Comparison of ground-based and space flight energy expenditure and water turnover in middle-aged healthy male US astronauts[1–3]

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ABSTRACT Energy requirements during space flight are poorly defined because they depend on metabolic-balance studies, food disappearance, and dietary records. Water turnover has been estimated by balance methods only. The purpose of this study was to determine energy requirements and water turnover for short-term space flights (8–14 d). Subjects were 13 male astronauts aged 36–51 y with normal body mass indexes (BMIs). Total energy expenditure (TEE) was determined during both a ground-based period and space flight and compared with the World Health Organization (WHO) calculations of energy requirements and dietary intake. TEE was not different for the ground-based and the space-flight periods (12.40 ± 2.83 and 11.70 ± 1.89 MJ/d, respectively), and the WHO calculation using the moderate activity correction was a good predictor of TEE during space flight. During the ground-based period, energy intake and TEE did not differ, but during space flight energy intake was significantly lower than TEE; body weight was also less at landing than before flight. Water turnover was lower during space flight than during the ground-based period (2.7 ± 0.6 compared with 3.8 ± 0.5 L/d), probably because of lower fluid intakes and perspiration loss during flight. This study confirmed that the WHO calculation can be used for male crew members' energy requirements during short space flights. *Am J Clin Nutr* 1997;65:4–12.

KEY WORDS Energy expenditure, space flight, doubly labeled water, dietary intakes

INTRODUCTION

Energy expenditure of individuals has not been measured previously during space flight. The National Aeronautics and Space Administration (NASA) uses the World Health Organization (WHO) calculations, which are based on sex, age, weight, and moderate activity levels, to calculate the energy needed by space crew members (1), but the accuracy of these estimates has not been confirmed. Simulated microgravity (horizontal or head-down bed rest) has been used to model space flight for the purpose of studying energy metabolism; these models have included assessments of the intake-balance (2–4) and doubly labeled water (DLW) (4) methods. In one such study (4), energy expenditure during bed rest was significantly lower than during an ambulatory control period. The energy utilization associated with physical activity in microgravity is unknown, and the relatively close confines of the spacecraft tend to limit the extent of physical activity. Ambient temperature and humidity are held relatively constant at 21–24 °C and 20–30%, respectively. Movements are clearly different in microgravity because there is no need to work against the gravitational vector.

Some evidence also suggests that energy requirements during flight could be greater than previously expected. Urinary cortisol concentrations remained elevated in seven crew members during Space Shuttle flights (5), a finding suggestive of stress. Stein et al (6) reported changes in protein turnover during Shuttle flights that are consistent with a stress condition. Stress is known to increase energy utilization, at least during short periods. How the combination of increased stress and limited physical activity might affect energy expenditure is unknown.

Estimates of energy requirements for space flight have relied on results from metabolic-balance studies conducted during the relatively long (28-, 59-, and 84-d) Skylab missions (7), or recorded food intake during the shorter Apollo (8) and Space Shuttle (9, 10) missions. Energy utilization in the Russian space program is calculated from a combination of change in body mass and carbon dioxide production in flight (11). The accuracy of intake methods outside of clinical research centers as a way of predicting energy expenditure has been questioned, especially without precise and accurate measurements of body composition (12, 13). Nonetheless, we contend that energy intake can be a good predictor of energy expenditure for space flight because the only food available to Space Shuttle crews during flight is provided as coded individual portions. Thus, food intake can be estimated fairly accurately from crew members' food logs, the disappearance of food from galley storage (subtracting that which is thrown away), and changes in body weight before compared with after flight.

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Although a crew member's hydration status affects his or her ability to adapt to microgravity (4), dehydration and negative fluid balance have been found consistently (5). The minimum water intake recommended by NASA for US Space Shuttle crews is 2000 mL/d, although water turnover has not been measured during space flight. Water intake is directly related to energy intake in space, because rehydrated food and fruit drink rations provide 80% of fluid intake (14).

The purpose of this study was to determine energy intake and expenditure and water turnover in healthy men during short space flights. Total energy expenditure (TEE) was calculated with a modified DLW protocol, from records of food and fluid intake (4), and from WHO calculations (1).

SUBJECTS AND METHODS

Subjects

The subjects were 13 healthy male crew members who flew on 8–14-d Space Shuttle missions between 1992 and 1994. All US astronauts have extensive physical examinations annually and immediately before and after flight. None smoked or had any history of chronic disease, and all were healthy throughout the experimental period. The subjects' characteristics are listed in **Table 1**. Body mass index (BMI; in kg/m^2) for all subjects was between 22 and 28. The type and amount of physical activity recorded for subjects during the ground-based and in-flight test periods is given in **Table 2.** This study was approved by the NASA Human Research Policy and Procedures Committee at Johnson Space Center, and written informed consent was obtained from each subject.

