Characterization of energy expenditure and body composition in military personnel during a cold field training exercise

By

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ABSTRACT

The purpose of the following study was to re-address the energy requirements of Canadian Armed Forces (CAF) during training in a cold winter environment. Twenty CAF personnel were recruited to participate in a 5-day winter training exercise at Canadian Forces Base Meaford in Ontario, Canada. Energy expenditure (*n=10*) and body composition (*n=14*) were measured via the doubly labelled water (DLW) method and the deuterium isotope dilution technique, respectively. Mean total daily energy expenditure (TDEE) was 4900±693 $\text{kcal}\cdot\text{day}^{-1}$ with no significant differences observed between sexes. Body mass and body composition of CAF personnel changed significantly ($p < 0.05$) across the 5-day exercise. This decrease was associated with a significant ($p < 0.05$) reduction in fat mass. Despite these losses, participants were able to maintain high physical activity level (PAL) values (2.6) and high TDEE levels throughout the study period. It is recommended to increase the caloric content of the rations via additional supplements that provide energy-dense foods in bar format that can be easily consumed at the convenience of the individual.

A qualitative review focusing on the future state of multisensor energy expenditure tracking devices is also presented. Recent technological advances have increased the functionality and feasibility of portable, non-obtrusive devices that measure multiple performance parameters including heart rate, body temperature, and energy expenditure (EE). When paired with indirect calorimetry, multi-sensor systems can provide a more robust assessment of EE and physical activity (PA) than provided by the DLW method alone. Further research utilizing the breadth of EE methods is warranted in CAF in order to provide a more accurate and complete assessment of energy requirements in all climatic conditions including the extreme heat and temperate climates.

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LIST OF ABBREVIATIONS

BF%	body fat percentage
BMI	body mass index
CAF	Canadian Armed Forces
DLW	doubly labelled water
DRDC	Defence Research and Development Canada
EE	energy expenditure
EI	energy intake
FFM	fat-free mass
FM	fat mass
HR	heart rate
HRM	heart rate monitoring
IMP	Individual Meal Pack
IRMS	isotope ratio mass spectrometry
PA	physical activity
PAEE	physical activity energy expenditure
PAL	physical activity level
*r*CO2	rate of carbon dioxide production
RMR	resting metabolic rate
TDEE	total daily energy expenditure
TBW	total body water

REVIEW OF THE LITERATURE

1.1 Introduction

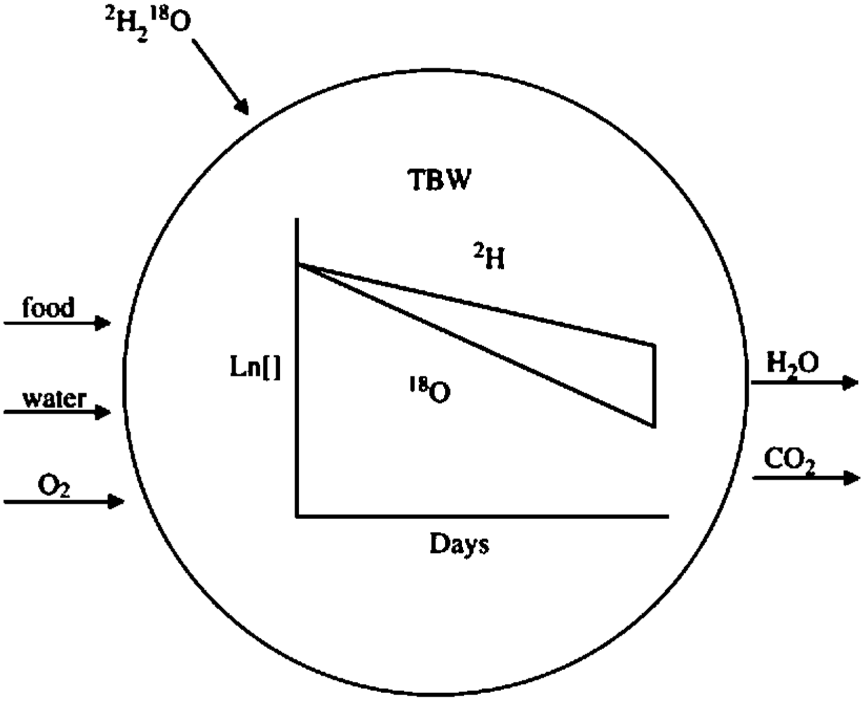
This review intends to serve two purposes. First, an in-depth discussion focusing on the principles of the doubly labelled water (DLW) method will be discussed. Second, a comprehensive review of the factors that impact the energy requirements of military personnel operating in extreme climates will be presented.

1.2 Doubly Labelled Water Theory

The DLW technique, first proposed in 1955 by Nathan Lifson, was originally developed to measure energy expenditure (EE) in small animals (Lifson, Gordon, & McClintock, 1955; Lifson & McClintock, 1966). The first human study was not conducted until 1982 because of isotope cost and instrument limitations (Schoeller & van Santen, 1982). Improvements in the sensitivity of isotope ratio mass spectrometers (IRMS) have improved the practicality of its use. The DLW method has been used within a variety of human participants including astronauts, professional soccer players, Tour de France cyclists, and mountain climbers (Ebine et al., 2002; Pulfrey & Jones, 1996; Stein et al., 1999; Westerterp, Saris, van Es, & ten Hoor, 1986). Allowing individuals to engage in regular activities without restriction has made the DLW method a preferred choice for the study of EE in active populations. Participants consume doses that are enriched with deuterium (^2H) and ^{18}O isotopes. Periodic urine and saliva samples are then collected over a period of approximately 4-21 days depending on the activity levels of the participants. Using elimination kinetics, the rate of carbon dioxide production (rCO_2) can then be calculated and used as estimation for EE.

The DLW technique measures CO_2 production by comparing the rates of turnover of oxygen and hydrogen from isotopically labelled water, based on the observation that the biological elimination rates of labelled oxygen and labelled hydrogen in water are different (Bluck, 2008; Schoeller, 2008). Hydrogen is eliminated from the body by water loss, such as urine, saliva, and water vapour, whereas oxygen is eliminated by both water loss and through CO_2 exhalation. Oxygen is therefore eliminated from the body faster than hydrogen and the difference in their elimination rates is taken as a measure of CO_2 production **(Figure 1.2)**, which can then be used to measure EE using the modified Weir equation (Hnilicka et al., 1994).

Figure 1.2. The stable isotope elimination rates of ^{2}H and ^{18}O from body water. Adapted from Schoeller 2008.



Due to the high activity situations encountered by military personnel, some fundamental considerations pertaining to the accuracy and validity of the DLW technique need to be addressed before its use. The optimal observation period is 1-3 biological half-lives of ^{18}O and ^{2}H, but during high activity levels, the half-lives of ^{18}O and ^{2}H decrease about 1/3, reducing the study period roughly 2-3 days (Schoeller, 1983; Westerterp et al., 1986). Between 5-10% of total body water (TBW) is turned over daily, with sweat being the most variable and consequential cause, as a loss of 1-3% body mass can be detrimental to performance (Sawka, Cheuvront, & Carter, 2005). Body water turnover is influenced by physical activity (PA), as better-trained individuals have a higher turnover and metabolic rate, further reducing the half-life of the tracers (Shimamoto & Komiya, 2000). An increase in water turnover is either caused by greater fluid intake or by a rise in the loss of body water, which accompanies heavy sustained exercise, as acute exercise sweat loss can reach levels of 1-2 $L \cdot hour^{-1}$ (Leiper, Pitsiladis, & Maughan, 2001; Sawka et al., 2005). Either the length of the study period needs to be adjusted accordingly or the dose increased in order to ensure turnover rates can be measured accurately and precisely.

Isotope fractionation is another important source of error at high activity levels, as the rate of water loss via fractionating gaseous routes increases during sustained exercise (Cole et al., 1990; Westerterp, Brouns, Saris, & ten Hoor, 1988). Isotope fractionation is a physical phenomenon that causes changes in the relative abundance of isotopes due to differences in their mass, creating either enriched or depleted samples (Westerterp et al., 1988). Fractionation occurs between water vapour and both ^{18}O and ^{2}H, and between CO_2 and ^{18}O is of interest, whereas there is little fractionation that occurs in sweat and urine because they are excreted as liquids. Without correction factors, the calculated rCO_2 becomes quite sensitive to changes, but because fractionation rates are estimated, there is still some error in the calculation. The calculated uncertainty in rCO_2 using fractionation corrections is less than 2% (Westerterp et al., 1988). Consequentially, the calculated rCO_2 is extremely sensitive to the k_O/k_D ratio. This is not usually a concern with healthy normal individuals, but because of the high water turnover and increased fractionation in physically active populations, the difference between k_O and k_D is much smaller.

Errors are magnified with a low k_O/k_D ratio because the method relies on distinguishing the elimination curves of k_O and k_D.

Isotopic exchange occurs when the isotopic label from the dose water exchanges with the hydrogen or oxygen of a different compound, resulting in an increase in the dilution space. Corrections for non-aqueous hydrogen exchange have been made to account for these isotope exchanges within the body. It is universally accepted that the ^2H space is 1.041 times and ^{18}O space is 1.007 times that of TBW (Hnilicka et al., 1994).

Another consideration is the adjustment of baseline isotopic enrichment shifts of ^2H and ^{18}O due to travel across latitudes. Heavy stable isotopes tend to be depleted closer to the poles compared to the equator, because of isotopic fractionation that occurs during the global transport of water and the baseline enrichments must be corrected to adjust for any intake that may have occurred just prior or during the study (Horvitz & Schoeller, 2001; Jones, Jacobs, Morris, & Ducharme, 1993). Without these corrections, significant errors in EE estimation can occur. These corrections have been previously applied in DLW experiments with military personnel operating under extreme conditions (DeLany, Schoeller, Hoyt, Askew, & Sharp, 1989; Hoyt et al., 1991; Jones et al., 1993).

The assumption that TBW is 60% of total body weight is used for dosing purposes, but to accurately predict rCO_2, TBW is determined using deuterium isotope dilution. Dilution space can be determined through enrichments using **Equation 1** (Davidsson, 2009):

$$N = ((W \cdot A/\mathrm{a}) / (\Delta \mathrm{DD}/\Delta \mathrm{BW}) / (1000)) \tag{1}$$

where N (kg) is the dilution space of ^2H or ^{18}O, W (g) is the amount of tap water in which the dose is diluted for analysis, A (g) is the given dose, a (g) is the amount of the dose diluted by tap water for analysis; ΔDD is the enrichment of the diluted dose, which is the measured abundance in the diluted dose minus that in the local tap water used to dilute it; ΔBW is the enrichment measured in body water, which is the measured abundance in a post-dose saliva sample minus that in the pre-dose baseline sample.

The average dilution spaces of ^{2}H and ^{18}O are then used to calculate TBW, where:

$$TBW_O = N_O/1.007 \tag{2}$$

$$TBW_D = N_D/1.041 \text{ and} \tag{2.1}$$

$$TBW_{av} = (TBW_O + TBW_D)/2 \tag{2.2}$$

where TBW_O and TBW_D are the measured TBW spaces of ^{2}H and ^{18}O, respectively.

TBW_{av} is then converted into moles and *r*CO2 is calculated using **Equation 3**:

$$rCO_2 = 0.4554 \cdot TBW_{av}\ (1.007k_O - 1.041k_D) \tag{3}$$

where TBW_{av} is total body water in moles, k_O the elimination rate of ^{18}O and k_D the elimination rate of ^{2}H.

Energy expenditure can then be estimated from *r*CO2 using the modified Weir equation and an assumed respiratory exchange ratio of 0.85 **(4)**:

$$\text{TDEE (kcal}\cdot\text{day}^{-1}) = 22.4 \cdot rCO_2 \cdot (1.10 + 3.90/R) \tag{4}$$

where *R* is the assumed respiratory exchange ratio.

The two-point method and the multi-point method are the most common and basic protocols for DLW. The two-point method minimally requires 3 urine samples (pre-dose baseline, 24 hours post-dose and end of study), whereas the multi-point collects samples daily. Although the two-point protocol is prone to analytical and sampling error, it has been shown to accurately predict total daily energy expenditure (TDEE) and is more feasible to conduct in the field compared to the multi-point protocol (Schoeller, 1988).

The protocol for DLW experiments can vary depending on the length and cost of the experiment, but in general terms, protocols follow a similar procedure. Participants are given an oral dose of DLW after an overnight fast and periodic urine and saliva samples are then collected during the duration of the study. Pre-dose urine and saliva samples are collected to adjust for baseline enrichment shifts and post-dose saliva samples 3 and 4 hours after are used to determine the original TBW from ^2H isotope dilution. Urine samples are collected 24 hours post-dose, at the midpoint (optional) and endpoint of the study. After the end of study, urine and saliva samples are collected and a dose of deuterium is then administered. Saliva samples are then collected 3 and 4 hours post-dose to account for any changes in TBW that may have occurred during the trial.

