Energy Expenditure and Water Turnover Assessed by Doubly Labeled Water during Manual Work in a Dry and Warm Environment

William J. Tharion1), Reed W. Hoyt1), Alana D. Cline1), James P. Delany2) and Harris R. Lieberman1)

1) U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760
E-mail: william.tharion@na.amedd.army.mil
2) Pennington Biomedical Research Center, Baton Rouge, LA 70808
(received on July 5, 2003, accepted on October 18, 2003)

Abstract

Objective: During training and other strenuous physical activity in the mountains, deserts, and other wilderness areas, those consuming pre-packaged rations or take-along-food often have difficulty maintaining adequate energy, water and electrolytes, and carbohydrate intakes. This study assessed the effects of ad libitum consumption of a carbohydrate beverage supplement (8% maltodextrin sweetened with aspartame) on energy and carbohydrate intakes of physically active test volunteers. Methods: Energy and carbohydrate intakes of volunteers randomly assigned to receive either a carbohydrate beverage supplement (CHO) (n=32) or a non-caloric placebo beverage (PLACEBO) (n=31) during an 11-day field training exercise were assessed. Mean total energy expenditure (TEE), water turnover (RH2O), and total body water (TBW) were measured in a sub-group of volunteers (CHO: n=10, PLACEBO: n=9) using the stable isotopes 2H2O and H2 18O. Results: The CHO group had greater daily energy intake (EI CHO: 12.8±0.6MJ/day; EI PLACEBO: 11.0±0.8 MJ/day; p<0.05) and carbohydrate intake (CHO: 470±139g/day; PLACEBO: 317±68g/day; p<0.05). No differences were observed in TEE (TEECHO: 18.41±4.40 MJ/day; TEEPLACEBO: 16.12±2.70 MJ/day), TBW (TBW-CHO: 46.9±5.5 L; TBWPLACEBO: 44.5±3.3 L) or water turnover (R H2O—CHO: 5.6±1.1 L/day; R H2O—PLACEBO: 5.1±0.7 L/day) between groups. Discussion: Providing a carbohydrate beverage may reduce energy and CHO deficits that commonly occur during recreational treks or in those working for extended periods in wilderness environments.

Key words: Carbohydrate Supplementation, Energy Intake, Physical Exercise, Sports Drinks

Introduction

Individuals participating in field operations such as firefighting (Ruby et al., 2002) mountaneous/arctic expeditions (Pulfrey and Jones, 1996) and military field training (Friedl, 1995) usually have energy expenditures (EEx) that far exceed their energy intakes (EIs), even though mission requirements, types of activities, environmental conditions, body size, and amount of load carried vary widely. For example, typical EIs in military field training average 11.9 MJ/day (1 MJ=239 kcal), while average total energy expenditures (TEEs) are about 18.0 MJ/day (Baker-Fulco, 1995). With rare exception, the energy needs of physically active workers in the field are not met by dietary intake, regardless of take-along-food availability (Friedl and Hoyt, 1997). Potential reasons for this negative energy balance include: not wanting to carry the food, lack of water, menu boredom, poor acceptability of the food, and decreased appetite (Kramer, 1995; Kramer et al., 2001; Popper et al., 1989). Furthermore, those deployed to the field such as soldiers or those on arctic expeditions often live and work for long periods in very austere environments. In contrast, Tour de France cyclists maintained energy balance over 22 days in spite of TEEs of 29.3 MJ/day (Hammond and Diamond, 1997; Westerterp et al., 1986). Although these cyclists engaged in sustained strenuous exercise, they could eat on-the-move, readily obtain water and flavored caloric beverages, and in the evenings had ready access to hot palatable food and conventional indoor sleeping quarters (Hammond and Diamond, 1997; Westerterp et al., 1986). While these cyclists often race under harsh environmental conditions they do not live in (are not exposed to) those environments.

Negative energy balance in the field is accompa-
nied by a difficulty maintaining adequate dietary carbohydrate intake. Carbohydrate reserves constitute only around 2% of the body’s energy reserves (Sahlin, 1986). The typical carbohydrate intake of soldiers in the field is only about 300 g/day (Friedl and Hoyt, 1997). This carbohydrate intake is far short of the 500–600 g/day minimum needed for glycogen resynthesis when engaged in endurance exercise (Ivy, 1991). Personnel working in field environments often have activities that are intermittent and strenuous. Since it takes time to mobilize, transport, and use fatty acids, the muscle metabolic demand for carbohydrate can be high (Stein et al., 1989).