Protocol

Each subject completed two test sessions, one before flight and the other during flight. The ground-based session was completed ≈2 mo before launch to allow the DLW dose to "wash out" before the mission. This timing also allowed subjects to maintain their typical levels of physical activity, because crew members are quarantined for several days before flight and tend to be more sedentary than usual during that time. The flight study began on the second or third day of flight to avoid any confounding effects from motion sickness.

Before consumption of the DLW dose, baseline urine and saliva samples were collected after an overnight fast. Saliva and urine samples were collected either 5 h (ground-based) or 4–7 h (flight) after dosing. For the next 4–6 d fasting, ground-based urine samples were collected every morning whereas in-flight urine and saliva samples were collected immediately after the daily sleep period and before breakfast. Urine was collected on the last day of flight. Body weight was determined at the beginning of the ground-based study, 2 d before launch, and on landing day. Before the studies all dose and specimen containers were individually labeled for each crew member.

TEE was determined with a modified DLW procedure during the ground-based and flight sessions. The potable water on board the US Space Shuttle is frequently enriched with deuterium and ^{18}O. Expressed as delta standard mean ocean water (DSMOW) values, the deuterium enrichment varied from −67.15 to 176.86 with a mean (± SD) of 12.68 ± 85.9 during flight compared with a ground-based value of −22.75 ± 6.39. The ^{18}O enrichment (expressed as DSMOW) was always greater in Shuttle water (32.70 ± 1.88) than in ground-based water (−2.93 ± 0.99). Because this enriched Shuttle water was the primary dietary water source (80% of dietary water), the DLW procedure was modified with the following changes (15) and the use of a baseline correction (16).

As illustrated in **Figure 1**, the source of the enriched Shuttle water was the Shuttle fuel of hydrogen and oxygen gas, which are used to produce the potable water. Before launch, the fuel cell hydrogen and oxygen isotope enrichments were determined, and these data were used to predict the potable water deuterium and ^{18}O concentrations. When the fuel cells were elevated in hydrogen and/or oxygen isotopes, a loading dose of deuterium and/or ^{18}O was given to each crew member before launch to raise the body water enrichments close to that of the potable water isotope enrichment. During the preflight ground-based period the subjects' mean ^{18}O and deuterium (DSMOW) values were −22.8 ± 10.49 and −1.60 ± 1.38, respectively. Dosing the subjects with ^{18}O and/or deuterium before flight

TABLE 1
Subject characteristics

Subject	Length of flight	Weight	Height	Age	BMI	FFM[1]
	d	*kg*	*cm*	*y*	*kg/m²*	*kg*
1	8	75.6	170.0	47	26.2	53.5
2	8	70.0	173.5	43	23.3	55.4
3	9	70.9	177.8	51	22.4	52.8
4	9	73.6	172.7	42	24.7	54.5
5	9	80.0	185.4	36	23.3	60.5
6	9	82.4	180.3	46	25.3	55.3
7	11	77.7	173.5	48	25.8	52.3
8	11	77.0	183.5	42	22.9	60.3
9	11	86.8	188.0	44	24.6	66.9
10	14	84.2	186.8	42	24.1	58.4
11	14	73.2	179.1	37	22.8	63.4
12	14	68.6	172.8	50	23.0	52.0
13	14	86.4	177.9	38	27.3	61.6
$\bar{x}$	10.8	77.4	178.6	43.5	24.3	57.5
SD	2.4	6.2	5.9	4.8	1.5	4.8

[1] Fat-free mass, calculated from total body water.

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TABLE 2
Physical activity of male US astronauts during a ground-based study and a flight study[1]

Subject	Ground-based study	Flight study
1	Ran (4 mi in 32–35 min each) and calisthenics and weights (20 min each), 2 times in 5 d; ran (4 mi in 32 min) and weights (30 min), 1 time in 5 d	Ergometer, 3 times in 6 d, 15–20 min each
2	Ran (3 miles each) and calisthenics (30 min each), 3 times in 5 d	Ergometer, 2 times in 6 d, 20 min each
3	None recorded	Treadmill, 1 time in 5 d, 20 min total
4	None recorded	Treadmill, 4 times in 7 d, 15–37 min each
5	Biked, 2 times in 5 d, 30 min each	Ergometer, 5 times in 7 d, 26–30 min each
6	Ran (4.2 mi in 32 min each) and walked (15 min each), 3 times in 5 d; plus swam (60 min), 1 time in 5 d; plus calisthenics, 1 time in 5 d	Ergometer, 5 times in 7 d, 30–33 min each
7	Ran, 2 times in 6 d, 2.5 mi each	Treadmill, 3 times in 9 d, 60 min each
8	Weights (10 min) and jogged (16 min), 1 time in 5 d	Ergometer, 7 times in 8 d, 120 min each
9	Weights (45 min), 1 time in 6 d; ran (25 min), 1 time in 6 d; biked (20–30 min each) 2 times in 6 d; ran (26 min) and weights (10 min), 1 time in 6 d	Ergometer, 7 times in 8 d, 20–90 min each
10	Ran, 2 times in 5 d, 30–60 min each	None recorded
11	Ran (4 mi in 30 min), swam (0.5 mi in 20 min), calisthenics (10 min), 1 time in 5 d; ran (4 mi in 32 min), biked (10 min), and weights (15 min), 1 time in 5 d	Ergometer, daily for 5 d, 25 min each
12	Ran (3–4 mi each) and weights (15 min each), 2 times in 6 d; ran, 2 times in 6 d, 3.5–4 mi each	Ergometer with a bungee cord—3 times, 52–65 min each; ergometer, 6 times in 12 d, 34–40 min each
13	Ran (4–4.2 mi each at 8 min pace), 2 times in 5 d; cross-country skiing machine (20–30 min each), 2 times in 5 d	Ergometer, 6 times in 12 d, 34 min each

