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DEVELOPMENT AND BIOMEDICAL TESTING OF MILITARY OPERATIONAL RATIONS[1]

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ABSTRACT

This article gives a brief history of military nutrition research in this century and reviews recent advances made through field testing. Although modern rations are nutritionally complete, ration developers are challenged to improve palatability to promote increased intakes in field training and combat settings. The principal goal for military nutritionists is to identify the optimal macronutrient mix and specific ration components that sustain a soldier's performance in the face of operational stressors such as sleep deprivation, intense physical activity, climatic extremes, and hypobaric hypoxia. Energy expenditures during typical field-training exercises average approximately 4000 kcal/day, whereas energy intakes are usually 3000 kcal/day or less when operational rations are consumed. One way to ameliorate the effects of this shortfall is to provide soldiers with a carbohydrate beverage supplement.

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INTRODUCTION

Operational rations are the packaged food items used to sustain soldiers when they are in the field, where regular kitchen facilities and fresh food are not available. These individual rations are intended to meet the Military Recommended Daily Allowances (MRDA). Some situations—such as long-range patrols, assault, and reconnaissance—require troops to temporarily subsist on a light-weight restricted ration. Restricted rations provide less than optimal nutrition, especially with long-term use, but they improve the likelihood of a successful mission by reducing the soldier's burden. Current military nutrition research seeks to develop ration components and feeding strategies that sustain performance in the face of operational stressors such as sleep deprivation, climatic extremes, hypobaric hypoxia, and continuous operations (25).

In 1917, a Nutrition Division was established in the Office of the Surgeon General to safeguard the nutritional interests of the Army. The division's task was to conduct surveys at army camps to quantitatively determine the consumption and wastage of food, and to evaluate whether rations met the nutritional requirements of the soldiers (81). An expert advisory council was also established, largely composed of individuals recognized today as founders of the science of nutrition research (98).

Military nutrition research guided by outside expert advisors has continued to the present, with the exception of a brief hiatus in the early 1980s. The highly successful nutrition research program at Letterman Army Institute of Research was closed when micronutrient deficiencies in soldiers were no longer routine findings and the US Department of Agriculture assumed the federal government's lead in general nutrition research. In 1984, Colonel David Schnakenberg reestablished the Army Nutrition Research Program, meeting the need for scientific research to guide the development of new operational rations.

In recent years, ration development has involved a collaborative effort among several institutions. Coordination within the government is provided by the Interagency Committee on Human Nutrition Research. The Secretary of the Army has overall responsibility for food and nutrition research

Table 1 Major workshops by the Committee on Military Nutrition Research[a]

1984	Cognitive testing methodologies for military nutrition research (83)
1984	Predicting decrements in military performance due to inadequate nutrition
1987	Calorie-dense rations (68)
1989	Use of carbohydrate-electrolyte beverages for fluid replacement (63)
1990	The relationship of soldier body composition to physical performance (69)
1991	Nutrient requirements for work in hot environments (62)
1992	Can food components be used to enhance soldier performance? (64)
1993	Not eating enough, overcoming underconsumption of military operational rations (65)
1994	Nutritional needs in cold and in high-altitude environments (66)
1995	Emerging technologies for nutrition research: potential for assessing military performance capability (15a)
1996	Nutritional sustainment of immune function in the field (RB Costello & SJ Carlson-Newberry, manuscript in preparation)
1997	Protein requirements for operational environments (RB Costello & SJ Carlson-Newberry, personal communication)

[a]Copies of these reports are available from National Academy Press, 2101 Constitution Avenue NW, Washington, DC 20418.

for the Department of Defense. Critical participants in this program include (*a*) food technologists and psychologists at the Natick Research Development and Engineering Center, Natick, MA; (*b*) biomedical researchers at the US Army Research Institute of Environmental Medicine, Natick, MA; (*c*) expert consultants from the Committee on Military Nutrition Research of the Food and Nutrition Board at the Institute of Medicine/National Academy of Science, Washington, DC (Table 1); (*d*) researchers at the Pennington Biomedical Research Center at Louisiana State University, Baton Rouge, LA; (*e*) logisticians at the Quartermaster Center and School at Fort Lee, VA; and (*f*) dieticians in the Office of the Surgeon General, Falls Church, VA. The Army Surgeon General is responsible for evaluating operational rations and for recommending changes needed for rations to meet nutritional requirements in all operational environments (107a).