1.3 Energy Expenditure of Military Personnel Operating in Extreme Climates

The EE of military personnel have been estimated in a variety of climatic conditions, including high altitude, hot, cold, and temperate. They are often performed during training exercises over a period of 3-10 days. Military personnel are more active in the field than they are in the garrison; therefore training exercises often mimic the actions seen during field missions and provide a representative way to accurately predict EE in the field.

Military personnel are typically given a set amount of rations that are to be consumed during the study period. For example, in a 7-day study on Norwegian Military Academy cadets, the effects of a negative energy balance caused by severe food deprivation and sustained exercise were observed (Hoyt et al., 2006). In the first study, participants received roughly 342 kcal·week^{-1}, whereas participants in the second study received roughly 454 kcal·day^{-1} or 3177 kcal·week^{-1}. The TDEE of the group was 6353±478 kcal·day^{-1} (means ± standard deviation (SD)) and 5230±478 kcal·day^{-1} for men and women, respectively, and the total weight loss was roughly

7.5kg for the men and 6.0kg for the women. This exercise is an example of such extreme limits of food deprivation that the military could potentially face in the field and is not reflective of the actual rations available to them. It should be noted, however; even though military personnel may be given rations that provide adequate energy supplies, they may or may not consume the entire portion. The self-created energy deficit is further compounded during intense physical exercise. Although it is recommended to consume the entire ration, certain circumstances may arise where they do not have the time to finish consuming their meal.

Nutritional strategies vary depending on the type of environmental stressors that overshadow the region. In cold environments, total caloric intake is more important than the macronutrient source, as cold exposure increases metabolic rate (Day, Young, & Askew, 2012; Jacobs, 1996). In addition, energy deficits coupled with extreme physical exertion and sleep deprivation impair the metabolic response to cold exposure, increasing the risk of hypothermia (Day et al., 2012; Young & Castellani, 2001). Nutritional interventions in warmer climates focus more on fluid and electrolyte replacement, as TDEE does not increase between hot and temperate climates (Day et al., 2012; Tharion et al., 2005).

Tharion et al. published a comprehensive review in 2005 that examined the energy requirements of military personnel (Tharion et al., 2005). The average EE of male military personnel was 4610±650 $\text{kcal}\cdot\text{day}^{-1}$ across all activities, and for women, EE was 2850±620 $\text{kcal}\cdot\text{day}^{-1}$. Energy requirements ranged from a low of 2340±382 $\text{kcal}\cdot\text{day}^{-1}$ in female administrative personnel to a high of 7117±215 $\text{kcal}\cdot\text{day}^{-1}$ for male Marines engaged in mountain warfare training (Baker-Fulco, Kramer, Lesher, Merrill, & Johnson, 2002; Hoyt et al., 1991). These data suggest that the environment and the intensity of work are the major influences of EE during field exercise training.

1.3.1 Rations

Canadian Armed Forces (CAF) combat rations must meet the North Atlantic Treaty Organisation (NATO) recommendations for use. Minimum caloric requirements are 3200 kcal·day^{-1}, with at least 10% coming from protein and 35-40% from fat (The Research and Technology Organisation of NATO, 2010). The CAF have 4 types of combat rations: the Individual Meal Pack (IMP), the Emergency Ration/Light Meal Combat (LMC), Survival Food Packets, and the Alternative Meal Pack. There are also 3 supplements available to CAF operating under extreme climatic stress or during continued arduous activity that requires extra caloric intake. These supplements are the Arctic, Tropical, and the High Protein Drink supplements.

The IMP is designed to sustain the nourishment of military personnel for up to 30 days (Canadian Armed Forces (CAF) *Food services* manual, 2012; Hatton, 2005; The Research and Technology Organisation of NATO, 2010). They are the primary food source when it is not feasible or practical to feed freshly prepared meals. IMPs are designated breakfast, lunch, or dinner, and contain roughly 1200 kcal·meal^{-1}, for a daily total just above 3600 kcal·day^{-1}. IMPs are designed to contain ready-to-eat items that can be heated without the addition of water, heating, or mixing, and to meet the Nutrition Recommendations for Canadians, except for calcium and folic acid, which is not significant if they are consumed for less than 30 consecutive days.

The Light Meal Combat Pack (LMC) can be issued whenever an IMP meal is missed up to 3-meals·day^{-1} for 48 hours. The LMC can also be added during intense periods of energy expenditure as a supplement to the IMP. It contains 1000 kcal·meal^{-1} and meets the NATO requirements as an emergency ration (The Research and Technology Organisation of NATO, 2010).

The Basic Survival Food Packets are emergency supplements in jelly form that can provide sustenance for 2 days and contain roughly 500 $\text{kcal}\cdot\text{meal}^{-1}$. These supplements are to be used when there are minimal energy costs and limited drinking water.

The final combat ration is the Alternative Meal Pack that provides CAF a vegetarian meal that meets both the Kosher and Halal requirements. These packs are served as an alternative to the IMP and provide 1200 $\text{kcal}\cdot\text{meal}^{-1}$.

The Arctic Supplement provides additional nutrients and fluids during cold weather exercises. It consists of hot chocolate beverage powders and granola bars. The Tropical Supplement increases liquid consumption, as it consists of fruit beverage powders. The High Protein Supplement is intended for individuals who are subsistent on the IMPs, has strict restrictions on its use, and is not intended to be a complete meal replacement. This supplement provides a good source of high quality protein and is only available for use in CAF operations. All three supplements must be procured and funded locally, therefore nutritional information will vary depending on the content of the supplement itself (CAF *Food services* manual, 2012).

Incremental allowances are also available to CAF to support increased levels of PA during operations and exercises. Their use is dependent on a variety of factors, such as the number of personnel and the duration of the exercise/operation. These allowances can consist of night snacks (coffee, tea, fruit, bread, etc.), workplace refreshments and other specific allowances that are outlined in the *Food Services Manual* (CAF *Food services* manual, 2012). Incremental allowances must be funded and procured locally, thus variation arises in the nutritional value depending on the location of the exercise, as do the costs.

1.3.2 Physical Activity Level

Military training exercises vary considerably based on time constraints, environmental conditions, and objectives set forth by the course commanders. Typically, no two exercises are identical, therefore in order to make comparisons regarding the intensity of military training, physical activity level (PAL) values are often used to quantify the intensity of PA by expressing TDEE as a multiple of the resting metabolic rate (RMR).

In the general population, PAL values of 1.2-2.5 are suggested as an appropriate range for maintaining energy balance, with an upper limit estimated between 2.2-2.5 (Westerterp, 2001). However, endurance athletes can achieve PAL values greater than twice that due to physical adaptations through training and by the consumption of energy-dense, carbohydrate-rich foods (Westerterp, 1998). Adapting to high-energy requirements by increasing energy intake (EI) is crucial towards the maintenance of energy balance, especially in military personnel operating in the field, as decreases in physical performance are often associated with a chronic negative energy balance caused by prolonged PA and reduced EI.

PAL values have been recorded in a variety of military settings, with an average of 2.40±0.46 being observed in 66 subjects in 5 different studies (Burstein et al., 1996; DeLany et al., 1989; Forbes-Ewan, Morrissey, Gregg, & Waters, 1989; Hoyt et al., 1991; Jones et al., 1993; Westerterp, 1998). More recently, PAL values ranging from 2.8 to 3.4 have been observed during U.S. Army special forces training and U.S. Marine training (Castellani et al., 2006a; Richmond et al., 2014). Although large energy deficits and body weight losses were observed in many of these training exercises, it was concluded that is it possible to sustain PAL values above the proposed upper limit through training and dietary manipulation.

1.3.3 Environmental Heat Stress

The effect of heat stress on EE has been studied extensively, but has not shown to affect EE directly, as EE is more closely related to the intensity of exercise or work than the environmental condition itself (Tharion et al., 2005). During their study that examined the TDEE of Zimbabwean soldiers conducting Commando combat training, Mudambo et al. concluded that strenuous work in hot, dry conditions increased energy requirements (Mudambo, McScrimgeour, & Rennie, 1997). The study was performed in the African bush where the mean daytime temperatures exceeded 40°C. The commando group, which performed 8 hours of exercise and training per day, expended an average of 5500±1000 kcal·day^{-1} during the 12-day trial, whereas the control group, which consisted of soldiers working in the kitchen and cleaning the facilities, only expended an average of 3340±240 kcal·day^{-1} during the same period. The rations provided 3800 kcal·day^{-1} which would have been sufficient for the combat support units if entirely consumed, but were severely deficient for the commando combat unit.

Forbes-Ewan et al. had previously shown similar results during their study in the Australian jungle (Forbes-Ewan et al., 1989). During the 7-day course in jungle warfare training, which included intense bayonet training and obstacle challenges, the average Australian soldier expended 4750±525 kcal·day^{-1}, but only received an average of 4040 kcal·day^{-1} in food rations, which is similar to the amount received by the Zimbabwean forces. This research was further expanded into a larger (*n=31*) group undertaking a longer (12 days) training program in the Australian jungle, where the temperatures were between 24 and 33°C (Booth, Coad, Forbes-Ewan, Thomson, & Niro, 2001). Eight participants were chosen for the DLW treatment and their TDEE was calculated as 3700±1050 kcal·day^{-1}, which is comparable to the 3940±167 kcal·day^{-1} calculated for Israeli soldiers during combat training in the summer in a different study (Burstein et al., 1996).

DLW studies have also been performed in desert climates where there is little to no humidity at all. These environments pose a much greater risk towards the development of dehydration, which can be responsible for a decline in performance not only in combat, but also regular activities such as marching and rifle marksmanship (Tharion, Cline, Hotson, Johnson, & Niro, 1997). Marine artillery crews expended an average of 4100±716 kcal·day^{-1} over a 12-day period and had an average energy deficit of roughly 1000 kcal·day^{-1}. It was concluded that the participants did not receive adequate supplies of energy for the duration of the study to meet their metabolic demands and that in desert-like environments, the addition of a carbohydrate drink may aid in meeting energy requirements. Moore et al. also recommended an EI increase in the rations given to Ranger trainees during the United States (U.S.) Army Ranger Training Course, a 62-day training program encompassing four different ecological zones (Moore, Friedl, Kramer, Martinez-Lopez, & Hoyt, 1992). From their report, it was concluded that the trainees expended roughly 3800 kcal·day^{-1} for the 2 weeks spent in the desert, but experienced excessive, but preventable weight loss. The average intake during this period was around 2800 kcal·day^{-1} and the average weight loss was 15.6% of body weight, resulting in an end-study 23% decrease in lifting strength. Although the EI limitations in this study were extreme and likely not representative of modern-day combat scenarios, it was important to characterize the upper limits of physical ability during extreme food deprivation during training exercises.

Based on these results, a follow-up study was conducted with increased caloric intake values with soldiers performing the exact same tasks and exercises as the U.S. Army Ranger Training Course (Shippee, Askew, Bernton, Martinez-Lopez, & Kramer, 1994). The goal of this follow-up study was to determine if an increase in EI had any significance on weight loss and body composition. EI was 16% higher in this study and the average energy deficit was roughly

350 kcal·day^{-1} less. Body weight loss was 3% lower and it was concluded that the increase in caloric intake had positive physiological benefits.

A more recent study analyzed the nutritional status, body composition, and physical fitness during a 6-month operational deployment in Afghanistan of British Royal Marines (Fallowfield et al., 2014). Anthropometric measures were recorded; dietary intake was assessed, as well as TDEE via DLW and physical activity questionnaires. The mean TDEE of 18 Royal Marines throughout a 7-day period during a military deployment was 3630±450 kcal·day^{-1}, with an average EI of 2530 kcal·day^{-1}, and an average energy deficit of roughly 1200 kcal·day^{-1}. However, it was concluded that the nutritional provisions provided to soldiers during deployment to Afghanistan was sufficient to maintain physical capability and nutrient status.

1.3.4 Environmental Cold Stress

Cold environments pose great risks to the health of individuals subjected to the environmental conditions because temperature, snow depth, wind, and food resources can vary on a daily basis. These conditions are often present in remote locations, such as Baffin Island or Alaska, where supplies and help are not within close proximity. Expenditure studies in these areas provide valuable information that can be used to accurately assess and calculate the energy needed not only to do work, but more importantly, to survive in any location.

Energy expenditure during environmental cold stress increases compared to warmer environments, with a predicted 20% increase relative to similar training in both hot and temperate conditions (Tharion et al., 2005). The caloric requirements in cold weather are 10-40% more than garrison feeding requirements (Castellani, O'Brien, Baker-Fulco, Sawka, & Young, 2001). The main contributors to the increase in EE in cold climates are the extra weight of additional clothing, the extra energy cost of movement caused by either snow or ice, and shivering. According to McCarroll et al., winter clothing can increase energy demands 16% over desert clothing and 8% over temperate clothing (McCarroll, Goldman, & Denniston, 1979). The additional weight of extra clothing is a necessity because it can delay the onset of shivering, which is a biological factor in cold climates as shivering can occur intermittently for days (Edwards, Askew, & King, 1995).