[1] 1 mile = 1.6 km.

changed their body water on day 3 of flight to a mean value of 4.66 ± 41.52 and 21.30 ± 2.84 DSMOW, respectively. This minimized changes in deuterium and ^{18}O baseline during the flight study period. Astronauts flying on the same Shuttle flights as the subjects were control subjects (not participating in TEE study). They consumed the preflight deuterium and/or ^{18}O dose to enrich their body water to the concentrations predicted to be found in the Shuttle potable water. Dosing before flight reduced the difference in isotopic abundances between baseline body water and drinking water during flight (**Figure 2**).

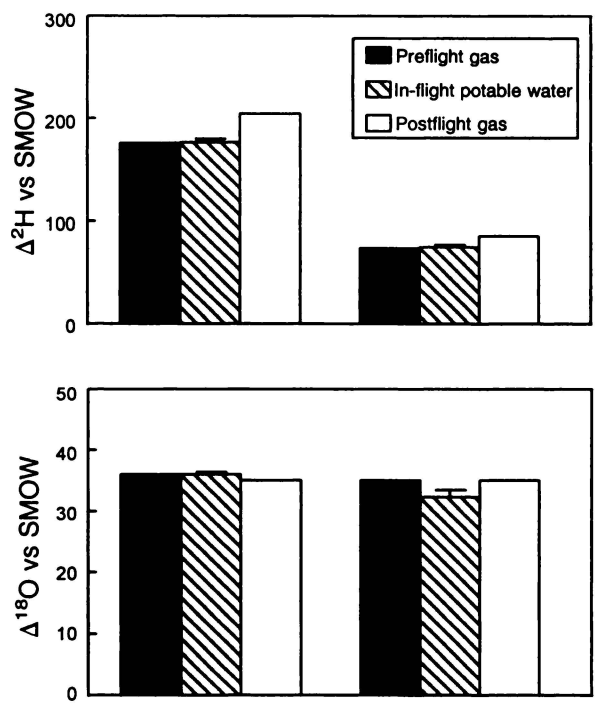

FIGURE 1. Examples of Shuttle gas and water enrichment for two missions. SMOW, standard mean ocean water.

The second means of minimizing the effects of varying enrichments in the potable water involved the DLW dose that was given for the TEE measurements. The dose for the flight study was twice as high as that given for the ground-based study, and this reduced the relative effects of changes in baseline that were due to the enrichment of the Shuttle potable water (16). Oral doses were given as follows: ground-based dose, 10% $H_2{}^{18}O$ (Isotec Inc, Miamisburg, OH) mixed with 99.8% ^2H_2O (Icon Services, Summit, NJ), at 2.5 g $H_2{}^{18}O$ and 0.12 g ^2H_2O/kg total body water (TBW); the flight dose was 5.0 g $H_2{}^{18}O$ and 0.24 g ^2H_2O/kg TBW. The exact time of dosing was recorded for each subject.

Diets

All crew members ate their usual diet during the ground-based study. Each subject was given a digital balance (which weighed to 0.1 g), verbal and written instructions, and a diet log, on which was recorded the food consumed, the method of preparation, the quantity, and the time and date of consumption. Exercise and drugs taken were recorded as well. Each crew member weighed all of his foods and fluids for the 5-d test period and provided brand names and recipes. Any food remaining after meals was weighed and the final weight of all foods consumed was recorded. A research dietitian worked with each crew member to maximize the accuracy of the diet records.

Crew members selected their flight menus after consultation with the Shuttle program dietitian. All space foods are packaged as individual servings (14), with each package having a