Research is changing the way warfighters are sustained nutritionally. Instead of focusing on providing a nutritionally balanced meal, emphasis is being placed on providing nutrition that meets metabolic needs in specific operational settings. In the future, soldiers in a high-stress situation will drink maltodextrin beverages (26, 52), possibly with glycerol (34, 61, 76), which supplements energy intake and reduces hypohydration in extreme environments. They may munch on candy bars loaded with neurochemical precursors such as tyrosine (9, 59, 60, 84, 101) and use caffeine (86) or melatonin (16) during rapid deployments and night operations. Antioxidants and phytochemical-enriched rations may offer protection from mechanical and biochemically induced injury such as tissue trauma, immune suppression, and acute toxicity (102, 103).

It is expected that some day the timing, quantity, and specific types of ration components ingested will be tailored both to individual metabolic needs as predicted by physiological profiles and to a particular mission's requirements. To meet these goals, new research tools and approaches need to be used (15a), for example, ambulatory monitors, which "learn" their soldier, gathering data on metabolic stress and sleep status in the field (12, 45). Through innovative research and ration development the metabolic demands of the modern soldier, who must often work under highly stressful and cognitively demanding conditions, can be met.

OPERATIONAL RATION TESTING

Evolution of Modern Operational Rations

The basic requirements for operational rations have not changed much in 200 years: The goal has been to provide a nutritionally adequate ration that maintains the health and performance of the soldier. Advances in food technology have reduced the weight and bulk and extended the shelf life of prepackaged rations. Current rations are simpler to prepare, and attempts have been made to accommodate changes in gastronomic expectations of soldiers. These factors are important given that soldiers may be deployed on short notice to anywhere in the world.

Originally, field rations were simply issues of meat, bread, and beans prepared in the field by individuals or small groups (75). In the Civil War, food was prepared for whole companies. In 1896, an individual emergency (haversack) ration was established, followed by garrison, field, and travel rations. By World War I, the reserve (or field) ration for individual use consisted of canned meat, hard bread, coffee, salt, sugar, and a cube of soup. This ration provided about 3300 kcal and weighed nearly 3 lb. The emergency ration contained three 3-oz cakes of beef powder and cooked wheat and three 1-oz chocolate bars. Shortly before World War II, this ration was replaced by the D ration. This was the first food packet in the military supply system. It was followed by numerous other nutrient-dense items intended for use when other means of subsistence failed or when resupply was limited (75). Johnson & Kark (50) summarized the ration development efforts of the 1940s: "There is a limit to the weight and bulk of equipment the soldier can carry. There is a natural desire to carry lethal weapons and ammunition to the greatest extent and to cut down the weight and bulk of rations. This has been reflected in the planning in three distinct ways: (*a*) cutting down the caloric content of a day's ration; (*b*) attempting to increase caloric density by providing high fat and low water contents, as in dehydrated food and biscuits; and (*c*) developing single component non-perishable rations such as the D bar and pemmican."

The K ration was the first packaged ration intended for use on a meal basis and one most remembered by troops and researchers alike. Dr. W. B. Bean summarized the common observations succinctly (10): "Dr. Ancel Keys had preceded us in the desert. He reported favorably on K rations. But we followed a path of a maneuvering unit by the trail of discarded K biscuits. Even small desert rodents avoided them... Experts who designed the ration must have thought in terms of animal husbandry. They concluded that each ration each day should have the liberal allowance of vitamins, etc., recommended by the Food and Nutrition Board. To get such constituents within the physical requirements of an emergency ration, brewers yeast, soybean flour, and liver extract had to be added. This was not what one would recommend offhand for flavor." The early World War II ration development effort emphasized nutrient density and not acceptability, prompting Dr. Bean's truism that "a ration is no good if it is not eaten" (10).

Other researchers of the era refuted the fallacy that US soldiers will eat anything when they get hungry, a recurring misconception even today: "Experience in the field and in trials has demonstrated again and again that North American soldiers would rather let themselves become sick and inefficient than live on single-component rations; that rations of very high caloric density, such as the British 24-hr ration, soon become monotonous because of food items that are unusual in texture, taste and consistency; and that reduction of caloric supply below requirements inevitably produces military deterioration" (50).

Many successive generations of individual rations labeled as "C rations" occurred between just before World War II until the 1980s, when the replacement ration, the Meal, Ready-to-Eat (MRE), was fielded.