The energetic costs of activities and caloric requirements also increase due to a reduction in movement efficiency, resulting in the early onset of fatigue which can be detrimental as body temperature will not be able to be maintained during severe cold exposure (Nimmo, 2004). Walking in 6 inches of snow also doubles EE compared to walking the same amount on blacktop (430 $\text{kcal}\cdot\text{hr}^{-1}$ vs. 190 $\text{kcal}\cdot\text{hr}^{-1}$), further compounding the energetic cost of exercise in cold environments (Castellani, O'Brien, Sawka, & Gamble, 2005).

1.3.4.1 Thermoregulation

Thermoregulation is defined as the ability of an organism to keep its core body temperature within certain boundaries. In humans, these boundaries are between 36-37°C, and represent a balance between heat production and heat loss from the body (Noakes, 2000a). The regulation of core body temperature is determined via behavioural thermoregulation and physiological thermoregulation (Castellani et al., 2005). Behavioural thermoregulation consists of the avoidance or reduction of cold exposure via clothing or shelter, and increasing PA. However, these options may not be available to military personnel during training or in combat, therefore the maintenance of body temperature is more reliant on physiological thermoregulation.

Physiological thermoregulation consists of heat conservation (vasoconstriction) and heat production (shivering). Acute cold exposure increases peripheral vasoconstriction, which reduces peripheral blood flow. Accordingly, convective heat transfer between the body’s core and shell (subcutaneous fat and skeletal muscle) is reduced and increases insulation by the body's shell (Castellan et al., 2006b). Skin temperature declines as a result of heat loss from exposed body surfaces. However, during prolonged cold exposure, the vasoconstrictor response extends beyond the peripheral tissues and can occur throughout the entire body, increasing the insulating layer and resulting in the progressive cooling of muscles and depletion of muscular strength. Core temperature is conserved due to this vasoconstriction response, but the reduction of blood flow from the peripheral tissue increases their susceptibility to peripheral cold injuries in digits (fingers and toes) and in appendages (ears and nose) (Castellani et al., 2005).

Heat loss can be offset by an increased production of metabolic heat caused by cold exposure. Cold-induced thermogenesis is attributed to skeletal muscle contractile activity, also known as shivering (Castellani et al., 2006b). Shivering occurs as a response to a drop in core temperature in order to maintain body homeostasis. It may occur immediately or after a few minutes of exposure. Muscles surrounding vital organs begin to shake incrementally, creating warmth by expending energy that is 2-3 times the resting metabolic rate (RMR), but upwards of greater than 4 times during immersion in cold water (Castellani et al., 2005). The intensity and extent of shivering depends on the severity of the cold stress. Prolonged shivering can potentially reduce the body's glycogen stores and lead to muscle glycogen depletion if an inadequate diet is consumed, which directly affects muscular strength and performance (Edwards et al., 1995).

As it pertains to exercise in the cold, thermal balance is usually maintained or core temperature increases, as heat production is greater than heat loss. Exercise intensity and thermoregulation during cold exercise are dependent on variety of factors, including the amount of clothing worn and individual factors that modify the physiological responses to cold. Variability amongst anthropometric characteristics, such as body size and subcutaneous fat, has the greatest effect in the ability to maintain core temperature. Subcutaneous fat provides greater insulation than any other body tissue, so heavier and more muscular individuals will be able to maintain body temperature more easily then leaner individuals. Gender, race, overall fitness levels, fatigue and dehydration are a few other examples in which thermoregulation in individuals is varied, however, these issues have been previously discussed in detail (Castellani et al., 2005; Nimmo, 2004).

The DLW method has been used extensively in cold environments because of its ease of administration that would make research difficult in these conditions, however, previous research using this method has become dated. Jones et al. investigated the adequacy of food rations in 20 CAF, 10 of which received the DLW treatment, on Baffin Island in the Canadian arctic (Jones et al., 1993). Outdoor temperatures ranged from -25 to -40°C and participants engaged in moderate intensity outdoor activities that included skiing, hunting, and igloo building. The TDEE accounted for isotopic shifts due to geographical relocation of participants and was calculated as 4300±931 $\text{kcal}\cdot\text{day}^{-1}$ over the 10-day trial. Self-reported caloric intakes obtained from food records only accounted for 61% of TDEE, however, there was no direct monitoring of food intake, which forced the participants to recall food intake on provided forms that were later processed in a computerized nutrient composition database. The apparent lack of food intake did not affect body composition, as fat-free mass (FFM) and fat mass (FM) did not change significantly. It was concluded that the ration packs provided sufficient energy when fully consumed, even though these packs only provided enough energy for 4 out of the 10 participants. Additional supplements were available to the participants and would have exceeded the energy requirements in these conditions.

A similar study performed in Quantico, Virginia, where the temperature ranged from -10 to 5°C, evaluated energy balance during a 10-day field exercise in 14 male U.S. Marine Corps volunteers (Hoyt, Buller, DeLany, Stultz, & Warren, 2001). The DLW method was used to estimate the TDEE and EI was calculated from the individual collections of food wrappers consumed daily. This study differed from that of Jones et al. in that it incorporated a prototype monitoring system that measured and recorded time series measurements of heart rate (HR), body temperature, activity patterns, metabolic costs of locomotion, and geolocation. HR monitors were strapped to the chest of the participants and body core temperatures were measured using a telemetry temperature pill, while activity monitors were attached to the non-dominant wrist and pedometers were attached to the laces of the boots.

The addition of motion sensors to the DLW method provided researchers the ability to monitor continuous data and correlate activity patterns to EE. A large energy deficit was noticed during the training exercises, as TDEE (5375±670 kcal$\cdot$day^{-1}) exceeded EI (1340 kcal$\cdot$day^{-1}) by roughly 4060 kcal$\cdot$day^{-1}, resulting in an average weight loss of 3.3kg. Each subject was only rationed one MRE$\cdot$day^{-1} (1340 kcal$\cdot$day^{-1}). The anthropometric data provided insight into the costs of exercise and is a useful tool in predicting EE along with the DLW method. Quantifying the nutritional needs of physically active soldiers is especially important in the field where resources are scarce.

Two other studies have evaluated EE and ration capability in extreme cold (Edwards, Roberts, & Mutter, 1992; King, Mutter, & Robert, 1993). Both studies were performed in Fort Greely, Alaska and had average temperatures of around -20°C and a low of -48°C was experienced. The first study examined 96 field artillery soldiers, 20 of which were assessed a DLW dose and TDEE was calculated as 4250±480 kcal$\cdot$day^{-1}, which was slightly higher than those participating in a similar exercise in desert conditions (4110±715 kcal·day^{-1}). The second study recorded an average TDEE of 5160 kcal·day^{-1}, which was much higher than what CAF expended in similar circumstances (4300 kcal·day^{-1}).

Extreme TDEE levels have also been observed in unique circumstances that are not representative of standard military training. These studies focused on 2 Norwegian Commandos in treks across Greenland and across the Arctic Ocean over the North Pole. Participants (n=2) expended 5330±1815 kcal·day^{-1} and 7100 kcal·day^{-1} respectively, and represent the most extreme values recorded by military personnel in harsh thermal environments (Frykman, Harman, Patton, Opstad, & Hoyt, 2001; Frykman, Sharp, Mello, & Kavanagh, 2001).

The biggest obstacle faced by the CAF in extreme cold weather climates has been the ability to fully consume rations. In all 3 extreme cold weather experiments, less than 70% of the rations were consumed, creating energy deficits that eventually led to preventable weight loss. Current U.S. military recommendations developed by the Department of the Army suggest that military members participating in prolonged intense physical activities consume up to 125% of the Military Dietary Reference Intake, roughly 4600 kcal·day^{-1}, an increase from the previous recommendations of 4500 kcal·day^{-1} (*Nutrition standards and education*, 2001; Edwards et al., 1995). Caloric needs increase in cold environments because of the weight of additional clothing, shivering, the increased energy cost of locomotion and the biomechanical inefficiencies that occur due to cold muscles.

1.3.5 Temperate Climate

Temperate climates present moderate seasonal changes and do not experience the extreme heat or cold as often as the desert or Polar Regions. In temperate climates, however, the main predictor of EE is not the harshness of the climate, but the amount and intensity of work that is being performed. Most expenditure field studies fell below 4300 kcal·day^{-1}, as noted in the 2005 review published by the U.S. Army Research Institute of Environmental Medicine (Tharion et al., 2005). There are some exceptions, however, that have pushed the upper limits of physical activity of military personnel in temperate conditions. For example, Armed Forces personnel expended 5180±334 kcal·day^{-1} during 8 days of the Special Forces Assessment and Selection course, which assesses an individual's potential and qualities, through rigorous physical and psychological challenges (Fairbrother, Shippee, Kramer, Askew, & Mays, 1995). Another field training exercise, the Crucible, is administered at the end of the U.S. Marine Crops basic recruitment (Castellani et al., 2006a). During this 54-hour exercise, recruits were on limited sleep and restricted rations, performing simulated combat operations. Energy expenditure was calculated as 6140±191 kcal·day^{-1} for men and 4730±143 kcal·day^{-1} for women, some of the highest expenditures ever calculated by the U.S. military. Although these exercise patterns do not accurately reflect the general expenditures in the field, they provide valuable information on the nature of exercise and the intensity at which expenditure becomes a serious threat to the health of individuals.

OBJECTIVES AND HYPOTHESES

2.1 Objectives

The purpose of the proposed research was to re-address the energy requirements of members of the CAF using both EI and EE methods for use by the CAF in their dietary planning for missions. The primary objectives of the proposed research are:

(1) to estimate the energy expended by participants during a cold winter training exercise using the DLW method and;

(2) to assess the energy content of military rations provided and consumed in terms of their adequacy to match the energy cost of the activities performed during a cold winter exercise using 4-day food waste collection.

2.2 Hypotheses

It is hypothesized that:

(1) the participants would be in a state of negative energy balance due to the high energy demands of intense military training and;

(2) the current energy content of CAF military field rations is inadequate to meet the high energy demands of participants training in a cold field environment.

METHODOLOGY

This project was a collaboration between groups from the University of Toronto, Defence Research and Development Canada (DRDC), and the University of Manitoba for the assessment of energy requirements of CAF in a cold environment during intense military exercise training.

Energy intake was monitored via 4-day food waste collection, which was the responsibility of the University of Toronto research team. The oversight and administration of the DLW method and the subsequent collection and analysis of urine and saliva samples obtained throughout the study was the responsibility of the University of Manitoba team.

The observation period was 5 days. During these 5 days, participants consumed IMPs and were directed to refrain from consuming any other food. Their waste was collected by the research team at designated times after each meal. The following experimental protocol and procedures are adapted from the ethics protocol submitted by DRDC and the University of Toronto.

A total of 20 CAF personnel from the CAF population volunteered to participate in this study. Research ethics review boards at the University of Toronto and DRDC approved the research protocol. This research was conducted during a regularly scheduled CAF training exercise at Canadian Forces Base Meaford during January 26th-31st, 2015. The volunteers were made aware of all procedures and gave free and informed written consent.

3.1 Inclusion/Exclusion Criteria

Interested volunteers were required to meet and/or agree with the criteria listed below for eligibility to participate in the study.

Inclusion Criteria

1. 18-60 years of age

2. Currently enrolled in the military

3. Agree to the following:

    a) Not consume a "natural health product" or dietary or nutritional supplement for 24 hours prior to the start of the study, without first checking with a Principal Investigator to determine if it will interfere with the study;

    b) Abstain from alcohol consumption for at least 24 hours prior to study start until study completion;

    c) Consume only military rations distributed to them for the duration of the study.