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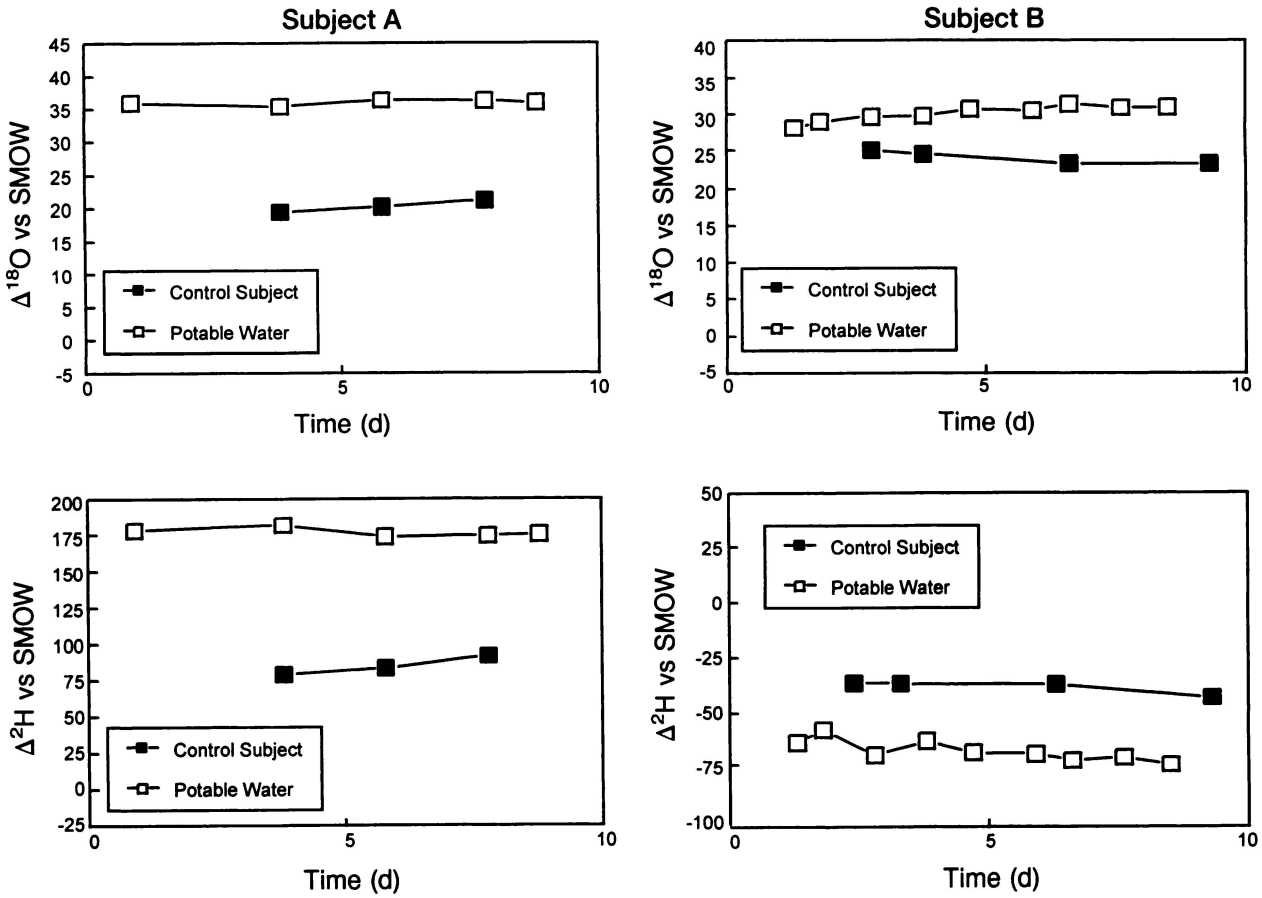

FIGURE 2. Isotope enrichments of two control subjects during two different flights. Time 0 indicates launch day. SMOW, standard mean ocean water.

unique bar code. Hand-held bar code readers were used to track all food and fluid intake and to record estimates of the percentage of each serving consumed, as well as the time and date of consumption. After each flight, the remaining food containers—including those in the trash—were inventoried and the results used to verify the crew's diet logs. More than 90% of the diet records were verified from returned food and trash. All space foods were analyzed at the Johnson Space Center for nutrient content, and nutrient consumption was calculated for each individual from these results. The US Department of Agriculture database (17) was used to calculate the nutrient content of the ground-based foods. Food quotients (FQs) were calculated for each individual from that person's diet records (*see* below).

Specimen collection and analysis

During the ground-based study, urine samples were collected in clean, dry cups; during flight, urine was collected in enclosed bags, a method feasible only for men. TEE was calculated from urine measurements except for subjects 5 and 6. During one 9-d flight (subjects 5 and 6), a urine monitoring system was available on board to obtain void volumes from both men and women. However, this system was rinsed twice between voids with the potable Shuttle water, thus contaminating ensuing voids. Thus, saliva was used for both TBW and TEE measurements for these two subjects. Subjects collected saliva samples before and during flight by placing dried dental cotton rolls in their mouths for 2 min. No foods or fluids were consumed during the 30 min before saliva collection (18). NASA has used ^{18}O enrichment in saliva to measure TBW in the past (5), primarily because urine specimens are difficult to obtain in microgravity. The exact times of all specimen collections were recorded for each subject.