Nutritional standards for rations have evolved gradually since World War I, as reviewed by Schnakenberg (99). For the last 50 years these have been directly traceable to the Food and Nutrition Board (FNB) standards. The FNB of the National Research Council was organized in 1940 in conjunction with the Defense Program (99) to help establish nutritional standards. US military ration standards today are adapted from the 1980 edition of the Recommended Daily Allowances. The MRDAs provide nutrient intake guidelines for groups of soldiers consuming operational rations over a period of several days. Separate nutrient standards for operational and restricted rations are used to evaluate the nutritional adequacy of rations being developed or in use (99). The current standards as elaborated in the triservice regulation *Nutritional Allowance, Standards, and Education* (107a) are shown in Table 2.

Nutritional Adequacy of the MRE and Weight Loss in the Field

The MRE is intended to deliver a nutritionally balanced meal, including an adequate supply of all micronutrients, as well as meet other challenging goals

Table 2 Nutritional standards for MRDA and rations (107a)[a]

Nutrient	MRDA Male	MRDA Female	Rations Operational	Rations Restricted
Energy (kcal)	3200[b]	2400	3600	1100–1500
Protein (g)	100	80	100	50–70
Carbohydrate (g)	—	—	440	100–200
Fat (g)	(<35% of total energy intake)		<160	50–70
Vitamin A (μg RE)	1000	800	1000	500
Vitamin D (μg)	5–10	5–10	10	5
Vitamin E (mg TE)	10	8	10	5
Ascorbic acid (mg)	60	60	60	30
Thiamin (mg)	1.6	1.2	1.8	1.0
Riboflavin (mg)	1.9	1.4	2.2	1.2
Niacin (mg NE)	21	16	24	13
Vitamin B_6 (mg)	2.2	2.0	2.2	1.2
Folacin (μg)	400	400	400	200
Vitamin B_{12} (μg)	3.0	3.0	3.0	1.5
Calcium (mg)	800–1200	800–1200	800	400
Phosphorus (mg)	800–1200	800–1200	800	400
Magnesium (mg)	350–400	300	400	200
Iron (mg)	10–18	18	18	9
Zinc (mg)	15	15	15	7.5
Iodine (μg)	150	150	—	—
Sodium (mg)	—[c]	—	5000–7000	2500–3500
Potassium (mg)	—[d]	—	1875–5625	950–2800

[a]MRDA, Military recommended daily allowance; RE, retinol equivalent; TE, alpha-tocopherol equivalent; NE, niacin equivalent.

[b]In cold-weather operations, the MRDA for energy increases to 4500 kcal/day for men and 3500 kcal/day for women.

[c]No MRDA established. The safe and adequate levels published in the recommended daily allowance are considered to be unattainable in the military food service system; an average of 5500 mg for men and 4100 mg for women is the target.

[d]No MRDA established. The safe range is 1875–5625 mg.

(22). In 1983, the MRE replaced the Meal, Combat Individual (MCI), usually referred to as the C ration.

Although development began in the 1970s, the nutritional adequacy of the MRE was not immediately assessed because of preoccupation with the change in packaging from tin cans to a flexible pouch. By the time the need for biomedical testing of the MRE was recognized (in the early 1980s), the Army had eliminated its nutrition research program. Ironically, one of the last research proposals written was for the 90-day field evaluation of the proposed MRE. Reconstituting the Army's nutrition research program would take time.

Laboratory and field tests of the MRE were conducted in 1983, just prior to it being fielded. Stocks of the MCI were rapidly being depleted and some military units were already eating the MRE and complaining about gastrointestinal problems (39). In a 44-day laboratory study, college students fed only the MRE consumed over 3000 kcal/day and lost only 1.5 pounds (39). In an operational field setting, ration consumption was significantly lower. A group of soldiers training at the Pohakuloa Training Area in Hawaii were fed three MREs daily for one month while another group received two hot, cook-prepared meals (A rations) and one MRE daily (40). The MRE group consumed only 2200 kcal/day and lost 10 lb, or nearly 5% of initial body weight, compared with 4.7 lb lost by the group receiving A rations (58, 109). Although the MRE was already in use, the unacceptably high weight loss observed in this field test resulted in retention of the "limited use" policy already in place for the old MCI. The policy stated that "although nutritionally adequate, the ration would not be used as the sole source of food for periods in excess of 10 consecutive days."

