metabolism during brief zero-gravity relative to baseline data. The zero-G gas metabolism indices also exceeded those recorded during intra-trajectory acceleration. Gas metabolism and energy expenditure data for the test subjects during parabolic trajectory flight are presented in Table 1.

The table shows the O_2 minute demand during weightlessness to be increased from 75 to 215 ml above baseline values. Similarly, energy expenditure increased by 0.36-1.0 kcal/min, and respiratory minute volume in six tests exceeded baseline values by 0.4-4.2 ℓ/min, and in one instance by 0.3 ℓ/min.

In a second series of experiments conducted with the spiro-anemometer "Rezeda-2", 36 flights were made of which 21 involved grab sampling the expired air. In addition to pulmonary respiration, gas metabolism, and energy expenditure studies in these experiments (9 flights), seven flights were conducted during which the subjects performed a specific physical, isometric tension exercise, and five flights involved a specific work output (100.8 kgm).

In Table 2 are presented gas metabolism indices for test subjects at rest (sitting) during brief weightlessness and during horizontal flight (baseline data).

As seen from Table 2, in all experiments of the second series--as in the first--weightlessness elicits an increment in gas metabolism indices to a point higher than those recorded during horizontal flight. Thus, the O_2 minute demand during weightlessness exceeded baseline recordings by 32-236 ml, and energy expenditure indices similarly by 0.16-1.08 kcal/min.

Statistical analysis of the data gathered from 24 flights (Table 3) showed pulmonary ventilation during brief weightlessness to be higher than during horizontal flight by 4.6 ℓ/min. Similarly, respiratory rate increased by 2.1 cycles/min and tidal volume increased by 400 ml. Respiratory cycle profile alteration was also noted during zero-gravity.

Gas metabolism study involving test subjects performing isometric tension exercises (Figure 1) showed pulmonary respiration, gas metabolism, and (thus higher) energy expenditure indices to be more greatly displaced when the exercise was performed during weightlessness than during horizontal flight. For test subjects under zero-G whose [rest] pulmonary ventilation increased by an average of 4.6 ℓ/min, the same index increased by 11.7 ℓ/min during the isometric exercise, and 16.6 ℓ/min after performing the assigned quantity of work. O_2 demand during weightlessness increased correspondingly: an average of 134 ml/min at rest, 185 ml/min under isometric tension, and 291 ml/min while performing work. Energy expenditure during weightlessness increased over that recorded during horizontal flight: by 39 kcal/hr at rest, by 55 kcal/hr under isometric tension and by 83.4 kcal/hr with performance of work.

Considerable individual fluctuation during brief weightlessness when performing one and the same isometric exercise is significant.

Energy expenditures of the same test subject varied widely from one [parabola] apex to the next and from one flight to the next. Energy expenditure involving one and the same activity varies widely relative to age, body weight, training and intensity of the work performed. It should be emphasized that when work is performed in special dress, changes in gas metabolism and energy expenditure were even more pronounced. Thus, for example, test subject S. working in normal clothing displayed increased pulmonary ventilation during weightlessness which exceeded horizontal flight recordings by 17.1 ℓ/min, but the same work performed in a special suit brought an increase of 22 ℓ/min. O_2 demand increased in the first instance by 207 ml/min, in the second by 533 ml/min. Energy expenditure increased by 83 and 153 kcal/hr respectively. In experiments of the third series (15 flights) involving the spiroanemometer "Rezeda-3", energy expenditures were computed for the magnitude of pulmonary ventilation (using the Ford-Hellerstein formula, 1959).

Analysis of our experimental results has shown that changes in respiratory rate, pulmonary ventilation and energy expenditure--as in both preceeding test series--were more pronounced during brief zero-G (Table 4). Thus, pulmonary ventilation during horizontal flight increased over baseline values from 11.15 to 11.51 ℓ/min, during intratrajectory acceleration up to 12.92 ℓ/min, and during weightlessness up to 14.18 ℓ/min. Correspondingly, energy expenditure increased from 2.35 to 2.50 kcal/min; during acceleration to 2.75 kcal/min, and during weightlessness to 2.98 kcal/min.