During flight, urine specimens were packaged in double polyethylene bags with zipper-lock mechanisms and were stowed, with the saliva samples, at ambient temperature in a locker separate from the DLW dose containers. The used DLW dose containers were resealed, restowed, and returned for quantification of the residue. The specimens were removed from the Shuttle and prepared for analysis within hours of landing. Samples from the ground-based study were handled similarly. The dental cotton was centrifuged to obtain saliva. The urine was filtered with charcoal (4) and frozen immediately at −20 °C. Baseline (before-dose) urine, 1 void/d for 5 d, along with the last urine collection was used for the isotope analysis. Multiple specimens were analyzed to eliminate concerns about the unknown effects of the changes in body-water distribution characteristic of space flight (5) on the TEE calculations (19).

Deuterium was analyzed with a Finnigan MAT DELTA (Bremen, Germany) stable-isotope mass spectrometer as follows. Water was vacuum-distilled and reduced over zinc (19).

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Deuterium analyses were performed in triplicate; SDs ranged from 1.5‰ for enrichments < 200‰ to 4.5‰ for enrichments approaching 2000‰. Oxygen samples were analyzed with a Finnigan MAT 251 stable-isotope mass spectrometer. The carbon dioxide equilibration method was used for measuring ^{18}O. A 1.5-mL sample was dispensed into a 7-mL evacuated container and the tube filled with 99.9% pure CO_2. Samples were then shaken in a water bath at 25 °C for ≥ 12 h, and the carbon dioxide was cryogenically removed and stored in 6-mm break-seal tubes for mass spectrometry (20, 21). The reproducibility of this method in our laboratory is generally better than 0.05% (21).

The isotope turnover rates and zero-time dilution spaces were calculated from the slope and intercept, respectively, of the semilogarithmic plot of isotope enrichment versus time after dosing. Elimination rates were corrected for changes in drinking water enrichment by substituting each subject's measured background abundance of deuterium and ^{18}O with the predicted, equilibrated background abundance calculated from the isotopic abundance and intake of drinking water, food, and air during the mission (16, 22, 23). Water turnover was calculated from the deuterium elimination rate as follows (24):

$$\text{Water turnover} = \text{TBW} \times \text{deuterium elimination rate} \quad (1)$$

where TBW was determined from the zero-intercept of the deuterium and ^{18}O linear regression. The dilution spaces of ^{18}O and deuterium were calculated with the assumption that they are 0.7% and 4.1% larger, respectively, than TBW (25). Metabolic water was calculated from the 5-d dietary mean for protein, fat, carbohydrate, and alcohol consumption.

Dilution spaces of $H_2{}^{18}O$ and ^2H_2O were calculated from the following equation:

$$N\,(\text{mol}) = (WA/18.02a) \times (\delta_a - \delta_t)/(\delta_s - \delta_p) \quad (2)$$

where N is the pool space, W is the amount of water used to dilute the dose, A is the amount of dose administered, a is the dose diluted for analysis, and δ is enrichment of the dose (a), tap water (t), peak enrichment (s), and before-dose baseline (p). Peak enrichment was calculated from the zero-time intercept of the isotope enrichment curves. Elimination rates were calculated by using the enrichment above the measured baseline for the ground-based period and the predicted baseline at equilibrium for the space-flight period (16). The space-flight baseline was predicted from mass balance based on the measured potable water (16).

The rates of carbon dioxide production were calculated from the following equation:

$$\text{Rate of } CO_2 \text{ production (mol/d)} = (N/2.078)(1.007k_O - 1.041k_H) - 0.0246r_{Gf} \quad (3)$$

where N is the average dilution space calculated from the time zero dilution spaces of $H_2{}^{18}O$ and ^2H_2O; k_O and k_H are the turnover rates of ^{18}O and deuterium, respectively; and r_{Gf} is the water lost by fractionation, which is estimated as $1.05N(1.007k_O - 1.041k_H)$.

Oxygen consumption was derived by dividing the carbon dioxide production rate by each crew member's FQ (26):

$$\text{FQ} = [(710.71P) + (1377.06F) + (746C) + (973A)] \div [(879.06P) + (1948.34F) + (746C) + (1461A)] \quad (4)$$

where P, F, C, and A are protein, fat, carbohydrate, and alcohol intakes expressed as g/d.

TEE was calculated from de Weir's equation 12 (27). Fat-free mass was calculated by dividing TBW by 0.732 (28).

Statistical analysis

Each crew member was his own control, and the ground-based assessment was the control period. One-way repeated-measures analysis of variance was used to identify any differences between energy intake and expenditure in the ground-based and flight periods and the WHO determination of energy requirements. The Student-Newman-Keuls test was used for post hoc comparisons. Paired t tests were used to detect any differences in dietary intake between the ground-based and in-flight periods. TEE was corrected for body weight and fat-free mass, and was tested similarly to detect differences between reported intake and expenditure. Statistical analyses were performed with SAS (SAS Institute, Cary, NC) and SIGMASTAT (Jandel Scientific Software, San Rafael, CA). Values are expressed as means ± SDs.