More field testing of the MRE was ordered by the Vice Chief of Staff of the Army, General Maxwell Thurman. He wanted assurances from his medical researchers that "this new ration gets adequately tested and fixed, if necessary, to ensure that we will maintain the health and performance of our soldiers when they have to eat this ration for extended periods. We may not have the cooks or the equipment there to serve them a freshly prepared, hot meal" (99).

A formal Army Operational Test involving 1600 soldiers was conducted, once again using the Pohakuloa Training Area in Hawaii (3). This 44-day study compared ration acceptability and consumption, and the nutritional and physiological status of soldiers consuming various combinations of hot, cook-prepared field rations (A and B rations), group operational rations (the tray "T" ration), and the MRE. No groups received the MRE as the sole source of subsistence. The study found that ration consumption met the criteria of good acceptance (65–70% overall consumption) and that the soldiers maintained physical performance and body weight (3). The only nutritional deficiency found relative to MRDAs was the calcium intake of female soldiers. Specific recommendations arising from this study included the following: adding a flavored beverage powder to all MREs to provide more carbohydrate and encourage water consumption; fortifying the MRE cocoa beverage powder with 200 mg of calcium; and increasing the portion size of MRE and T-ration entrees. The review also concluded that there was no need for a vitamin or mineral supplement if calcium fortification was accomplished (99).

These field studies resulted in an MRE improvement program designed to improve soldier acceptance and to increase intakes. Changes to the MRE included adding new menus, replacing old items, increasing entree size from 5 to 8 oz, adding fruit-flavored beverage powders, providing Tabasco sauce in each meal, replacing some dehydrated fruits with wet-pack fruits, and adding commercial candies. Modification of the MRE has resulted in greater acceptance and increased intakes in subsequent field studies (e.g. 89). During the Persian Gulf War, additional improvements included an innovative shelf-stable bread in a standard MRE pouch, a palatable chocolate that would not melt in the desert heat, and a flameless (chemical) ration heater pouch that provided an easy way to heat the entree (22). Improvements in the MREs and the associated research efforts in food technology are reviewed elsewhere (24, 39, 74).

Although the Surgeon General's recommendation was to limit intake of the MRE to no more than 10 days of sole-subsistence use, there was a continuing requirement to reevaluate this policy for improved versions of the ration. Furthermore, the evidence that led to this limitation was body weight loss in excess of 3% in 30 days, a level of weight loss that has not been associated with deficits in physical or psychological test performance (35, 72). There was also a need to know the consequences of a prolonged diet of MREs, even if this revealed degraded performance. As General Thurman had predicted in 1985, combat troops have since relied on MREs for periods in excess of the official policy. Some troops in the Persian Gulf subsisted on MREs for periods of 60 days or longer during Operation Desert Shield (22). Anecdotal information about large weight losses among soldiers subsisting on MREs in the Persian Gulf was never confirmed but is believable.

In one of the General Officer briefings on the results of an early MRE test, researchers were told: "Inadequate consumption of the MRE is just a peacetime problem. During combat, troops will eat anything rather than go hungry." Observations collected from field researchers in World War II indicate otherwise. Johnson & Kark (50) observed that "by the time men reach the eat-anything stage it may be assumed that the stage of optimum nutrition has been left far behind." Dill (50) observed in the North African theater: "Reports of 20–40 pounds lost in 2 months at the front are not rare. Although initially popular with the American soldier due to its novelty appeal the K ration is now detested. There are authenticated cases of the continuous use in combat of C or K rations singly or combined for as long as 67 days, with very serious deterioration in combat efficiency."

A 30-day MRE study was finally conducted with an engineering unit during a field exercise at Fort Chaffee, AK, to determine the health and performance consequences of long-term consumption (107). Ration intakes, body composition, hydration status, subjective symptoms, and acceptance of the ration were assessed in male soldiers receiving only the MRE in comparison to a group receiving A rations. In 30 days, the MRE group lost 6.8 lb (3.8% of initial body weight), double the rate of loss in the A-ration group. However, the greatest weight loss occurred in soldiers who were intentionally trying to lose weight to meet Army body-fat standards. Nondieting participants lost 3.1% (MRE group) and 1.2% (A-ration group) of initial body weight during the 30-day test.