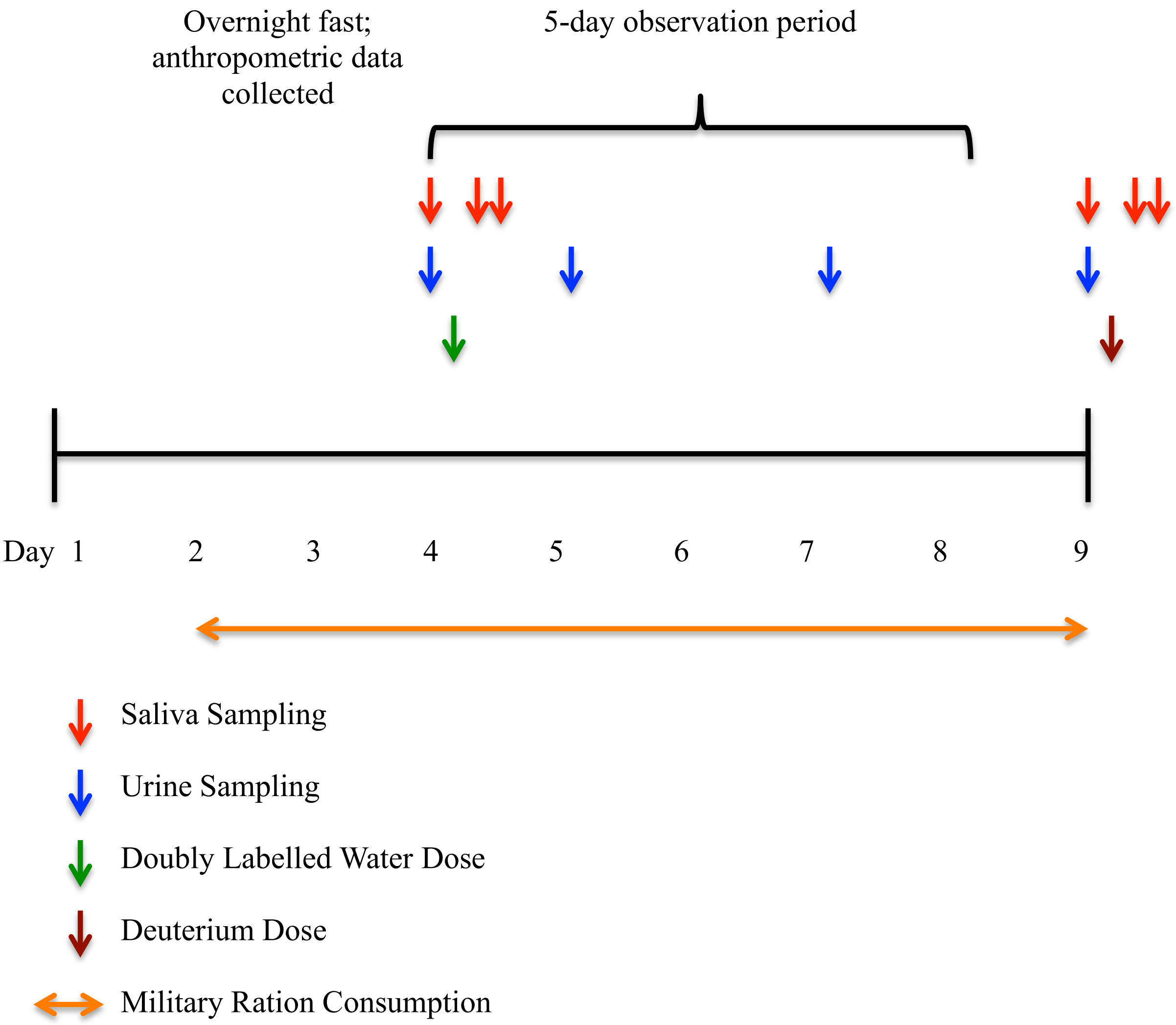
Exclusion Criteria

1. History of alcohol or substance abuse;
2. History of anxiety, depression or psychosis;
3. Use of prescription drugs or clinically significant use of over-the-counter medication, within 14 days of the study that are deemed by the Principal Investigator to complicate the interpretation of results;
4. Participation in a drug ingestion or exercise research study within 30 days of the study;
5. Pregnant, lactating, or planning to become pregnant during the study;
6. Have chronic and/or infectious diseases.

3.2 Experimental Protocol: (Figure 3.2)

All of the screening as well as all of the pre-study, study, and post-study procedures occurred on base.

Figure 3.2. Experimental protocol.



3.3 Data Collection

Preliminary measurements

Participants were weighed wearing their standard issued exercise clothing before and after the training exercise using a standard scale. Their height was measured using a stadiometer.

Energy expenditure and body composition measurements

Total daily energy expenditure was assessed by the DLW technique. Between 0500 and 0600 hours on the Monday before the training exercise, ten participants provided baseline urine samples and then ingested 2.0g H_2O_{18} per estimated kg TBW, and 0.12g ^2H per estimated kg TBW. A 50 ml rinse of bottled water was consumed following the dose to ensure the entire dose was fully consumed. Standard doses were prepared in the laboratory beforehand according to a graded estimated TBW scale due to logistical constraints. TBW was estimated as 60% total body mass and participants were assigned a dose that corresponded the closest to their estimated TBW. Urine was then collected approximately 24 hours post-dose, 72 hours post-dose, and at the end of the study, 120 hours post-dose. Average TDEE was calculated throughout the 5-day study period. Physical activity level (PAL) was calculated as TDEE/resting metabolic rate (RMR), where RMR was estimated from De Lorenzo's equation (ten Haaf & Weijs, 2014). PAL quantifies physical activity by expressing TDEE as a multiple of RMR. Physical activity energy expenditure (PAEE) was estimated as TDEE – RMR.

Body composition was assessed via deuterium isotope dilution. Fifteen participants provided baseline saliva samples and then ingested standard doses of 0.12g ^2H per estimated kg TBW. Standard doses were used as stated above. Participants then provided saliva samples 3 and 4 hours post-dose. This procedure was repeated at the end of the 5-day study period to compare body composition from the start and the end of the training exercise.

Urine samples were collected from 5 participants who did not receive any of the isotope treatments to account for changes in the background abundance of ^2H and ^{18}O in the local drinking water. These participants served as the control group during the field study.

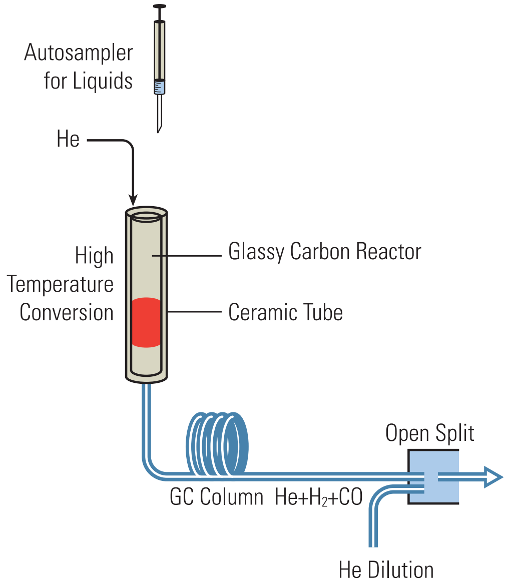
Energy intake measurement

Dietary intake of 18 male and female CAF was assessed using the 4-day daily food waste collection method. All food and beverage items were weighed in order to estimate the amount consumed. If the container was empty, the item was considered fully consumed. The nutritional content of IMPs was provided by CAF Directorate Food Services and inputted into ESHA Food Processor program (ESHA Food Processor SQL, Version, 2015, ESHA Research, Salem) to obtain a detailed nutrient analysis of the participants' dietary intakes.

3.4 Data Analysis

Levels of enrichment of ^2H and H_2O_{18} were analyzed using the High Temperature Conversion Elemental Analysis (TC/EA) method, which allowed for the direct continuous flow isotope analysis of both ^{18}O and ^2H. Oxygen in the sample was converted to CO and hydrogen was converted to H_2 gas. Samples were introduced by an auto sampler (CTC Analytics, Leap Technologies, North Carolina, United States) into the elemental analyzer (Finnigan, Thermo Electron, Bremen, Germany). The reaction occurred in a glassy carbon reactor at 1400°C encased in a ceramic tube composed of aluminum oxide (Al_2O_3), which helped prevent oxidation with the continual flushing of helium gas (He) (**Figure 3.4**). A gas chromatograph (GC) column then separated the products, CO and H_2. The gaseous products were then transferred through a continuous flow interface (ConFlo III, Thermo Electron, Bremen, Germany), which reduced gas flow to an acceptable rate for entry into the Delta V Plus IRMS (Thermo Electron, Bremen, Germany). The IRMS collected ion beams at *m/z* 2 and *m/z* 3 for the H_2 peak and then automatically switched to *m/z* 28 and *m/z* 30 to collect ion beams for the CO peak. Delta values obtained from the IRMS were then normalized using the following

Figure 3.4. Schematic diagram of the high temperature conversion elemental analyzer. Adapted from Thermo Scientific 2010.



international standards: Vienna standard mean ocean water (VSMOW), Greenland Ice Sheet Precipitate (GISP), Standard Light Antarctic precipitate (SLAP), RO56 and 302-A. All samples were run in triplicate.

Statistical Analysis

Results are presented as mean ± SD. Student's paired t-tests were used to determine significant differences between endpoints. Student's unpaired t-tests were used to determine significant differences between groups. Correlations between variables were calculated using Pearson's product moment correlation. Statistical analysis for the energy intake data was performed using SPSS version 22 (SPSS, Chicago, IL). Nutrient intakes were expressed in grams and as percentages of total energy and data for males and females participants were compared by a *t*-test. A standard multivariate model was used to control for covariates (age, total energy and BMI). Statistical significance was set at $p < 0.05$.

RESULTS

Ambient conditions

Weather information was collected daily during the duration of the field study from January 26th-January 30th, 2015. The average mean temperature was -11°C, with a minimum of -22°C, a maximum of -2°C, and a low wind-chill of -25.9°C.

Research participants

In total, 20 participants volunteered for the study. Of those 20, 18 completed the exercise and 2 dropped out due to medical reasons. Physical characteristics for the 18 participants that completed the study are presented in **Table 4.1**. During the 5-day observational period, there was a significant reduction in body mass and composition. Total body mass was reduced by 2.7% (-2.05 ± 1.09 kg) and body mass index (BMI) was reduced by 2.7% (-0.81 ± 0.39 kg·m^{-2}).

Table 4.1. Physical characteristics of all study participants.

Physical Characteristics (all)	All (18)	M (9)	F (9)
Age (years)	33.07±7.36	31.39±5.67	34.76±8.74
Height (m)	1.73±0.08	1.78±0.07	1.68±0.06
Body Mass Pre-Study (kg)	77.70±9.85	78.11±9.22	77.29±10.99
Body Mass Post-Study (kg)	75.65±9.52*	76.09±8.92*	75.21±10.61*
BMI Pre-Study (kg·m^{-2})	26.07±3.87	24.58±2.28	27.57±4.65
BMI Post-Study (kg·m^{-2})	25.26±3.66*	23.95±2.13*	26.69±4.40*

Note: values are presented as mean ± SD.
* significantly different from pre-study, $p < 0.05$.

Body composition

Overall, 15 participants received deuterium for body composition analysis. Of those, 14 completed the study. The average body mass and BF% at the onset of the study in this group were 79.89 ± 9.42 kg and 27.76 ± 7.26%, respectively. Body mass and BF% were reduced ($p < 0.05$) to 77.71± 9.10 kg and 23.76± 8.37%, respectively. FFM increased ($p < 0.05$) from 57.44±6.90 kg to 58.81±6.00 kg, while FM decreased ($p < 0.05$) from 22.46±7.31 kg to 18.89±7.97 kg. Mean differences and percent changes from pre- and post-study are presented in **Table 4.2**. Body mass and BF% were reduced significantly in all subjects. No significant differences were observed between sexes for either body mass or BF%.

Table 4.2. Changes in body mass, body fat percentage, and body mass index of participants who received deuterium for body composition analysis.

	Mean (14)	% Δ (14)
Δ Body Mass (kg)	-2.19±1.13*	-2.78±3.55
Δ FFM (kg)	1.38±1.93*	2.37±14.00
Δ FM (kg)	-3.57±1.64*	-17.24±8.64
Δ BF%	-4.01±2.46*	-15.56±14.16
Δ BMI ($kg \cdot m^{-2}$)	-0.74±0.42*	-2.82±5.61

Note: values are presented as mean ± SD.
* significantly different from pre-study, $p < 0.05$.

Energy expenditure

Individual DLW group data are presented in **Table A.1** in Appendix A. No significance difference was observed between sexes for TDEE, RMR, PAL, and PAEE (**Table 4.3**). The mean TDEE of the 10 participants in the DLW group was 4917±693 $kcal \cdot day^{-1}$, with a minimum of 3761 $kcal \cdot day^{-1}$, and a maximum of 5985 $kcal \cdot day^{-1}$. When normalized against FFM, no significance difference was observed between sexes. Correlation coefficients (**Figures 4.1** and **4.2**) showed a positive relationship between TDEE and FFM, and TDEE and body mass (r = 0.37, $p < 0.05$ and r = 0.66, $p < 0.05$, respectively). A negative relationship between TDEE and total body mass lost (**Figure 4.3)** was also observed (r = 0.73, $p < 0.05$), indicating that the participants who expended the most energy throughout the study period also lost the most amount of body mass.

Table 4.3. Energy expenditure data of the participants given the DLW treatment.

	All (10)	M (6)	F (4)
TDEE (kcal·day^{-1})	4916.61±693.06	5099.26±676.15	4642.62±559.46
TDEE·kg FFM (kcal·day^{-1}·kg^{-1})	83.79±11.48	82.38±12.90	85.90±2.75
RMR (kcal·day^{-1})	1871.18±151.25	1891.58±194.90	1850.79±98.44
PAL	2.56±0.31	2.62±0.31	2.46±0.27
PAEE (kcal·day^{-1})	2994.67±520.95	3150.24±583.26	2761.32±534.95

Note: values are presented as mean ± SD.

Figure 4.1. The relationship between TDEE and FFM in the studied participants.