RESULTS

Energy intake and TEE for each crew member during the ground-based and in-flight periods are listed in **Table 3**. Although ground-based energy intake for eight subjects seemed less than the TEE for that period, the difference between the two was not significant (11.38 ± 2.06 MJ/d intake and 12.40 ± 2.83 MJ/d expenditure). The largest difference between individual intake and expenditure was 6.88 MJ/d with a mean difference of −1.02 MJ/d. The correlation between ground-based reported intake and TEE was 0.45 (NS); correcting TEE with body weight or fat-free mass made no difference in the statistical comparisons. No difference was found between TEE and the WHO-calculated energy requirement. Within this data set, there was one subject that had low TEE (no. 2) and one that had high TEE (no. 13). Subject 13 obviously had a very active lifestyle with a large lean frame. There is no explanation for the low value for subject 2.

During flight, energy intake (8.76 ± 2.26 MJ/d) was less than flight TEE (11.70 ± 1.89 MJ/d; $P < 0.005$). The intake-TEE difference for individuals varied from 5.60 to 0.69 MJ/d; six subjects had intake deficits > 4 MJ/d. Correcting TEE with body weight or fat-free mass did not affect differences between intake and TEE or WHO-calculated energy expenditure. Body weight was less at landing than at 2 d before launch (76.45 ± 6.13 compared with 77.94 ± 5.97 kg, respectively; $P < 0.05$). No correlation was found between weight loss and energy deficit ($r = 0.10$). Intake and TEE were positively correlated ($r = 0.72$, $P < 0.01$) during the flight study.

No differences were found between ground-based and in-flight energy expenditures, nor were differences found between flight TEE and the WHO calculations. Ground-based TEE was slightly higher than flight TEE for eight subjects; however,

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TABLE 3
Energy intake and expenditure before and during space flight

Subject	Ground-based study			Flight study			
	Calculated energy requirement (WHO)[1]	Reported intake	Expenditure	Calculated energy requirement (WHO)[2]	Reported intake	Expenditure	Weight change[3]
		MJ/d			*MJ/d*		*kg*
1	12.49	10.68	13.64	12.40	7.64	13.24	1.0
2	12.03	10.43	7.60	12.10	5.10	8.30	−3.9
3	12.10	12.17	12.91	12.09	5.49	11.24	−1.6
4	12.32	11.41	9.24	12.52	8.78	11.03	−3.0
5	12.85	12.68	13.65	12.98	7.83	11.42	−1.1
6	13.05	9.03	13.34	13.17	7.80	11.75	−1.9
7	12.66	8.08	7.79	12.89	7.28	8.19	−1.0
8	12.61	10.56	13.20	12.63	9.16	12.08	−0.7
9	13.42	13.97	13.09	13.15	11.24	13.30	0.0
10	13.20	13.55	13.93	13.11	9.84	13.57	−2.6
11	12.29	15.18	14.60	12.46	13.29	14.46	−0.7
12	11.92	9.47	10.70	11.88	10.02	10.71	−1.4
13	13.38	10.68	17.51	13.49	10.35	12.81	−2.5
$\bar{x}$	12.64	11.38	12.40	12.68	8.76[4]	11.70	−1.5
SD	0.51	2.06	2.83	0.49	2.26	1.89	1.3

[1] Calculated from body weight measured at the beginning of the ground-based study.
[2] Calculated from body weight measured 2 d before launch.
[3] Weight change from 2 d before launch to landing day.
[4] Significantly different from WHO determinations of energy requirement, ground-based and flight energy expenditure, and ground-based energy intake, $P < 0.001$ (repeated-measures ANOVA).

four subjects had higher TEEs during flight than before. Between-subject variance tended to be lower during flight than before and was not accounted for by the recorded physical activity levels.

Other dietary variables calculated from the diet histories are listed in **Table 4**. Ground-based fat intake was ≤ 30% of energy intake for 5 of the 13 crew members; fat intake was never > 40% of energy intake for any of the crew members. Five subjects consumed alcohol during the 5-d ground-based test session; for subjects 4 and 7, alcohol constituted > 5% of their energy intake during that time. Alcohol is not allowed on US space flights. Total carbohydrate intake declined during space flight (374 ± 10 g/d before compared with 309 ± 85 g/d during flight; $P < 0.05$). This decrease resulted from the overall decrease in energy intake during flight; the percentage of energy from carbohydrates was higher during flight than before ($P < 0.05$). All subjects met their protein requirement during both test periods.

Ground-based water intake (from food and fluids) ranged from 2408 to 3597 mL/d, amounts that fulfilled the NASA fluid recommendation. Total water intake was significantly less during flight (2153 ± 538 mL/d) than before (2697 ± 351 mL/d) ($P < 0.05$). When water intake was calculated in terms of energy consumed, flight amounts were no different from ground-based amounts, indicating that the lesser fluid intake during flight was due to the lesser food intake. Six subjects did not meet the recommended minimum fluid intake during flight. Calculated metabolic water was significantly higher during the ground-based study than during the flight study: 371 ± 67 and 285 ± 73 mL/d, respectively, by paired *t* test ($P < 0.05$).