The purpose of this study was to determine energy, carbohydrate, and fluid requirements of physically active individuals working in a warm dry desert environment and determine whether providing a carbohydrate beverage supplement would improve carbohydrate and energy intakes. The results of this study will presumably also pertain to wilderness treks where take-along-food may not meet one’s nutritional needs.

Methods
The test volunteers consisted of 63 Marines participating in a physically demanding training exercise in a warm dry desert environment. The overall average maximum daytime and minimum nighttime temperatures and associated relative humidities were 27°C and 16%, and 14°C and 35%, respectively. The days were sunny with solar radiation averaging 800 W/m². Daily wind velocities ranged between 7 and 25 km/hr.

These test volunteers (mean±standard deviation notation used throughout) were 22.6±3.5 yrs of age, 179.3±8.2 cm in height, and weighed 76.8±8.1 kg, with an initial percent body fat of 19.7±3.7%. Volunteers were briefed on the purpose, risks, and benefits of the study and gave their written informed consent. This study was approved by the Scientific and Human Use Review Committees at the U.S. Army Research Institute of Environmental Medicine and the U.S. Army Medical Research and Materiel Command. Volunteers were randomly assigned in a double-blind manner to one of two experimental groups, receiving either a carbohydrate beverage (CHO) or a similarly flavored non-caloric beverage (PLACEBO). Energy expenditures were measured by doubly labeled water (DLW) over 11 days in a subset of 19 volunteers (10 in the CHO and 9 in the PLACEBO group) (Figure 1).

Field training activities consisted of equipment setup on Day 1, followed by 10 days of physically active training including bouts of repetitive lifting of 45 kg of weight. Other routine manual work that included cleaning various vehicles, fixing broken equipment, running, and doing calisthenics.

**Total energy expenditure, body fluids and physical activity assessments**

The DLW technique used to measure TEE followed previously described methods (DeLany et al., 1989; Hoyt et al., 1994; Schoeller, 1988). On Day 0, volunteers supplied baseline saliva and first morning urine samples and had their body weights recorded. They had not consumed anything orally for the previous 12 hr. Volunteers then drank 0.22 g/L estimated total body water (TBW) of H₂¹⁸O (Isotec, Miamisburg, OH) and 0.16 g/L estimated TBW of H₂¹²O.

<table>
<thead>
<tr>
<th>Day</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotopic Water Dosing*</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saliva Samples</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urine Samples</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Food Intake Record</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Body Weight</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Composition</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Day 0 dosing with H₂¹⁸O + H₂O; Day 12 dosing with H₂¹²O

Figure 1. Schedule of tests.
Costill (1989) as follows: measurements using equations developed by Barr and Stein lost. ages consumed and the amount of body fat and protein compositions of the rations and beverages, was calculated from the fuel quotient, which reflects both food intake and en- tope tracers (DeLany et al., 1989). The metabolic ground isotope abundances in three test volunteers (2 and 18O were corrected for the changes in back- test beverage) calculated as: (fraction of total fluid intake attributable to test beverage) \times (preformed dietary water intake). Preformed dietary water intake was estimated from water turnover (\( R_{H2O} \)) calculated from \(^2\text{H}_2\text{O} \) elimination, as described previously (DeLany et al., 1989; Hoyt et al., 1994). Isotope elimination rates for \(^2\text{H} \) and \(^18\text{O} \) were corrected for the changes in background isotope abundances in three test volunteers (2 from the CHO group and 1 from the PLACEBO group) who were given tap water rather than the isotope tracers (DeLany et al., 1989). The metabolic fuel quotient, which reflects both food intake and energy store combustion, was calculated from the macronutrient compositions of the rations and beverages consumed and the amount of body fat and protein lost.

Water requirements were calculated from the EE measurements using equations developed by Barr and Costill (1989) as follows:

\[
\text{Energy Expended as Heat Loss} = (1 - \text{Mechanical Efficiency}) \times \text{TEE}, \quad (1)
\]
\[
\text{Fluid Loss as Water Vapor (in L)} = (\text{Energy Expended as Heat Loss} \times 1 \text{ L of Water Vapor})/2.43 \text{ MJ}. \quad (2)
\]

The mechanical efficiencies of exercise of 20% (Barr and Costill, 1989; Sidossis et al., 1992) and 23.8% (Sidossis et al., 1992) were used.