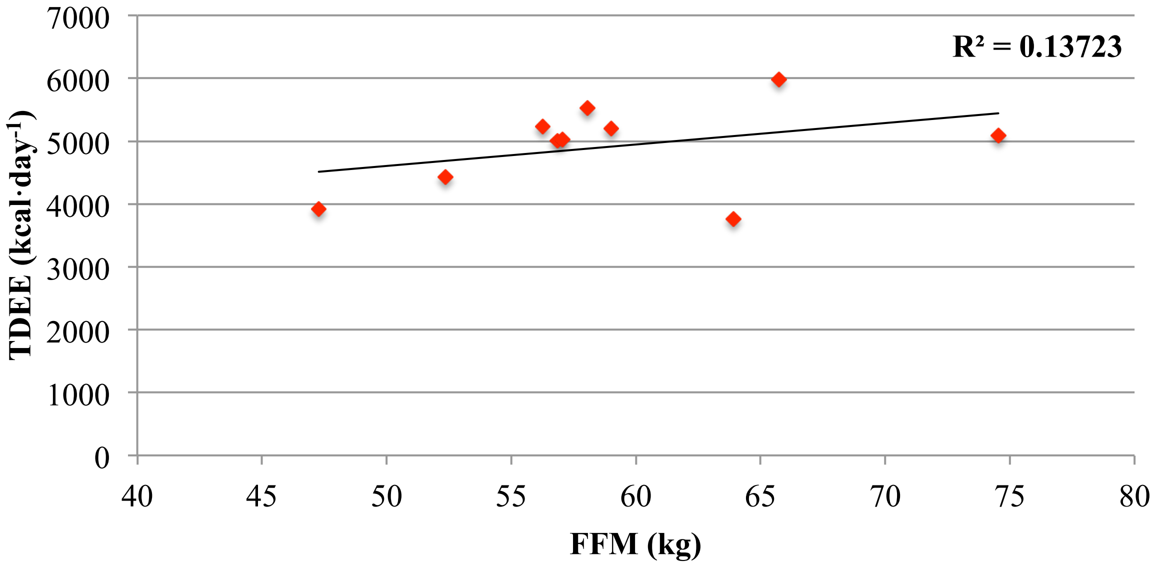


Figure 4.2. The relationship between TDEE and body mass in the studied participants.

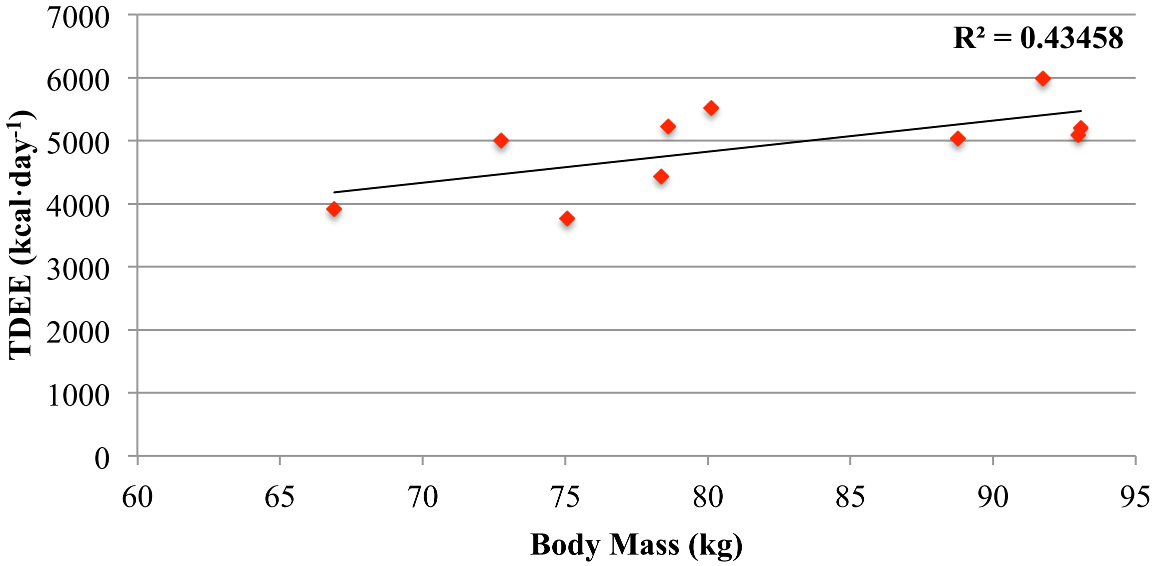
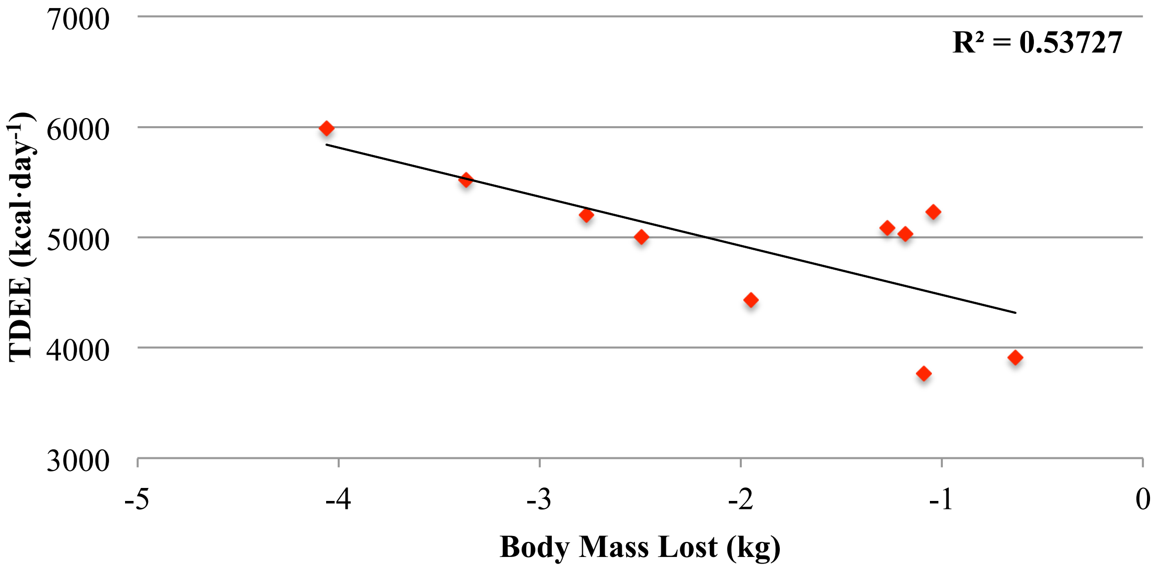


Figure 4.3. The relationship between TDEE and body mass lost in the studied participants.



Energy intake

Average EI was 2098±1190 kcal·day^{-1}, with 53% of total energy from carbohydrates, 33% from fat, and 14% from protein (**Figure 4.4**), which are within the acceptable DRI Average Macronutrient Distribution Range, with the exception of fat. Intake was higher in males than females, although not statistically significant. Nutrient intakes for CAF overall and according to sex are shown in **Table 4.4** and the average caloric and macronutrient composition of the IMPs is shown in **Table 4.5**. Participants' total macronutrient intake consumption was significantly less than the macronutrient composition provided by IMPs ($p < 0.05$).

Figure 4.4. Macronutrient intake as a percentage of total energy.

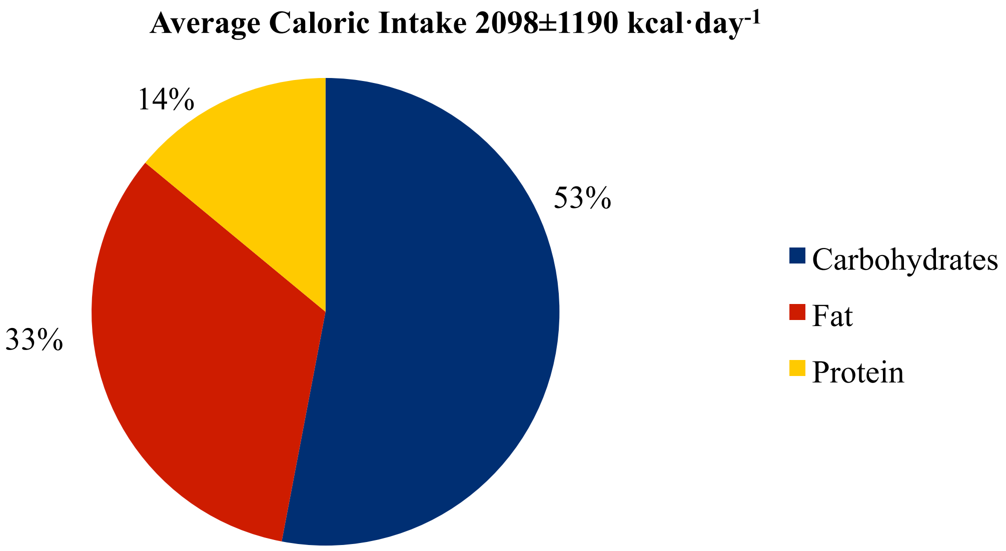


Table 4.4. Daily intake of energy and selected macronutrients and cholesterol of study participants.

	All (18)	Males (9)	Females (9)
Energy Intake (kcal·day^{-1})	2098±1190	2284±1046	1911±1194
Carbohydrates (g)	276±137	298±134	253±143
Fat (g)	76±45	84±44	68±46
Saturated Fat (g)	32±17	35±16	29±19
Protein (g)	83±51	90±40	76±62
Cholesterol (mg)	196±141	205±65	188±194

Note: values are presented as mean ± SD.

Table 4.5. Average caloric and macronutrient composition of IMPs.

IMP	Calories (kcal)	Carbohydrates (g)	Total Fat (g)	Saturated Fat (g)	Protein (g)	Cholesterol (mg)
Breakfast	1306	211	62	13	30	67
Lunch	1416	220	68	16	39	77
Supper	1278	196	61	16	39	70
Total Sum	4000	627	191	45	108	214

Note: values are presented as the mean.

Enrichment data for both isotopes are presented in **APPENDIX A**.

DISCUSSION

The present study investigated changes in body mass, body composition, and EE of CAF personnel during a winter training exercise. Our primary findings were that despite a negative energy balance (>2800 kcal·day^{-1}) and body mass and BF% losses of 2.05 kg and 4.01% respectively; participants were able to maintain a high TDEE (4900 kcal·day^{-1}) and high PAL (2.6) over the short (5-day) observational period. No differences were observed between males and females for TDEE when adjusted for body mass and FFM.

The average energy deficit experienced by the CAF in this study was just slightly over 2800 kcal·day^{-1} and corresponded significantly to changes in overall body mass and body composition. Total body mass losses showed a negative correlation to higher TDEE levels ($r = 0.73$), along with total body mass and TDEE ($r = 0.66$). TDEE per kg FFM also showed a positive correlation, however, it was much weaker ($r = 0.37$). These results are similar to body composition changes observed in other cold environment field studies using military personnel (Burstein et al., 1996; Edwards et al., 1992; Hoyt et al., 1991; King et al., 1993). Soldiers lost between 0.6-1.1% body mass during a 10-day field study in Alaska while performing an Arctic training exercise, comparable to the 2.7% body mass lost in our study (King et al., 1993). Similarly, significant differences in body mass lost were observed in light infantry soldiers during an 8-day field exercise, where the average weight loss was roughly 1.6% of total body mass (Edwards et al., 1992). In addition, Israeli commandos lost roughly 0.6 kg during a 12-day winter exercise (Burstein et al., 1996).

Extreme weight loss during a short-term field exercise can have a significant impact on the degradation of physical performance, such as decreases in aerobic fitness, power output and strength (Moore et al., 1992; Nindl et al., 2007; Richmond et al., 2014). Although the physiological consequences of extreme reductions in body mass were not assessed in this study, they have been previously examined in military personnel and found to be substantial (Jacobs, 1987; Nindl et al., 2002; Nindl et al., 2007). These data highlight the importance of maintaining an adequate energy balance during field training and combat. However, the high intensities experienced during these situations often restrict the time and opportunities for military personnel to fully consume their food. Trends in body composition and body mass during training exercises provides unique insight into the importance of maintaining energy balance via the development of nutritional strategies that promote energy intake.

Energy expenditure levels fell within the range of previous studies that utilized the DLW method for measurement of TDEE in military personnel. Values ranging from 4200-5400 kcal·day^{-1} have been observed during training exercises in the cold (Edwards et al., 1992; Hoyt et al., 1991; Hoyt et al., 2001; Jones et al., 1993; King et al., 1993). The average TDEE in this study was roughly 4900 kcal·day^{-1} and corresponded to an average weight loss of 2.05 kg, which was similar to what Hoyt et al. recorded during an 11-day cold weather field exercise in 23 U.S. Marine Corps volunteers (Hoyt et al., 1991). These volunteers expended 4920 kcal·day^{-1} and loss an average of 2.48 kg while performing a demanding course. Compared to a previous study using CAF individuals, TDEE was roughly 600 kcal·day^{-1} higher in our study, possibly due to differences in study length and EI and the correlating energy demands. Our study measured TDEE across 5 days and had an average EI of roughly 2100 kcal·day^{-1}, whereas Jones et al. measured TDEE across 10 days and had an EI of just over 2600 kcal·day^{-1} (Jones et al., 1993). The increased energy demands and decreased EI throughout the shorter observational period could explain the differences in TDEE, however it is very difficult to make conclusions between the two studies as there are too many variables to consider, such as the environmental conditions and the amount of work done.