Hydration status remained normal, and dual energy X-ray absorptiometry and anthropometry showed the weight loss was almost exclusively fat. The weight loss was attributable to a 600-kcal/day deficit relative to total daily energy expenditures of 3000–3200 kcal/day. Only half of the carbohydrates provided were consumed; however, even with deficient energy intakes, the highly fortified ration provided more than 100 g of protein/day.

Although calcium, vitamin B_{12}, zinc, iron, magnesium, and folacin intakes were below the MRDA, nutritional status was unaffected over the 30-day study (107). This is consistent with other studies where the bioavailability of nutrients from MREs (and from body stores) is adequate to maintain serum levels even when amounts lower than the prescribed MRDA standards are consumed (5, 58, 78, 79, 109). On the basis of this study, the policy on MREs has been changed to permit its use as the sole means of subsistence for 21 consecutive days. For good morale, commanders are still encouraged to provide fresh foods and kitchen-prepared meals whenever feasible.

A key goal is to improve MRE palatability. A Committee on Military Nutrition Research workshop focused on why soldiers in the field do not eat enough to maintain their weight from the perspective of psychologists and food technologists (65). Discussions encompassed a field study where soldiers fed hot A rations at regular times maintained body weight, whereas those eating operational rations lost weight (94). In this instance, food palatability and the availability of time to prepare and eat were more important determinants of food intake than was the work environment per se. This was consistent with other observations that college students maintained weight eating the MRE in laboratory studies, whereas soldiers lost weight consuming the ration in the field (39). Ration developers are continuing to offer new recipes, and food psychologists are actively seeking ways to make a limited number of menu choices more attractive to soldiers (74).

Typically, military rations have been used to nourish healthy young adults, but in recent disaster and refugee relief missions, rations have been the first foods provided to populations for which they were not specifically intended. To accommodate various ethnic and religious dietary customs, the Multi-Faith Meal (MFM), satisfying halal, kosher, and vegetarian needs, has been developed.

FUNCTIONAL TESTS APPROPRIATE TO RATION EVALUATION

Military medical research is necessarily problem-oriented. The design of nutrition field studies as well as the choice of outcome measures depends on current concepts for the future battlefield (e.g. "Army After Next," "Navy Vision 2020," and "Operational Maneuver From the Sea"). Increasing technological complexity and lethality on the digitized modern battlefield requires correct and timely responses from human operators. No longer hampered by nightfall or adverse environments, a high operational tempo increases stress and problems of fatigue for the warfighter. Even a momentary lapse in vigilance may result in substantial military losses.

The demand for optimal cognitive function under stressful and fatiguing conditions makes appropriate psychophysiological end points critical in current and future research studies. These are particularly challenging end points to measure. "Experimenter-administered tests of cognitive and affective behavior are often insensitive to changes induced by nutritional and exercise stress, because the demand characteristics of the setting induce subjects to marshal their resources and perform to standard" (107). Even high weight losses in a number of ration studies have not produced decrements in a variety of psychomotor performance tests (72). So far, the only consistent changes in performance have been measured in nutrition studies that included a sleep-deficit component (71) or in a study where refeeding appeared to restore some aspects of cognitive performance (36). Clearly, this is an area for further research.

Previously, the most fundamental measure of the adequacy of a ration was whether or not it maintained body weight. However, relatively small losses (e.g. 3%) may variously reflect efficient utilization of fat stores, an undesirable loss of lean mass, or poor hydration. Accurate electronic scales, calibrated on-site, are a basic tool in any ration study. An index of hydration status is needed to interpret body-weight changes. This can be estimated by urine-specific gravity (32). Alternatively, bioelectrical impedance analysis can be used in the field to estimate changes in total body water and hydration (41). Whenever practical, tracer measurements of total body water made with stable isotopes of water are useful in interpreting body composition changes; these have been used in field studies since the 1950s (33).

Anthropometric assessment of body composition is a suitable method for tracking any important changes in body fat; the equation of Durnin & Womersley using four–skin-fold thicknesses has proven to be highly reliable in the hands of experienced anthropometrists (see 37). The far more expensive and less portable dual-energy X-ray absorptiometry has proven less useful in field-ration studies where the increased level of precision is not required and measurable changes in bone mineral are not likely to occur.