Activity monitors (Actigraph model AMA-32C, Precision Control Design, Inc., Fort Walton Beach, FL) worn on the non-dominant wrist were used to monitor activity patterns. The output (zero crossing of the monitor’s piezoelectric motion) of the sensor was recorded in continuous 1 min intervals. Activity was differentiated from inactivity using an existing algorithm (Cole et al., 1992).

Descriptions of test beverage and field rations

The carbohydrate beverage was 8% maltodextrin, with 0.015% aspartame and 0.273% lemon flavoring. The placebo beverage had the same levels of aspartame and lemon flavoring as the carbohydrate beverage. Volunteers were instructed to consume only the beverage they were assigned. All volunteers were fed a military heat-and-serve ration. The ration, com- posed of fresh and semi-perishable foods, was de- signed to feed groups of people in field environments when standard food service facilities are available. All food preparation was overseen by researchers to ensure compliance with recipes, to record any deviations, and to validate the contents of the heat-and-serve ration. This heat-and-serve ration averaged 5.0 MJ/meal for breakfast and 6.2 MJ/meal for lunch and dinner. Volunteers typically consumed this group ra- tion at breakfast and dinner, and a Meal, Ready-to-Eat (MRE) field ration for lunch. The MRE is an in- dividual meal containing mainly thermo-processed (wet pack) food components, which require no prepa- ration except for reconstitution of beverages. There are 12 menus available, each containing an entree, crackers, a spread, cold beverage powder, a dessert, and an accessory packet. Each meal had a gross weight of about 0.68 kg and contained about 5.4 MJ of energy (King et al., 1993).

Dietary Intake

While away from the field kitchen and dining area, volunteers used individual dietary log cards to record daily consumption and the type and amount of fluid consumed. Transparent canteens with graduated markings were provided to facilitate monitoring of fluid intake. Upon returning to the central feeding area, trained dietary technicians went over each log card with the volunteer to resolve any discrepancies. This included asking about unusually large amounts of food recorded, meals not recorded, and inquiring about portion sizes that were shown on the log cards.

At the central feeding site, individual ad libitum consumption of food and fluids was recorded using a visual estimation method (Rose et al., 1987). Techni- cians were responsible for estimating and recording the amount of food and fluids, including water, served to each individual and the amount returned. Portion sizes were compared with a pre-weighed sample of each food item. Nutrient and energy con- tent of each food item was calculated using a computer program that used standard nutrient data for in- dividual ration components and commercial food products provided by the manufacturers and standard food tables from the U.S. Department of Agriculture (2000). A detailed description of the nutrient intakes and nutrition status of these volunteers is published (Cambridge Isotope, Andover, MA). Total body water was estimated as (body weight–fat weight) \( \times 0.73 \) (Schoeller and van Santen, 1982). Percent body fat was estimated from the sum of 4 skinfolds accord- ing to the Durnin and Womersley (1974) equation for men ages 20–29 yrs of age. Body composition and body weight were measured in all volunteers. An additional 50 ml of tap water, used to rinse the dose containers, was also consumed. Saliva samples were obtained 3 hr and 4 hr after DLW ingestion to deter- mine TBW (Schoeller, 1988). At the end of the 11- day field exercise, a second dose of 0.16 g/L estimated TBW of \(^2\text{H}_2\text{O} \) was administered to determine final TBW.

The fraction of total fluid intake attributable to test beverage consumption was calculated from fluid in- take records. Test beverage consumption was calcu- lated as: (fraction of total fluid intake attributable to test beverage) \( \times \) (preformed dietary water intake). Preformed dietary water intake was estimated from water turnover (\( R_{H2O} \)) calculated from \(^2\text{H}_2\text{O} \) elimination, as described previously (DeLany et al., 1989; Hoyt et al., 1994). Isotope elimination rates for \(^2\text{H} \) and \(^18\text{O} \) were corrected for the changes in back- ground isotope abundances in three test volunteers (2 from the CHO group and 1 from the PLACEBO group) who were given tap water rather than the isotope tracers (DeLany et al., 1989). The metabolic fuel quotient, which reflects both food intake and energy store combustion, was calculated from the macronutrient compositions of the rations and beverages consumed and the amount of body fat and protein lost.