Water turnover was calculated for each crew member from the deuterium elimination rates during the two test periods (**Table 5**). During space flight, water turnover was significantly less than before flight (2731 ± 610 compared with 3768 ± 509 mL/d, respectively; $P < 0.05$). Water turnover during flight was less than during the ground-based study for every subject.

DISCUSSION

For space flight, the important conclusion from this study is that energy expenditure for 13 men during short space flights was nearly identical to that measured in a 5-d ground-based period. During the ground-based test period, crew members carried out their normal activities, which included various levels of exercise. During flight, the environmental conditions (temperature and humidity) were more uniform, as were physical activity levels, which may explain the small variability between subjects during flight relative to the ground-based study. The WHO calculation produced nearly exact estimates of energy needs on the ground, but seemed to overestimate them slightly during space flight. For healthy, physically fit men, the WHO calculation can be used to predict energy expenditure during flights up to 14 d. TEE during flight (11.70 ± 1.89 MJ/d) for subjects in this study was similar to that from a metabolic-balance study conducted with nine Skylab crew men (12.88 ± 1.53 MJ/d) (7, 9). Energy expenditure calculated from food disappearance and carbon dioxide production in space ranged from 8 to 11 MJ/d for six Shuttle flights (9).

The ground-based TEE in this study (12.40 ± 2.83 MJ/d) was lower than that reported from studies of younger men (aged 19–36 y), whose TEE was ≈14 MJ/d (29–34). Two other studies (35, 36) of older men (mean ages 53 and 68 y, respectively) found TEE to be 10–11 MJ/d. Both the mean age and TEE for the astronauts in the present study were between those studies. However, many variables aside from age can affect TEE, eg, physical activity level and lean body mass. The

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TABLE 4
Dietary measures before and during space flight

	Intake									
	Water		Carbohydrate		Fat		Protein		Alcohol	
Subject and study	Per day	Per energy	Per day	Per energy	Per day	Per energy	Per day	Per energy	Per day	Per energy
Ground-based study	*g/d*	*g/kJ*	*g/d*	*% kJ*	*g/d*	*% kJ*	*g/d*	*% kJ*	*g/d*	*% kJ*
1	2575	0.24	371	58	95	33	80	13	0	0.0
2	2408	0.23	330	53	98	35	83	13	0	0.0
3	2457	0.20	453	62	71	22	95	13	5	1.2
4	2443	0.21	321	47	108	36	118	17	0	0.0
5	2776	0.22	443	59	98	29	98	13	0	0.0
6	2416	0.27	245	45	91	38	67	12	24	7.9
7	2576	0.32	190	39	66	31	82	17	44	15.8
8	2779	0.26	310	49	94	34	113	18	0	0.0
9	3240	0.23	501	60	101	27	115	14	0	0.0
10	2512	0.19	395	49	133	37	110	14	8	1.7
11	2571	0.17	572	63	114	28	99	11	0	0.0
12	2708	0.29	391	69	39	15	87	15	5	1.6
13	3597	0.34	346	54	89	31	102	16	0	0.0
$\bar{x}$	2697[1]	0.24	374[1]	54[1]	92[1]	31	96[1]	14[1]	7	2.2
SD	351	0.05	103	8	23	6	16	2	13	4.6
Flight study										
1	2179	1.19	289	63	41	20	76	17		
2	1750	1.43	206	68	28	20	39	13		
3	1511	1.15	214	65	42	29	34	10		
4	1724	0.82	286	54	71	30	79	15		
5	1745	0.93	274	58	57	27	71	15		
6	1443	0.77	246	53	63	30	80	17		
7	2049	1.18	246	57	57	29	65	15		
8	1951	0.89	282	51	74	30	101	18		
9	2716	1.01	398	59	77	26	105	16		
10	2577	1.10	367	62	61	23	85	15		
11	2652	0.83	514	65	81	23	100	13		
12	2476	1.03	365	61	74	28	73	12		
13	3219	1.30	328	53	96	35	80	13		
$\bar{x}$	2153	1.05	309	59	63	27	76	15		
SD	538	0.20	85	5	19	4	21	2		

[1] Significantly different from flight values, $P < 0.05$.

astronauts studied here may represent American men of similar ages who have sedentary occupations, routine leisure-time exercise, and normal body weight.

Because astronauts must maintain glycogen stores and muscle mass for potential emergencies during landing and egress from the Space Shuttle, the reduction in flight energy intake was disturbing. The crew members could have underreported their food intake during flight (12); however, this seems unlikely in light of the accuracy with which ground-based intake was reported. Another reason to doubt that intake may have been underreported (12) is the way in which space foods are packaged and inventoried after landing. Because all space foods, including beverages, are provided as individual, coded portions, and because all containers are brought back from flight (food unused and used), both the amounts of food consumed and the amounts remaining can be assessed, and the amounts checked against the diet logs recorded by the bar code reader. The close agreement of all these data implies that the flight dietary records in this study were accurate.