Metabolic status has been assessed in the field using urine ketone measurements made by simple colorimetric tests. Nitrogen balance can also be measured directly. Stable isotope techniques are particularly useful for understanding early changes in muscle and organ protein turnover (105). Similarly, bone changes are not easily detected in less than a year or without marked changes; thus, biochemical balance methods are critical to understanding true bone balance. Hormonal markers such as insulin-like growth factor-1 may be sensitive markers of protein and energy balance (77). For example, testosterone falls to castrate levels with energy deficiency and returns to normal levels within 24 hr of improved feeding, even with continued stress; similarly, menstrual status and luteinizing hormone levels are suppressed in women with an energy deficit.

Energy balance can be estimated from changes in body composition, assuming values for the energy density of the weight loss. Energy requirements of activity have been estimated from continuous heart-rate monitoring (104). Measurements of total daily energy expenditure in military field studies have been substantially improved through the use of the doubly labeled water method (100), although until recently it has been used exclusively with male volunteers. The energy expenditure of specific tasks has been measured with a portable oxygen-consumption device (85).

Micronutrient status has been assessed on the basis of physical examination; however, US soldiers of the present era are well nourished, and even after two months of severe energy restrictions for Army Ranger students, we could find no physical signs of deficiencies other than those related to food restriction (77). Similarly, no changes in clinical chemistries are expected in field-ration studies of less than a 30-day duration because of the nutritional reserve of modern soldiers. Standard blood analyses have revealed nothing of importance in the past decade of field research, except to confirm the absence of any gross error in ration formulations. These negative results are important in the first assessments of new rations but not for relatively minor menu modifications.

Although nutritional supplements such as glutamine, or an "antioxidant cocktail," have not been shown to improve immune function and disease resistance in military field studies, nutrition clearly modulates immune function, just as infection modulates nutritional status (11). Immune function indices can be sensitive markers for nutritional status (97). This was evident in Ranger students enduring a 1000- to 1200-kcal/day deficit for eight weeks (56). A valuable marker, if good laboratory methods are used, is phytohemagglutinin-stimulated blastogenesis. Several related cytokines, such as interleukin 2 and the interleukin 2 receptor, also appear to be sensitive indices of nutritional status. The critical issue in immune function studies remains, linking altered immune-function indices and nutritional markers to actual changes in disease susceptibility (70).

Physical performance tests suffer many of the same problems as psychological performance tests, including a high dependence on motivation (35). However, a new device has been developed that may improve our ability to test the effects of nutritional supplements on muscle fatigue (38). This new dynamic knee-extension device allows periodic determinations of maximal voluntary contractions during the course of exercise. The ability to follow the time course of fatigue, rather than to simply depend on the time of exhaustion, should provide a more sensitive way to test the ability of nutritional supplements to enhance physical performance.

Expanding capabilities for noninvasive physiological monitoring will continue to drive refinements in soldier nutrition. For example, continuous noninvasive assessments of muscle and liver glycogen and phosphocreatine using nuclear magnetic resonance technology will make it possible to develop more effective strategies to replenish and sustain individuals in continuous operations. Until such systems become more portable, military field studies will continue to rely on invasive methods such as muscle biopsy (47). Ambulatory monitor data on the precise levels of activity and sleep deprivation will help distinguish differences in the individual response to potential nutritional countermeasures to fatigue. The use of an in-the-boot foot-contact monitor will help to drive the design of more effective training and feeding strategies and will provide a quantitative outcome to evaluate the benefits of specific interventions (45).

Eventually, some of these monitoring technologies will be adaptable to integrated warfighter systems, built into personal equipment and tied into personal computer and communications systems for the benefit of individuals, commanders, and logisticians. These Warfighter Physiological Status Monitoring systems will also be of importance to researchers by providing actual data for modeling strategies, including dietary interventions, to maximize performance.

SPECIAL-PURPOSE RATIONS

Foot soldiers can face a daunting array of stressors such as sleep deprivation, sustained physical activity, heavy loads and rugged terrain, high-altitude hypoxia, extreme ambient temperatures, and restricted food and water availability. The challenge for military nutrition researchers is to design rations that enable soldiers to maintain normal physiologic functions in spite of these stressors.

Current US military rations developed for specific types of missions (Table 3) include the Ration, Cold Weather (RCW) and supplement packs, and the calorically restricted rations: the Long-Life Ration Packet (or Long-Range Patrol, Improved); the Ration, Light Weight, 30 day (RLW-30); and the New Generation Survival Ration (NGSR). The NGSR (53) is the latest refinement in the survival rations in a long succession since the World War I emergency ration.