Water requirements were calculated from the EE measurements using equations developed by Barr and Costill (1989) as follows:

\[
\text{Energy Expended as Heat Loss} = (1 - \text{Mechanical Efficiency}) \times \text{TEE}, \quad (1)
\]
\[
\text{Fluid Loss as Water Vapor (in L)} = (\text{Energy Expended as Heat Loss} \times 1 \text{ L of Water Vapor})/2.43 \text{ MJ}. \quad (2)
\]

The mechanical efficiencies of exercise of 20% (Barr and Costill, 1989; Sidossis et al., 1992) and 23.8% (Sidossis et al., 1992) were used.

Activity monitors (Actigraph model AMA-32C, Precision Control Design, Inc., Fort Walton Beach, FL) worn on the non-dominant wrist were used to monitor activity patterns. The output (zero crossing of the monitor’s piezoelectric motion) of the sensor was recorded in continuous 1 min intervals. Activity was differentiated from inactivity using an existing algorithm (Cole et al., 1992).
Statistical analyses

Descriptive statistics were calculated by beverage group and by day. Data were analyzed using the Statistical Package for the Social Sciences (SPSS, Inc. Chicago, IL). A repeated measures analysis of variance over days with beverage group (CHO vs. PLACEBO) as a grouping factor was conducted on each dependent variable: EI, TEE, TBW, and RH₂O, with statistical significance set at \( p < 0.05 \). Post hoc differences were evaluated using Tukey’s multiple comparison tests.

Results

Total energy expenditure

The TEE for all 19 individuals was 17.22±3.01 MJ/day, with no difference \(( p > 0.05)\) over days or between beverage groups (TEECHO \([n=10]\): 18.41±4.40 MJ/day vs. TEEPLACEBO \([n=9]\): 16.12±2.70 MJ/day). The workday lasted 12–15 hr, as documented by activity monitor records. Volunteers were inactive, presumably asleep, for approximately 6.1±0.5 hr per night. The pre- to post-test percent body fat (pre-test: 19.7%±3.7%; post-test: 19.0%±3.6%) and body weight (pre-test: 76.8±8.1 kg; post-test: 76.5±7.7 kg) were not significantly different \(( p > 0.05)\).

Fluid balance

The RH₂O calculated from \(^2\)H₂O elimination rates showed no differences between beverage groups. A significant difference developed over time \(( p < 0.05)\), with a greater RH₂O on Days 1 to 6 (5.53±0.95 L/day) compared to Days 7 to 11 (5.25±0.95 L/day). The TBW levels were stable pre- to post-test for both groups (pre-test: 45.8±4.6 L, post-test: 45.6±5.0 L). There were no significant differences between groups for mean TBW (TBWCHO: 46.9±5.5 L; TBWPLACEBO: 44.5±3.3 L) or RH₂O (RH₂OCHO: 5.6±1.1 L/day; RH₂OPLACEBO: 5.1±0.7 L/day).

The water requirements calculated from the TEE measurements (i.e., 17.22 MJ/day) and using the equations of Barr and Costill (1989) are similar to the water turnover rates obtained from \(^2\)H₂O. Calculated water requirements, with water primarily lost through sweating, were 5.7 L/day (using a mechanical efficiency of 20%) and 5.4 L/day (using a mechanical efficiency of 23.8%).

Energy intake and macronutrient distribution

There were no significant differences in dietary intakes between the sub-group administered DLW and the complete sample of volunteers. However, the differences in the amount of carbohydrate, macronutrient distributions, and total calories consumed between the CHO and PLACEBO groups were significant (see Table 1). The mixture of macronutrients consumed did not change significantly over time during the 10 days of the study, averaging 14±1% protein, 32±2% fat, and 54±5% carbohydrate. The CHO group consumed a significantly greater proportion of energy from carbohydrate \(( p < 0.05)\) and had a greater EI \(( p < 0.01)\) than did the PLACEBO group. For the subgroup of 19 volunteers that had complete EI data \((n=9)\), the CHO group \((n=3)\) consumed 14.3±0.6 MJ/day and the PLACEBO group \((n=6)\) consumed 12.8±0.8 MJ/day. From Table 1 it is apparent that although the CHO and PLACEBO groups received similar amounts of carbohydrate from food and other beverages (i.e., beverages that came with the meals but were not the supplemental beverages per se), the supplemental test beverage significantly enhanced overall carbohydrate intake. Overall the