In this manner, the experimental findings bore witness to the uniformity of changes in pulmonary ventilation, gas metabolism, and energy expenditure during weightlessness, independent of the experimental methods employed.

The fact that gas metabolism and energy expenditure are more intense during weightlessness than during horizontal flight or G-loading leads to the conclusion that zero-G can greatly effect the human body. Cosmonaut energy expenditure in the space cabin or spacesuit--especially during EVA-- will greatly exceed that recorded during brief zero-G or on earth. Thus, determining the energy expenditure required for various operations by the cosmonaut in space is of paramount significance.

Figure 1

Variation in Pulmonary Ventilation, Gas Metabolism, and Energy Expenditure Indices with Subjects at Rest (I), under Isometric Tension (II) and Working (III).

1--horizontal flight 2--Zero-gravity 3--after flight

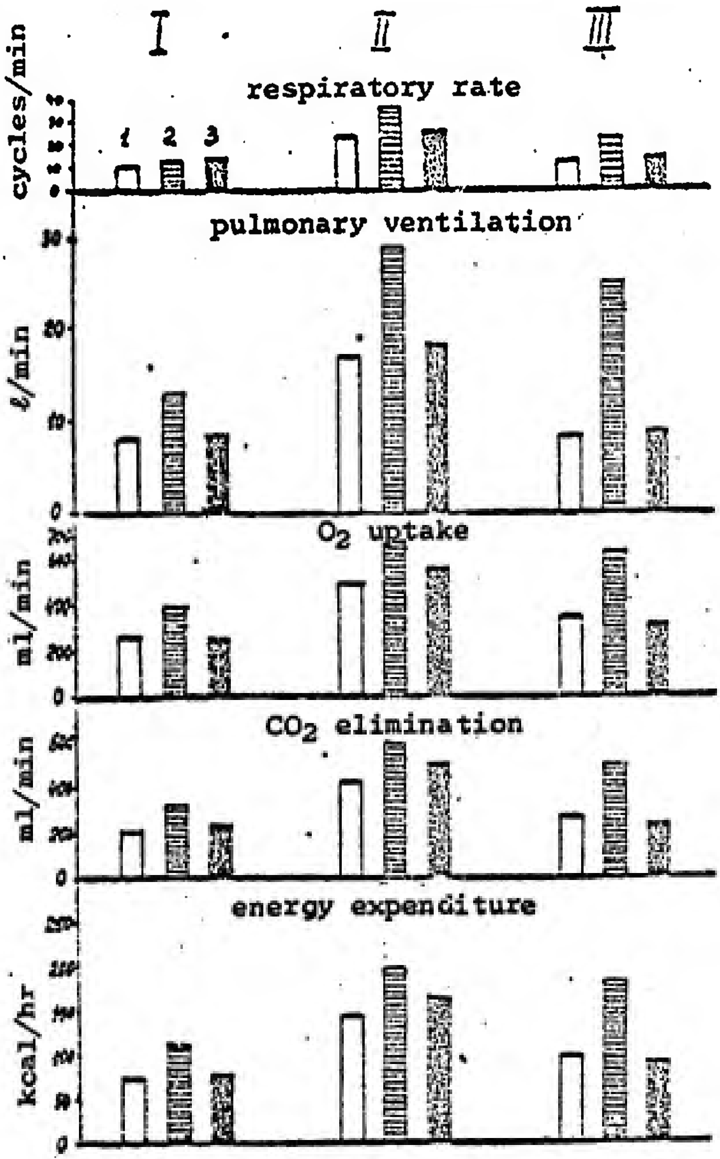

Table 1

Douglas-Haldane data (at rest; Keplerian trajectory)