We sought to validate the accuracy of flight intake by calculating changes in body weight and comparing them with differences in intake and expenditure. The difference between intake and expenditure was -2.94 ± 1.60 MJ/d. By using weight loss, corrected for mission duration, and assuming that the energy density of fat is 39.75 MJ/kg and that of fat-free mass is 4.18 MJ/kg (4), the calculated mean energy deficit was 4.67 ± 4.95 MJ/d. This suggests that these results cannot be explained by underreporting, although individual weight loss was not correlated with individual energy deficit during flight.

Interpretation of the changes in body weight during space flight is confounded by the countermeasure that requires crew members to consume fluid with salt tablets (equivalent to 1 L normal saline) during deorbit. Thus, 1 kg body weight at landing may reflect this "fluid load." During two space flights, six crew members measured their TBW and body mass during flight as well as on landing day (5). In that study, only one crew member had lost > 1 kg body weight at landing (relative to preflight body weight) and the other five had slightly higher TBW at landing than during flight. Thus, the weight loss observed at landing could reflect loss of tissue or combined loss of water and tissue. Only measures of body composition during flight and at landing can elucidate the exact nature of these weight changes.

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TABLE 5
Water turnover as measured by deuterium elimination[1]

Subject	Ground-based study	Flight study
	mL/d	
1	3628	2014
2	2979	1734
3	3330	2201
4	3492	2746
5	4315	2712
6	3766	2473
7	3745	2853
8	3053	2575
9	4364	3419
10	4388	2624
11	3991	3066
12	3459	2967
13	4477	4120
$\bar{x}$	3768	2731
SD	509	611

[1] Mean ground-based water turnover was significantly higher before than during flight, $P < 0.05$.

Random errors in TEE during flight may also have led to a reduction in the correlation between individual estimates of energy balance and weight change. In ground-based studies, the DLW method has an analytical uncertainty of 4.5% (15) at standard isotope loading doses. For the larger doses used in this flight study, the uncertainty should have been reduced to 3.5%. The effects of the unusual isotopic composition of the Shuttle water consumed by the astronauts during flight, however, probably degraded the precision of the DLW method. In a ground-based validation study in subjects consuming water that simulates the unusual isotopic composition of Shuttle water, we showed that excellent precision could be obtained after subjects began to equilibrate with the Shuttle water. As shown in Figure 2, however, the flight was too short for equilibration to occur. To correct for the effects of Shuttle water on the baseline, we used a method of predicting the equilibrium baseline values based on isotope mass balance (16). This method of predicting the baseline was shown to give TEEs that were accurate on a group basis, but individual uncertainties were large (16). Although it is difficult to theoretically estimate what the individual uncertainty would be for the astronauts in flight, the repeat-measure study design allows calculation of the within-subject CV for the change between ground-based and space-flight TEE. The within-subject CV was 12%, which indicates that the individual uncertainty was no worse than 12%.

Reductions in energy intake have been well documented on short flights in the Apollo and Shuttle programs (8, 9, 37). Intakes were adequate during the longer Skylab missions, undoubtedly because metabolic diets were enforced and high-quality foods were provided (7). The question remains as to whether reduced energy intake during flight is somehow characteristic of short flights, and is corrected later during longer ones. Alternatively, it may have to do with the food quality. The consistent finding of low in-flight dietary intake remains a problem in terms of providing adequate energy during space flight.

As was found in previous US space flights (9), the relative proportions of energy shifted during flight, with that from carbohydrate increasing, protein remaining stable, and fat declining. This finding has been consistent over several types of space food systems (9, 10, 37). The adequacy of protein intake was consistent with previous assessments of ad libitum food intake during flight (10). Fat consumption was within recommended amounts.

Water turnover was slower during flight than before, and can be partially accounted for by significantly lower intake of fluids and metabolic water production during flight. Another contributor to this difference could be water lost through perspiration during the ground-based period, because most of the astronauts exercised outdoors in Houston. Although perspiration was not assessed in the current study, this possibility is supported by results from Skylab that showed an 11% mean decrease in perspiration water loss during heavy exercise in flight relative to that associated with the same exercise in Houston (38). However, water turnover could be expected to increase if water intake were adequate. Given the bone resorption and high urinary calcium concentrations during space flight, water intake must be sufficient to eliminate ion loads and decrease the risk of kidney stone formation (39).

In conclusion, results from this study have shown that the amount of energy needed for 8–14-d space flights is similar to that needed for ground-based activities, and that the WHO calculation using moderate activity is a reasonable way of estimating energy requirements for men on short space flights. Future studies are needed to determine whether these results are related to the cost of physical activity in space or to long-term stress that raises resting energy expenditure.

We appreciate the time and cooperation of the astronauts who participated in this study. David Leestma, Director of Flight Crew Operations, provided practical assistance in planning and implementing the flight study. Barbara Rice was the research dietitian for the study; Vickie Kloeris and members of the Lockheed-Martin Engineering and Science Services provided invaluable assistance with the flight foods; and Sandra Prow programmed the bar code reader and trained the astronauts.

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