PAL values averaged 2.6±0.3 during the 5-day exercise and were similar to other high-intensity military training exercises (Burstein et al., 1996; DeLany et al., 1989; Forbes-Ewan et al., 1989; Hoyt et al., 1991). Problems with maintaining energy balance can occur above PAL values of 2.5 in the general population, however, higher PAL values, such as the 3.4 observed in Marines during a continuous 54 hour training exercise, are achievable though training (Castellani et al., 2006a; Westerterp, 1998).

The energy value of an average day's rations (4000 $kcal \cdot day^{-1}$) represents the maximal energy content provided to the CAF, assuming that all meal items were consumed. When comparing the caloric level of the rations provided to the EE measured via DLW, the rations would have met the needs of only 2 of 10 participants studied. Reported EI was substantially below the energy content provided in terms of gross calories, as only 53% of the rations were consumed on average. This indicates that even if the participants were to fully consume the provided rations, they would still be in an energy deficit. The present data would suggest that the rations were highly inadequate to meet the caloric needs of the participants. Body weight and composition changes measured throughout the training exercise tend to agree with that statement, however observations in the field have provided insight into the reliability and feasibility of obtaining EI data and also preferences in eating habits.

The 4-day weighed food collection method is one of the more advanced and comprehensive EI assessment tools available for field use. Collecting individual food wastes after every meal and subsequently weighing them in order to estimate the amount consumed provided a labour-intensive way to accurately assess EI. However, the reported intake of 53% is directly affected by participant motivation and time constraints. Field observations indicated that as the training exercise progressed, the participants were less likely to remember to adhere to the EI protocol. In addition, there were some instances where the training exercise did not permit enough time for a full meal to be consumed, causing participants to eat throughout the day and to place their food wastes into different collection bags or to discard it altogether. Therefore, the calculated EI could have been higher if full compliance was observed and maintained throughout the entire study period. Additionally, as it was a training exercise, some participants were not aware that they had to provide their own propane fuelled grill, causing food to freeze overnight and consequentially, inedible the following day, lowering the measured EI.

Based on observational and analytical data, it is recommended to increase the caloric content of the rations with additional supplements that provide energy-dense foods in a feasible and palatable manner. Through observation and communication with the participants, it was widely agreed upon that there was a preference for foods in bar format, as they provided an on-the-go supplement that was compact and could be quickly consumed in the field. During military training or in combat, there will not always be an opportunity to sit down and consume a meal in its entirety. Providing additional calories in a quick and palatable fashion, such as fruit bars or protein bars, is an ideal method of ensuring that military personnel are continually consuming food.

CONCLUSION

In conclusion, body mass and body composition of CAF changed significantly during a 5-day winter training exercise. This decrease was associated with a significant reduction in fat mass. Despite these losses, study subjects were able to maintain high PAL and TDEE levels throughout the study period. It is concluded that the rations did not provide sufficient calories to match the high TDEE experienced during winter training. It is recommended to increase the caloric content of the rations via additional supplements that provide energy-dense foods in bar format that can be easily consumed at the convenience of the individual. Furthermore, additional research is warranted using more robust techniques to measure TDEE, as quantifying PAEE during extreme climatic training exercises is important for the precise assessment of energy requirements of military personnel. As such, the DLW method does not have the ability to distinguish between the variable components of EE, such as PAEE, the thermic effect of food and RMR. The DLW method provides a gross energy estimate that is artificially averaged. It does not provide insight into the different forms of activities that occur during training and cannot measure PAEE, which is highly variable amongst individuals. Therefore, utilizing a combination of methods, such as indirect calorimetry and multisensor systems, can provide a much more specific estimate of both TDEE and PAEE.

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BRIDGE TO CHAPTER 8

The following chapter comprises a manuscript that provides an overview of the current and future state of method development for the estimation of energy expenditure during high intensity exercise. It has been submitted for publication in *Sports Medicine* and it currently under review.

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APPLICATIONS OF MULTISENSOR ENERGY EXPENDITURE TRACKING DEVICES IN SPORTS NUTRITION RESEARCH

The following work has been submitted for publication in *Sports Medicine*.

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8.1 ABSTRACT

Variability amongst body size, body composition, sex, and physical fitness of elite athletes highlights the importance of the need for precise assessments of energy expenditure (EE). The measurement of physical activity energy expenditure (PAEE) during periods of high-intensity exercise increases the precision of the estimate of energy requirements needed in making appropriate dietary recommendations for athletes. The doubly labelled water (DLW) method remains a gold standard for EE estimation despite high operating costs and expertise required to analyse isotopic data. However, DLW cannot distinguish between the most variable components of energy expenditure, limiting its use in athletes. Recent advances in motion sensor technology have allowed for development of multi-sensor devices that use pattern recognition for accurate monitoring of energy expenditure associated with physical activity (PA). Incorporating multiple sensors into small, portable, non-obtrusive devices allows for a more thorough activity assessment profile that accounts for the inter-individuality of fitness levels that occurs amongst athletes which cannot be directly measured by the DLW. The feasibility and functionality of multi-sensor devices increases their application in metabolic sports nutrition. These devices will likely continue to improve and, when paired with indirect calorimetry, will probably eventually replace DLW as the preferred choice of energy expenditure assessment for athletes.

8.2 KEY POINTS

- Estimating physical activity energy expenditure in athletes is important for the precise assessment of energy requirements during training.
- Combining indirect calorimetry with heart rate monitoring and accelerometry provides a more thorough and accurate assessment of physical activity than DLW alone.

8.3 INTRODUCTION

Athletes have elevated energy needs due to increased energy expenditure (EE). Therefore, the accurate measurement of physical activity (PA) parameters, such as EE and heart rate (HR), during periods of intense exercise, is important for their training. At maximum performance, athletes can expend 4-5 times their resting metabolic rate (RMR) and professional athletes have achieved an upper limit of sustainable metabolic rate 2 times greater than the general population (Westerterp, 2001). Athletes can become chronically energy deficient during prolonged bouts of exercise, indicating that their current nutritional practices do not adequately cover the energetic costs of their training programs, and that the availability and convertibility of their energy stores define an energetic ceiling for maximum performance (Loucks, 2004; Melzer, Kayser, Saris, & Pichard, 2005; Westerterp et al., 1986). Athletes are more susceptible to disordered eating habits due to increased physiologic demands from their respective sports (Bonci et al., 2008). Maintaining an adequate energy balance during the competitive season is important, as it is essential for the maintenance of lean tissue mass, immune and reproductive function, and optimized performance (Burke, 2001; Rodriguez, DiMarco, & Langley, 2000). As such, it is important to accurately assess EE.

The nutritional priority of athletes is to manipulate body composition and fuel stores in order to maximize performance during competition. Nutritional priorities can be categorized into acute (game-day) and chronic (seasonal), where acute nutritional programs focus on hydration and proper fuelling for the competition while chronic programs relate primarily to maintaining an adequate energy balance throughout the course of the training and competing season (Mujika & Burke, 2010). The goal of sports nutrition, therefore, is to maximize performance according to an athlete’s sport- and time-specific nutritional and training needs.

Body size, body composition, and stored metabolic fuels differ amongst athletes based on their specific sport. Energy spent during exercise exhibits large individual variances depending on the physical fitness level and body composition of the athlete. Indeed, the most variable component of total daily energy expenditure (TDEE) is activity associated with exercise, which can contribute up to 70% of TDEE (Koehler et al., 2011; Zhang, Pi-Sunyer, Xavier, & Boozer, 2004). Endurance athletes, for example marathon runners, tend to be smaller and have less body fat compared to strength and power athletes such as rugby players or weight lifters (Holway & Spriet, 2011). Intra-sport position-specific variations also exist in body size, most notably seen in American football players (Kraemer et al., 2005).

The energy requirements of athletes participating in either individual or team sports have been documented using a variety of EE techniques including the doubly labelled water method (DLW), HR monitoring (HRM), accelerometry, energy intake (EI) methods and combined multisensor systems (Ebine et al., 2002; Ekelund, Yngve, Westerterp, & Sjostrom, 2002; Koehler et al., 2011; Russell & Pennock, 2011; Santos et al., 2014; Silva et al., 2013). The DLW method is considered the gold standard for TDEE estimation in a free-living environment, representing an attractive choice for athletes as it allows them to engage in regular activities without restriction and requires minimal sampling (Schoeller, 1999). However, analyses for this technique require highly skilled technicians and the method has high measurement variability due a complex set of theoretical assumptions used in calculating EE as well as inter-laboratory differences in sample preparation and analysis, such as instrumentation, working standards, and calibration. Furthermore, DLW cannot distinguish between the various components of EE, such as resting metabolic rate (RMR), physical activity energy expenditure (PAEE), or thermic effect of food (TEF). On the other hand, improvements in motion sensor and HRM technologies allow for integration of multiple sensors into compact devices that provide more complete PA profiles, including the ability to accurately estimate PAEE. This results in more specific information pertaining to individuals during training (Drenowatz & Eisenmann, 2011; Johannsen et al., 2010; Koehler et al., 2011; Rousset et al., 2014). The increased functionality of wearable personal multisensor systems has improved their potential for PAEE estimation in athletes and may replace DLW as the more feasible and preferred choice for metabolic studies. This may be especially relevant for athletes, since PAEE can account for up to 70% of their TDEE (Koehler et al., 2011).

The purpose of this review is therefore twofold: 1) discuss the limitations of the use of the DLW technique for the determination of PAEE in athletes, and 2) to compare the relative strengths and weaknesses of EE devices, and to identify the best approach going forward.

8.4 MEASUREMENT OF ENERGY REQUIREMENTS IN ATHLETES

8.4.1 Energy Expenditure Assessment

Methods used to measure EE should be easy, practical, reliable and most of all, accurate (Levine, 2005). Lab studies often utilize direct or indirect calorimetry techniques, whereas field studies use free-living assessment tools such as DLW, HRM, and motion sensors (Leonard, 2012; Shephard & Aoyagi, 2012). Direct and indirect methods have been shown to record similar EE data in controlled environments (Seale, Rumpler, Conway, & Miles, 1990). Direct calorimetry is limited in its application, as participants are placed in thermally isolated chambers where the heat they dissipate is recorded and measured (Ainslie, Reilly, & Westerterp, 2003). This type of measurement can only be completed in a confined space, which limits PA, and is time consuming and expensive, and thus, not suitable for free-living EE assessments.

Indirect calorimetry tracks total energy production by measuring whole body oxygen uptake and carbon dioxide (CO_2) production as an estimator of metabolic rate (Koehler et al., 2010). Measuring the maximum rate of oxygen consumption during incremental exercise, the VO_2 max test is the most common method of indirect calorimetry used in performance testing (Noakes, 2000b). Indirect calorimetry is an accurate predictor of TDEE and fuel utilization during rest and steady state exercise, but cannot assess free-living TDEE and requires considerable care and expertise for reliable measurements (Ainslie et al., 2003; Macfarlane, 2001). The development of portable metabolic systems has shown promise, as validity results from these systems are generally deemed acceptable (Meyer, Davison, & Kindermann, 2005; Vogler, Rice, & Gore, 2010). However these systems are physically cumbersome and necessitate reliability and validation procedures in the field for future use in sport-specific applications (Macfarlane, 2001; Meyer et al., 2005).

8.4.2 Doubly Labelled Water

The development of the DLW method has allowed for accurate validation of dietary assessment methods and the ability to quantify energy needs and recommendations for athletes when EI is not known (Thompson & Manore, 1998). The DLW technique, first proposed by Nathan Lifson in 1955, was originally developed to measure EE in small animals (Lifson et al., 1955; Lifson & McClintock, 1966). The DLW technique measures CO_2 production by comparing the rates of turnover of oxygen (k_O) and hydrogen (k_D) from isotopically labelled water based on the observation that the biological elimination rates of labelled oxygen and labelled hydrogen in water are different (Bluck, 2008; Schoeller, 2008). Hydrogen is eliminated from the body by water loss, such as urine, saliva, and water vapour, whereas oxygen is eliminated by both water loss and through CO_2 exhalation. Oxygen is therefore eliminated from the body faster than hydrogen and the difference in their elimination rates yields a measure of CO_2 production, which can then be used to estimate TDEE by estimation of the respiratory quotient (RQ) or food quotient (FQ) (Schoeller, 2008).

TDEE from DLW is estimated indirectly through measurement of CO_2 production (Butler, Green, Boyd, & Speakman, 2004). Converting CO_2 into EE is achieved using estimates of RQ or FQ. The RQ is often estimated as the FQ derived from dietary records, which lack accuracy (Dhurandhar et al., 2015) and can introduce significant errors due to large individual variations in TDEE during exercise experienced by athletes.