Cold-Weather and High-Fat Rations

Thermoregulatory requirements in cold-weather operations drive up energy requirements; however, energy expenditure is higher for soldiers operating in the cold even when they have adequate clothing. In part, this has been attributed to the hobbling effect of heavy, cold-weather clothing and footgear (19).

Table 3 Principal Operational Rations in Use by the Department of Defense (75)

Ration	Purpose (references to biomedical field tests)	Energy and macronutrient content (protein/fat/CHO)
Main operational rations		
Standard B	To sustain groups with organized food service facilities without refrigeration or resupply of perishable foods	4300 kcal/day (13, 33, 54%)
Tray packs	To sustain the army in the field, especially in highly mobile situations, with high-quality, nutritionally adequate hot meals	1400 kcal/breakfast meal; (16, 31, 53%) 1500 kcal/dinner meal; (17, 29, 54%)
Meal, Ready-to-Eat (MRE)	To sustain individuals during operations without organized food service facilities	1300 kcal/meal (15, 36, 49%)
Specialized and restricted rations		
Ration, Cold Weather (RCW)	To sustain an individual during assault, reconnaissance and other nonresupply operations in frigid conditions	4500 kcal/day (8, 32, 60%)
Ration, Light-Weight, 30 day (RLW30)	To sustain Special Operations Forces during surveillance and reconnaissance operations for up to 30 days	2132 kcal/day (18, 30, 52%)
Long-range patrol, improved [LRP (I)]	Extended life operational ration to sustain personnel during initial assault and special operations; primary ration for prepositioned war reserve stocks	1570 kcal/day (15, 35, 50%)
New Generation survival ration (NGSR)	To sustain personnel in any survival situation for periods (<5 consecutive days)	1405 kcal (5, 41, 54%)

Appetite may also be stimulated in remote cold-weather regions (57). In 1945, Kark et al (54) studied Canadian soldiers during a motorized 3400-mile journey across northern Canada in winter. With average intakes of 4400 kcal/day over the 78-day trek, they observed no weight loss, no clinical or biochemical indications of nutritional deficiencies, and no decrements in performance. The current MRDA for daily energy content of cold-weather rations (4500 kcal) is based primarily on the observations from this Operation "Musk Ox" study (99).

Inuits and other cold-region natives have long subsisted on high-fat diets. However, no clear physiological advantage to a high-fat intake has been identified, even though restriction of dietary fat may be detrimental to endurance exercise (80), and even health. There also appears to be no basis for a shift to a higher preference for fat in the cold. However, because the higher energy requirement in cold-weather operations frequently coincides with geographical isolation, away from easy resupply, such as in arctic areas, cold-weather feeding has typically centered on high-fat, energy-dense rations convenient to transportation. "Pemmican" and other compact sources of energy have been used in cold-weather patrols in other countries, such as the Danish sled teams, which still patrol Greenland in the winter months (108). A high-fat diet can work if one is gradually adapted to it (87, 88). Nevertheless, there is repeated concern about the health consequences (e.g. gastrointestinal disturbance, heart burn, pancreatitis) from feeding a high-fat diet to unaccustomed soldiers (68).

A ration with 60–70% of calories from fat was considered (68). This compact, calorie-dense restricted ration would provide a dismounted soldier with a 3- to 5-day supply of food to meet a 3600-kcal/day requirement and to help maintain overall energy and fat balance. However, ration developers soon realized that outside of survival situations such a ration made little sense (4). Body fat reserves are readily available to meet shortfalls in dietary fat intake (43), whereas body carbohydrate stores are limited, making adequate dietary carbohydrate intake more critical to maintaining a soldier's capacity for sustained heavy exercise (6).

Ration, Cold Weather

The RCW, a light-weight, dehydrated ration that can be reconstituted with hot or cold water or consumed dry, is specifically designed for cold-weather operations. The RCW was designed to be used in cold-weather deployments in place of MREs, which were too bulky or heavy, contained excessive sodium and protein that increased water requirements by 150–350 ml/soldier/day, and were susceptible to freezing (55, 92). The RCW weighs about half the caloric equivalent of MREs and has more carbohydrate and less sodium and protein. Avoiding unnecessary protein intake makes it easier to remain adequately hydrated in cold environments (66).