Test Subject	Flight No.	Mode, ℓ/min*			O_2 Demand, ml/min**			Energy Expenditure, kcal/min		
		Base-line	Zero-grav.	G-loading	Base-line	Zero-grav.	G-loading	Base-line	Zero-grav.	G-loading
N-v	18th	9.5	13.7	9.1	320	533	326	1.54	2.54	1.57
N-v	23rd	7.9	10.3	8.5	300	383	314	1.43	1.84	1.49
Sh-ts	15th	9.4	10.8	9.6	337	428	368	1.58	2.05	1.76
Sh-ts	16th	9.5	9.2	8.2	292	391	333	1.40	1.87	1.61
Sh-ts	18th	9.2	9.9	8.3	277	352	304	1.34	1.80	1.50
D-v	3rd	9.4	11.4	8.8	280	393	300	1.35	1.91	1.46
B-v	25th	9.1	10.8	9.5	279	395	308	1.33	1.86	1.47

* - at BTPS

** - at STPD

Table 2

O_2 Demand and Energy Expenditure of Test Subjects at Rest during Various Phases of Parabolic Trajectory Flight ("Rezeda-2" recordings)

Test Subject	O_2 Demand, ml/min			Energy Expenditure, kcal/min		
	Before Flight	Zero-grav.	Difference	Before Flight	Zero-grav.	Difference
V-o	274	306	+ 32	1.32	1.48	+0.16
G-n	254	432	+178	1.21	2.14	+0.93
G-v	330	549	+219	1.54	2.62	+1.08
Zh-v	227	465	+238	1.12	2.20	+1.08
K-yan	214	325	+111	1.07	1.61	+0.54
K-in	233	434	+201	1.15	2.09	+0.94
K-yan	230	252	+ 22	1.09	1.19	+0.10
K-yan	256	283	+ 27	1.22	1.33	+0.11
K-yan	366	546	+180	1.77	2.65	+0.88

Calculations at STPD

Table 2

Table 3

Keplerian Trajectory Changes in Pulmonary Ventilation with Subjects at Rest ("Rezeda-2" data)

Statistical Indices		Pulmonary Ventilation Indices		
		Mode, ℓ/min	Resp. frequency cycles/min	Tidal vol., ml
Arithmetic mean M + m (24 cases)	Preflight	8.0 ± 2.19	11 ± 2.79	3000 ± 436
	Zero-grav.	13.0 ± 2.72	13 ± 3.76	4200 ± 702
Mean difference (Xm) M mean error (in diff.) before flight and during Zero-G		4.65 ± 0.534	2.1 ± 0.65	400 ± 98.4
reliability criteria (t)		8.7	3.3	5.2
probability (P)		0.001	0.01	0.001

Calculations at BTPS

Table 4

Respiratory Rate, Pulmonary Ventilation, and Energy Expenditure of
Keplerian Trajectory Flight ("Rezeda-3" dat

Statistical Indices	Baseline data			Horizontal Flight			G-loading			Zero-G		
	Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Ene Exp itu
M	10.3	11.15	2.3576	9.7	11.51	2.5095	10.4	12.92	2.7517	10.5	14.18	2.
σ	2.18	3.13	0.5701	3.56	2.78	0.7746	3.30	3.43	0.6000	4.04	3.16	0.
C%	24.2	28.14	23.2	36.4	24.2	33.1	31.8	26.9	21.8	38.2	22.4	18.

A

Table 4

ntilation, and Energy Expenditure of Subjects Recorded During
ian Trajectory Flight ("Rezeda-3" data)

G-loading			Zero-G			G-loading			Horizontal Flight		
Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Energy Expenditure	Resp. Rate	Pulmonary Vent.	Energy Expenditure
10.4	12.92	2.7517	10.5	14.18	2.9766	10.4	13.15	2.8036	10.2	11.28	2.4779
3.30	3.43	0.6000	4.04	3.16	0.5385	3.17	4.27	0.7416	3.20	30.68	0.6403
31.8	26.9	21.8	38.2	22.4	18.2	30.5	32.5	26.53	31.6	32.7	26.05

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