PAEE from DLW can be derived from TDEE via subtraction of RMR and TEF, which is estimated as 10% of TDEE. However, quantifying and classifying the frequency, intensity, duration or type of PA during specific training periods is impossible to determine using the values derived from DLW analysis. There is a need to separate the EE derived from accumulated ambulatory exercise (daily mobility) from PAEE, as athletes will expend significantly more energy during training compared to non-athletes. Although DLW provides accurate estimates of TDEE, several technical and theoretical aspects limit its usefulness in the estimation of PAEE. These limitations are described below.

8.4.3 Doubly Labelled Water Limitations During High Energy Expenditure Situations

Using DLW, limited demands are placed on participants, as typically an overnight fast accompanies periodic urine and/or saliva samples after ingestion of an enriched dose of water containing ^{2}H and ^{18}O isotopes, for a study period of 4-21 days. Due to high activity levels in elite athletes, some of the fundamental considerations pertaining to the accuracy and validity of the DLW technique need to be addressed before its use is considered. The optimal observation period for the assessment of TDEE by DLW is 1-3 biological half-lives for ^{18}O and ^{2}H. During high activity levels, the half-lives of ^{18}O and ^{2}H decrease by about 1/3, reducing the study period to 7-10 days (Schoeller, 1983; Westerterp et al., 1986). Between 5-10% of total body water (TBW) is turned over daily, with sweat being the most variable and consequential cause (Sawka et al., 2005). TBW turnover is influenced by physical activity, as better-trained athletes have higher water turnover and metabolic rate, further reducing the half-life of the tracers (Shimamoto & Komiya, 2000).

Isotope fractionation is another important source of error during high activity levels, as the rate of water loss via fractionating gaseous routes increases (Cole et al., 1990; Westerterp et al., 1988). Isotope fractionation is a physical phenomenon that causes changes in the relative abundance of isotopes due to differences in their mass, creating either isotopically enriched or depleted samples (Cole et al., 1990). Fractionation between water vapour and both ^{18}O and ^{2}H, and between CO_2 and ^{18}O, are of interest, whereas little fractionation occurs in sweat and urine because these fluids are excreted as liquids. Without correction factors, the calculated CO_2 production rate becomes erroneous, and using correction factors, the calculated uncertainty in CO_2 production rate is less than 2% (Cole et al., 1990). Consequentially, the calculated CO_2 production rate is extremely sensitive to the turnover rates of oxygen and deuterium, which is not usually a concern in sedentary individuals. In athletes, however, because of the high water turnover and increased fractionation due to sweat, the differences are magnified and become a source of error in the measurement.

Correcting for background isotope abundance is another factor that contributes to error in the estimation of TDEE via the DLW method. Athletes travel quite often, thus the natural abundance of isotopes in the body varies with geographical latitude as well as the source and amount of food consumed (Horvitz & Schoeller, 2001). Heavy stable isotopes tend to be depleted closer to the poles compared to the equator because of isotopic fractionation that occurs during the global transport of water. As such, baseline enrichments must be corrected to adjust for any change in natural abundance related to water intake that may have occurred just prior or during the study (Jones et al., 1993). Uncorrected background abundances will introduce errors into the calculation of CO_2 production, as seen in patients beginning total parenteral nutrition (Schoeller, Kushner, & Jones, 1986).

DLW has been validated against several other techniques and shown to have an accuracy of 1-2% and a precision of 5-7% in well-controlled laboratory settings (de Jonge et al., 2007). However, the inherent cost of isotopes required for analysis limits its broad application. The method does not enable identification of the type, duration or intensity of exercise, and stops short of providing a measured PAEE for a given exercise, which is a crucial factor in the energetic assessment of athletes. For these reasons, other field-based EE techniques have been at the forefront of development in recent years (**Table 8.1**).

8.4.4 Heart Rate Monitoring (HRM) for PAEE Estimation

HRM represents a relatively cost-effective method of estimating EE because of the close association of HR with VO_2 and its ability to characterize the amount of time spent in high-intensity activity (Ainslie et al., 2003). HRM is mainly used to determine the exercise intensity of a training session and provides satisfactory estimates of EE on a group level, but is not a good predictor of TDEE in individuals (Spurr et al., 1988). In addition, intermittent EE cannot be measured as accurately using HR monitors because of the slow response of HR to sudden changes in work rate, limiting its use in high-intensity interval sports such as ice hockey and American football (Achten & Jeukendrup, 2003).

FLEX HR, an emerging method, is defined as the mean of the highest HR during rest and the lowest HR during light exercise, requiring individual HR and VO_2 calibration activities in the lab from which EE can be estimated along calibration curves (Brage, Brage, Franks, Ekelund, & Wareham, 2005; Leonard, 2003). FLEX HR has been shown to produce similar results to DLW and has been validated and reviewed (Ekelund et al., 2002; Livingstone et al., 1990). Issues remain regarding the calibration and whether or not the results translate well with free-living situations as consensus on the definition of FLEX HR has yet to be established (Leonard, 2003). However, this method offers a promising and lower cost alternative for measurement of EE relative to DLW.

HRM provides physiological monitoring of PA by identifying physiological strain during exercise. However, the method is reliant on individual calibration as it is subject to other stimuli, such as prescription drugs and stimulants, in order to improve the accuracy and precision of PAEE (Butte, Ekelund, & Westerterp, 2012). Concerns also exist regarding missing data. HR monitors pick up and register electric signals generated from the heart and is thus susceptible to interference from electric appliances (Assah et al., 2011). In addition, optimal signal detection requires good skin contact and, during high-intensity exercise, the electrodes attached to the chest may become loose, causing noise or loss of signal. However, cleaning and recovery algorithms have previously addressed these issues. The HR method has several other limitations as reviewed elsewhere that impact its reliability and accuracy compared to DLW (Davidson, McNeill, Haggarty, Smith, & Franklin, 1997; Livingstone, 1997). Used alone, HRM may not be the most appropriate choice for the measurement of PAEE, but when used in conjunction with other methods, such as accelerometry (described in detail below), it can offer athletes a more complete PA assessment.

8.4.5 Accelerometry for PAEE Estimation

Accelerometry is the most frequently used technique for the assessment of PA because of its suitability for field-testing and its potential for accurate measurements. This technique is considered the most practical and effective compromise between accuracy and feasibility (Johannsen et al., 2010; Warren et al., 2010). Activity monitors or motion sensors are wearable devices that measure body movement while accelerometers are sensors within the monitors that quantify the duration and intensity of exercise using algorithms to provide an estimate of EE (Crouter, Churilla, & Bassett, 2006). These devices are worn at the waist, ankle, wrist, or forearm and are minimally intrusive to normal subject behaviour, although intrusiveness could become problematic during in-season competition for certain sports, such as baseball, ice hockey, and water sports such as distance swimming.

Body movement is commonly measured using piezoelectric sensors that detect acceleration across different planes and convert the mechanical motion into electric signals, providing immediate activity estimates, whereas DLW cannot provide minute-to-minute expenditure data, limiting its ability to accurately predict PAEE (Ainslie et al., 2003). Activity monitors have been successfully validated against DLW (Berntsen et al., 2010; Ishikawa-Takata, Kaneko, Koizumi, & Ito, 2013; Leenders, Sherman, Nagaraja, & Kien, 2001; Leenders, Sherman, & Nagaraja, 2006; Plasqui & Westerterp, 2007; St-Onge, Mignault, Allison, & Rabasa-Lhoret, 2007; Tudor-Locke et al., 2012). However, similar to DLW, several challenges exist that limit their usefulness in the collection, processing and interpretation of data, especially during high-intensity exercise.

The most significant drawback associated with accelerometry is a linearity of response, ie: the overestimation of EE during low-intensity exercise and the underestimation of EE during high-intensity exercise (Anastasopoulou et al., 2014; Crouter et al., 2006). Used independently, activity monitors are unable to distinguish different types of activities and movements(Butte et al., 2012). These monitors can only reliably detect dynamic movements, such as walking and jogging, and significantly underestimate non-ambulatory activity, such as carrying a load, hill climbing, bicycling and resistance exercise, as the accelerometer output is not proportional to the increase in expenditure (Corder, Brage, & Ekelund, 2007; Ekelund, Yngve, Brage, Westerterp, & Sjostrom, 2004; Leenders et al., 2006). Accelerometers cannot measure fatigue, which increases proportionally with exercise intensity, and thus would underestimate PAEE during high-intensity exercise, as a plateau effect occurs around 10 METs, which is equivalent to running 6 mph (Chen & Bassett, 2005; Drenowatz & Eisenmann, 2011).

Similar problems occur when walking up and down stairs, as monitors do not perceive the increase in energetic cost because the acceleration pattern remains similar to normal walking and results in the underestimation of PAEE (Anastasopoulou et al., 2014). Improving the accuracy of activity monitors often means increasing their complexity as is reflected in their price, size, and comfort (**Table 6**) (Bonomi, Plasqui, Goris, & Westerterp, 2009; Zhang et al., 2004).

Perhaps the greatest issue concerning the use of stand-alone activity monitors is not the underestimation of free-living EE during high-intensity exercise, but the lack of standardization and quality control that make their cross-device comparison increasingly more difficult for validation purposes. Most of these devices obtain kinetic data from accelerometers, but internal processing leads to different outputs, generally termed "counts", that cannot be compared between monitors due to differences in data acquisition, processing, filtering, and scaling (Welk, Mcclain, & Ainsworth, 2012). In order to facilitate cross-comparison amongst devices, storage of the raw data using international standards is recommended (Intille, Lester, Sallis, & Duncan, 2012). Welk et al. (2012) and Intille et al. (2012) have provided an in depth analysis regarding the current and future state of the standardization of activity monitors (Intille et al., 2012; Welk et al., 2012).

Table 8.1. Summary of methods for the evaluation of PAEE in athletes.

Technique	Duration of Use	Cost	Advantages	Limitations	References
Direct Calorimetry	1-7 days	\$\$\$\$\$	Precise measurement of EE	Not suitable for free-living situations; extremely high costs	(Ainslie et al., 2003; Leonard, 2012)
Indirect Calorimetry	<12 hours	\$\$\$	Accurate measurement of EE and fuel utilisation during rest and steady state exercise	Not suitable for free-living situations; high costs and expertise required for analysis	(Macfarlane, 2001; Meyer et al., 2005; Seale et al., 1990; Vogler et al., 2010)
DLW	1-3 weeks	\$\$\$\$	Ideal field method (limited participant requirements); considered safe; measures EE over the entire study period	High costs of ^{18}O limits its use in large groups; requires sophisticated analytical equipment and technical support; cannot separate components of EE (TEF, RMR, PAEE)	(Butler et al., 2004; de Jonge et al., 2007; Ebine et al., 2002; Jones et al., 1993; Schoeller & van Santen, 1982; Schoeller, 1999; Schoeller, 2008; Westerterp et al., 1986)
HRM	1-3 weeks	\$	Determines the exercise intensity of a training session; cost-effective method of estimating EE;	Large individual error in EE estimation; requires individual calibration as it is subject to stimuli such as prescription drugs and stimulants	(Ekelund et al., 2002; Leonard, 2003; Spurr et al., 1988)

			reusable		
Accelerometry	1-2 weeks	$	Most frequently used technique; provides a practical and effective compromise between accuracy and feasibility; minimally intrusive; provides instantaneous data	Overestimates EE during low-intensity exercise and underestimates at high-intensity; unable to distinguish different types of activities and movements; can only reliably detect dynamic movements; cannot measure fatigue	(Anastasopoulou et al., 2014; Corder et al., 2007; Crouter et al., 2006; Johnstone, Murison, Duncan, Rance, & Speakman, 2005; Leenders et al., 2006; Warren et al., 2010)
Multisensor Systems	1-10 days	$$	Combines physiological and mechanical measures that are considered less error prone than single measurement devices	Underestimates PAEE during high-intensity exercise; require further validation during high-intensity exercise	(Calabró, Stewart, & Welk, 2013; Drenowatz & Eisenmann, 2011; Duncan, Lester, Migotsky, Higgins, & Borriello, 2012; Koehler et al., 2011; Van Remoortel et al., 2012)

DLW doubly labelled water, *HR* heart rate, *EE* energy expenditure, *TEF* thermic effect of food, *RMR* resting metabolic rate, *PAEE* physical activity energy expenditure

8.4.6 Multisensor Approach for PAEE Estimation

In more recent years, the multisensor approach integrating physiological and mechanical measures into a single device has developed into an acceptable and more accurate method for the determination of PAEE. Combining accelerometry with body responses to exercise, such as HR and body temperature, into one device providing a more complete PA assessment is considered less error prone than single measurement devices (Van Remoortel et al., 2012).