Table 1. Comparison of energy distribution of macronutrient consumption by group.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>CHO GROUP (n=32)</th>
<th>% of Total</th>
<th>PLACEBO Group (n=31)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Carbohydrate*</td>
<td>470±139</td>
<td>7.9±0.5</td>
<td>317±68</td>
<td>5.3±0.3</td>
</tr>
<tr>
<td>Ration</td>
<td>293±15</td>
<td>4.9±0.2</td>
<td>310±14</td>
<td>5.2±0.3</td>
</tr>
<tr>
<td>Drink*</td>
<td>177±9</td>
<td>3.0±0.2</td>
<td>7±0</td>
<td>0.1±0.0</td>
</tr>
<tr>
<td>Protein*</td>
<td>93±20</td>
<td>1.6±0.1</td>
<td>105±19</td>
<td>1.8±0.1</td>
</tr>
<tr>
<td>Fat*</td>
<td>95±20</td>
<td>3.6±0.5</td>
<td>108±23</td>
<td>4.1±0.4</td>
</tr>
<tr>
<td>Total Intake*</td>
<td>13.1±0.8</td>
<td>100</td>
<td>11.2±0.8</td>
<td>100</td>
</tr>
</tbody>
</table>

Mean ± SD

* Denotes significant differences \(( p < 0.05)\) between groups.
CHO group consumed an additional 153 g of carbohydrate and 1.9 MJ/day of energy as a result of consuming the supplemental carbohydrate beverage.

Discussion

Providing a supplemental carbohydrate beverage significantly increased carbohydrate intake and overall EI of these volunteers during this field training exercise. These results are consistent with those of Montain et al. (1997) who found that providing a carbohydrate/electrolyte beverage resulted in a significant increase in carbohydrate consumption. The use of the carbohydrate beverage helped meet the high energy requirements documented in this study of volunteers doing manual work and physical training in the desert. Calorie compensation, that is, a significant reduction in EI from rations when receiving calories from a supplemental beverage, was not evident in the reduction in EI from rations when receiving calories from a supplemental beverage.

Furthermore, total RH2O was similar in CHO group. However, the macronutrient distribution from a supplemental beverage, was not evident in the reduction in EI from rations when receiving calories from a supplemental beverage. Calorie compensation, that is, a significant increase in carbohydrate consumption. The use of the carbohydrate beverage helped meet the high water demands imposed by this exercise. Body weight and TBW did not change pre- to post-exercise and RH2O approximated daily sweat loss as determined through fluid loss as water vapor from the Barr and Costill (1989) equation. Therefore, the drinking behavior of these volunteers met their relatively high water requirements. The slightly higher R_H2O on Days 1–6 may have been associated with slightly higher ambient temperatures, more diligent drinking discipline at the beginning of the field exercise, or the novelty of a new flavored beverage. It has been shown previously that individuals will voluntarily drink more of a flavored, sweetened drink over water alone (Hubbard et al., 1984).

While this study used an 8% carbohydrate solution, a carbohydrate beverage powder can be prepared in various percentages to meet various fluid, energy, and carbohydrate requirements, or palatability preferences. For example, higher fluid requirements would typically necessitate a more diluted beverage. Solutions of up to 8% carbohydrate have been recommended, as there are few negative effects of these concentrations on gastric emptying, especially when high gastric volumes are maintained (Coyle and Montain, 1992). This approach is applicable to both military and civilian personnel engaged in physical exercise or manual work, especially in hot and/or dry conditions.

In conclusion, this study of Marines in the field showed that food EI of 11.0–13.0 MJ/day did not meet TEEs of 16.7–18.0 MJ/day. However, providing a supplemental CHO beverage significantly increased CHO and EI intakes. Providing a CHO beverage supplement is an effective way to both meet fluid requirements and increase CHO and EI requirements of physically active Marines or others working or trekking in warm/dry environments.

Acknowledgements/Disclaimers

We would like to express our appreciation to Dr. Scott Montain for providing his scientific expertise regarding hydration issues. We would like to thank the U.S. Marine test volunteers who made this study possible.

The U.S. Army Medical Research and Materiel Command (USAMRMC) supported this work. Approved for public release; distribution is unlimited. The views, opinions and findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Citation of commercial organizations and trade names in this report does not constitute an official Department of the Army endorsement or ap-
proval of the products or services of these organizations.

References


Sidossis, L. S., J. F. Horwitz and E. F. Coyle: “Load and velocity of contraction influence gross and delta mechanical efficiency”. International Journal of Sports Medicine,