The SenseWear Armband (SWA; BodyMedia, Inc., Pittsburgh, PA) is a multisensor device that integrates 5 sensors including a two-axis accelerometer, together with a heat flux sensor, skin temperature sensor, near-body ambient temperature sensor, and galvanic skin response sensor into an armband that is worn on the upper arm. The device is practical and comfortable, as it attaches via an elastic strap, and requires no tape unlike most HR monitors, increasing its ability to assess wear time, which is important for the accurate estimation of PAEE. The SWA has been validated in free-living adults (Assah et al., 2011; Berntsen et al., 2010; St-Onge et al., 2007) and children (Arvidsson, Slinde, & Hulthén, 2009; Calabró et al., 2013) and during low-moderate intensity exercise (Fruin & Rankin, 2004; Jakicic et al., 2004). However, the approach requires further validation during high-intensity exercise, as the armband consistently underestimates PAEE (Brazeau et al., 2014; Drenowatz & Eisenmann, 2011; Johannsen et al., 2010; Koehler et al., 2011; Koehler, De Marees, Braun, & Schaenzer, 2013).

The underestimation of PAEE during high-intensity exercise is proportional to the increase in exercise intensity (Drenowatz & Eisenmann, 2011; Koehler et al., 2011). A strong correlation between running speed and raw acceleration data has been observed, indicating that the armband's output is sensitive to small speed changes during high-intensity running and that running-specific prediction equations are needed to improve expenditure measurements(Koehler et al., 2013). The pattern recognition algorithms used to estimate EE are continuously updated and improved with newer models (Lee, Kim, Bai, Gaesser, & Welk, 2014). For example, the SenseWear Mini uses a triaxial accelerometer, whereas its predecessor used a biaxial accelerometer, and has been recently validated against DLW (Calabró et al., 2013). Assessing body posture and body movement using GPS, Bluetooth® systems and barometers potentially provides a future direction in monitoring of PAEE of athletes, but require further validation studies (Duncan et al., 2012; Van Remoortel et al., 2012).

Other monitors such as the Actiheart and the Intelligent Device for Energy Expenditure and Activity (IDEEA; MiniSun, Fresno, CA) have been recently developed as alternatives to the SWA. The Actiheart is a combined HR and movement monitor that is designed to clip onto 2 standard electrocardiogram electrodes on the chest (Brage et al., 2005). The system requires further validation, as it has only been validated against DLW in free-living conditions on 3 occasions (Assah et al., 2011; Rousset et al., 2014; Villars et al., 2012). No significant mean bias was found between the PAEE measured from the Actiheart or measured by DLW, indicating that the Actiheart is a valid tool for EE estimation as long as regular individual calibration practices occur.

The IDEEA is a microcomputer-based portable PA measurement device that identifies the type, duration, frequency, and intensity of PA (Zhang et al., 2004). This unit consists of 5 sensors attached to the skin via hypoallergenic tape. The multisensor array is able to correctly identify 32 different types of activity 98.7% of the time and is able to correctly determine the duration and intensity of walking and running (Zhang, Werner, Sun, Pi-Sunyer, & Boozer, 2003). The estimated EE was also calculated as 95% accurate when compared to values obtained in a calorimetry chamber (Zhang et al., 2004). This new method of determining EE from such multisensor systems provides promise as the reliability and accuracy of the data improve. However, the most substantial drawback is the need for multiple wires connecting different anatomical regions, which can interfere with or detach as a result of movement during PA (Zhang et al., 2003).

8.5 ENERGY INTAKE ASSESSMENT

Although we have only focused on one side of the energy balance equation and realize that EI assessments are also important in estimating the energy needs of athletes, the use of assessment tools for EI is highly criticized for their lack of accuracy and validity and under much scrutiny. A recent review on energy balance measurements asserts that EI methods should be, “recognized as inaccurate measurements by the scientific and funding communities” and that “their use should be discontinued” as they may “cause misguided […] health care advice to individuals” (Dhurandhar et al., 2015). Measuring EI in free-living individuals is reliant on self-reporting, which is fraught with biases and errors. On the other hand, no other, more accurate, method for collecting EI data exists (Schoeller, Bandini, & Dietz, 1990). Many of the techniques currently available are labour-intensive and time-consuming. Furthermore, error is often introduced subjectively, as being observed can affect an individual’s intake and recording errors often occur due to memory and reliability issues when data are collected retrospectively (Ballew & Killingsworth, 2011; Burke, Cox, Culmmings, & Desbrow, 2001). Although EI assessment methods provide cheap alternatives for the estimation of TDEE compared to other EE techniques, some have called for their use to be discontinued due to the substantial degree of error inherent in these techniques (Dhurandhar et al., 2015.

8.6 CONCLUSION

The current shift away from the use of EI methods to estimate energy requirements in athletes places an importance on the accurate measurement of TDEE. Quantifying the energetic cost of exercise is the first step towards the development of more robust and accurate EI methods. The inherent variability in energy requirements of various sports and amongst the physical fitness levels of individual athletes increases this importance. The DLW method allows for an accurate analysis of the TDEE of athletes, however, the derived values of PAEE from DLW lack the specificity that can be gained through the use of combined multisensor systems. Therefore, the energy estimates from the DLW method are not reflective of the specific exercise itself. Consequentially, energy requirements derived from these studies are highly dependent on variables surrounding the athlete, type of sport (team or individual), and the competition itself, not withstanding variability in environmental conditions. Using indirect calorimetry for the estimation of RMR and accelerometers equipped with HR monitors for the assessment of PAEE provides a more accurate assessment of PA in athletes compared to the DLW method.

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SUMMARY AND FUTURE DIRECTIONS

This field study provided an opportunity to re-visit the energy requirements and body composition changes of CAF during a cold winter exercise. Using the doubly labelled water method and the 4-day food waste collection method, energy expenditure (*n=10*), body composition (*n=14*) and energy intake (*n=18*) were assessed. TDEE exceeded 4900 kcal·day^{-1}, while EI was roughly 2100 kcal·day^{-1} and led to an energy deficit of roughly 2800 kcal·day^{-1}. As a result, body mass and body composition of CAF changed significantly during the 5-day winter training exercise. However, only 53% of the rations were consumed daily, indicating that a greater priority on meal consumption should be recommended during intense exercise. Despite the large energy deficit, participants were able to maintain high PAL and TDEE levels throughout the study period. Although limited by sample size and observational length, the results of this study suggest that CAF are severely energy deficient during training exercises and it is recommended to provide additional supplements in bar format to promote EI. To provide more credence to these claims, further research is warranted for the estimation of energy requirements during similar training exercises in the extreme heat and temperate conditions.

Following the results of the trial, a critical appraisal of the current state of energy expenditure estimation techniques was assessed. Future directions in the field of energy estimation articulate around advances in motion sensor technology that allow for more robustness in the estimation of TDEE. The combination of indirect calorimetry and the quantification of PAEE using compact, not-intrusive multisensor devices is recommended in future studies. Such combinations would allow for the precise assessment and comparison of energy requirements of military personnel operating in varying environmental stresses.

APPENDIX A

Table A.1. Individual energy expenditure data as measured by the DLW method.

Identifier	Sex	Δ BM (kg)	Δ FM (kg)	Δ BF%	TDEE (kcal·day^{-1})	TDEE·kg FFM (kcal·day^{-1}·kg^{-1})	PAL
PAN100	F	-0.64	-4.22	-6.09	3911.43	82.73	2.14
PAN102	M	-3.37	-5.32	-5.72	5523.44	95.14	2.87
PAN104	F	-2.77	-1.96	-1.05	5200.25	88.14	2.56
PAN105	M	-1.04	-4.59	-5.53	5229.98	92.96	2.65
PAN106	M	-1.09	-3.20	-4.11	3761.01	58.84	2.07
PAN113	M	-4.06	-4.95	-0.67	5985.42	91.04	2.71
PAN114	M	-1.27	-5.20	-0.14	5089.20	68.28	2.38
PAN115	M	-2.49	-4.30	-5.91	5006.53	88.05	3.07
PAN117	F	-1.95	-1.74	-5.31	4429.47	84.60	2.47
PAN118	F	-1.18	-0.38	-0.70	5029.35	88.14	2.68
Average		-1.99	-3.18	-3.52	4916.61	83.79	2.56
SD		1.14	1.64	2.55	693.06	11.48	0.31

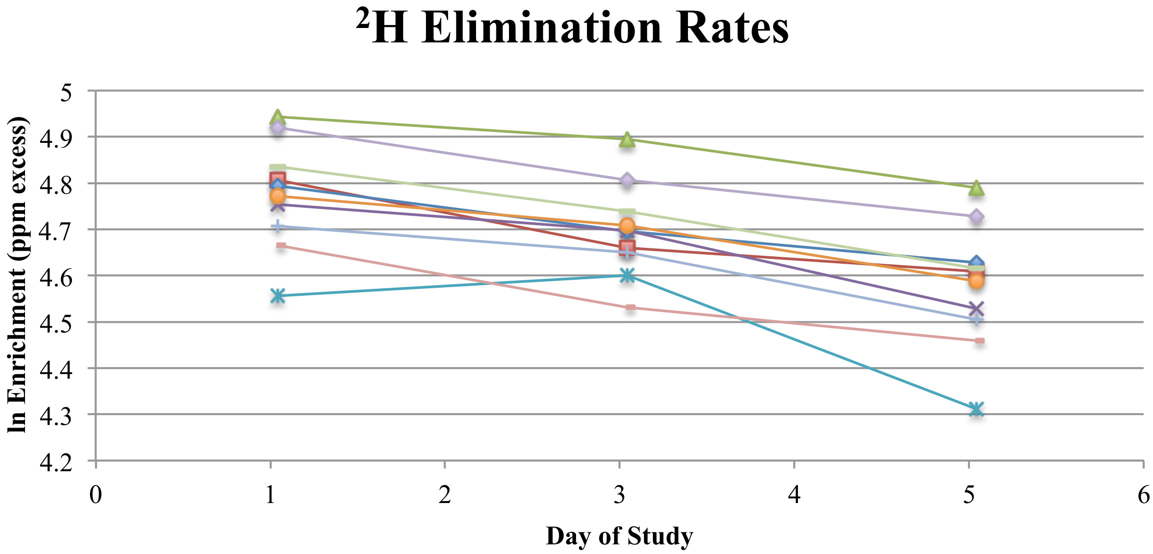
Note: values are presented as means.

Table A.2. Elimination rates, total body water, and energy expenditure.

	k_D (day^{-1})	k_O (day^{-1})	TBW (kg)	TDEE (kcal·day^{-1})
Males (n=6)	-0.07±0.04	-0.11±0.04	45.80±5.15	5099.27±676.15
Females (n=4)	-0.06±0.01	-0.10±0.01	39.47±3.83	4642.62±559.46
Total (n=10)	-0.07±0.03	-0.10±0.03	43.27±5.51	4916.61±693.06

Note: values are presented as means ± SD. k_D, ^{2}H elimination rate constant, corrected for change in baseline isotope abundance; k_O, ^{18}O elimination rate constants, corrected for change in baseline isotope abundance; TBW, average total body water; TDEE, total daily energy expenditure measured by doubly labelled water.

Figure A.1. ^{2}H and ^{18}O elimination rates.


^{2}H Elimination Rates

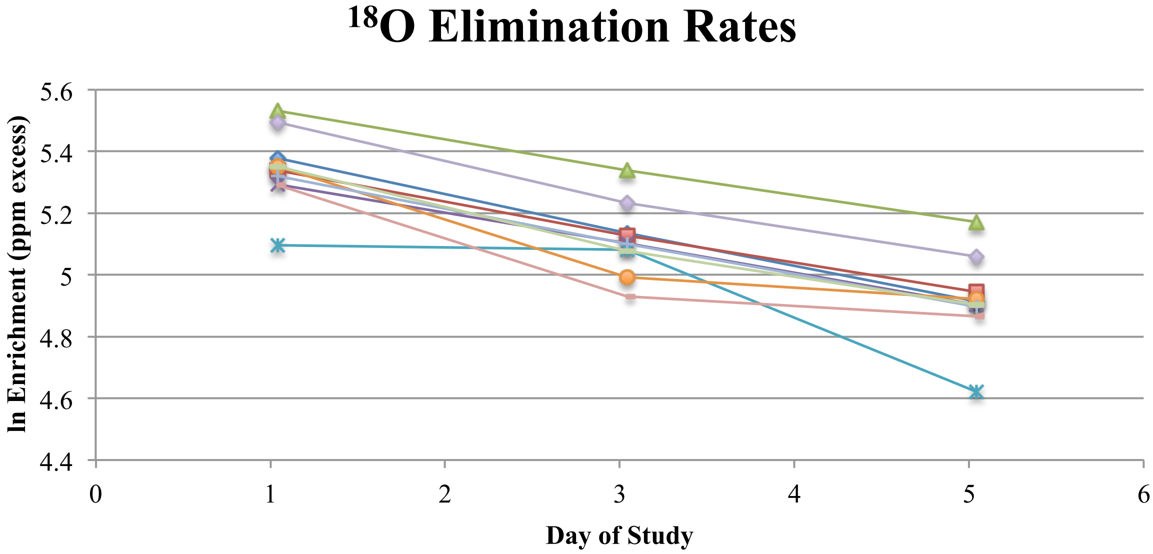

^{18}O Elimination Rates

Figure A.2. ^{2}H and ^{18}O enrichments in urine.