Studies comparing individual rations with equal energy content (e.g. one RCW, four MREs, or three MREs with a cold-weather supplement pack) have found no meaningful differences in health and performance outcomes. In one study with Special Forces soldiers participating in a 10-day winter warfare exercise in the White Mountains of New Hampshire, soldiers lost 6 lb on the RCW and 7 lb on the caloric equivalent MRE (92). The weight loss was attributed to intakes of approximately 1000 kcal below actual requirements. However, the weight loss was confounded by dehydration, indicated by high urine-specific gravities. Most of all, these findings highlighted the problem of maintaining hydration in cold environments and led to a recommendation that items that enhance fluid consumption, such as chicken noodle soup, cocoa, and cider, be added to the rations. The RCW group consumed more carbohydrate (380 g/day) and less fat, a trend in macronutrient consumption that may better maintain muscle and liver glycogen and favor some aspects of performance.

Although isokinetic muscle strength and endurance improved, probably due to a learning effect, no differences in the physical performance between groups were noted.

The improved MRE (four meals per day), RCW, and RLW (two rations per day) were compared during winter training at the Marine Corps Mountain Warfare Training Center in Bridgeport, CA (79). During the 10-day exercise, Marines consuming the RCW had the highest proportion of energy intake from carbohydrates (410 g/day), but all groups lost in excess of 3% of initial body weight with energy deficits of about 1500 kcal/day, even though hydration was adequately maintained. This indicated that any of these rations were adequate for short-term use.

The MRE plus a high-carbohydrate supplement pack was compared with the RCW in a study of two Light Infantry companies during a 10-day field exercise in Alaska, where temperatures fell to $-40°F$ (28). Hydration was again inadequate and only improved when an enforced drinking schedule was instituted (28). Water availability in cold weather operations is a key factor in encouraging adequate food consumption (93). Negative energy balance was also evident, but it was less pronounced in the group receiving the supplemental packet. The supplemental packets contained popular items, notably pouch bread, commercial candies, and other snacks, providing an additional 650–800 kcal (27).

An early field study at moderate altitude by Askew and coworkers (6) suggested that carbohydrate supplementation might improve the physical performance of soldiers. A subsequent study of feeding at altitude was conducted with US soldiers living at 3500–4050 m during a deployment to Bolivia (26). Over 15 days, soldiers fed a mixture of B rations and MREs lost the same amount of weight (nearly 4 lb) whether or not they received a high-carbohydrate (125 g) food supplement (26). Ration acceptability was good, and hydration was adequately maintained. However, this study suggested a beverage rather than a solid food supplement might be a more effective way to increase fluid and carbohydrate consumption.

Hot-Weather Field-Feeding Requirements

Energy requirements in soldiers increase with cold exposure and the need to increase heat production. However, military field studies by Consolazio (17) clearly indicate that energy requirements do not decline in the heat. Indeed, Consolazio & Schnakenberg hypothesized that active metabolic processes such as sweating increase requirements over those of thermoneutral environments (17, 19). In any case, it remains important to counter heat-induced anorexic effects by increasing soldiers' intakes in hot environments. Providing soldiers with maltodextrin-based beverages containing modest amounts of sodium, potassium, and anions such as chloride or citrate appears to be an effective way to increase carbohydrate intake and replace electrolytes lost in sweat (1, 2, 95).

Subsistence with Restricted Intakes and High-Energy Expenditures

Light-weight operational rations with a long shelf life are essential to the increasingly mobile and widely dispersed soldiers on the modern battlefield. Soldiers were concentrated in relatively fixed positions in World War I and averaged 404 men/km^2; this declined to 36 men/km^2 in World War II and 2.3 soldiers/km^2 in the recent Persian Gulf War. Soldiers may have to carry their food supply for an extended period of time. Voluntary consumption of currently available field rations rarely exceeds 3000 kcal/day (8). Possible reasons include limited ration palatability, menu boredom, inability to work on a full stomach, lack of water, lack of scheduled meals or time to prepare meals, anxiety, and intentional dieting (90, 94). However, earlier studies by Consolazio et al led to the conclusion that soldiers could perform reasonably well even with only 500–600 kcal/day for relatively short periods of time, whereas comparison studies with total fasting demonstrated impaired cognition and declines in performance (18). Using four different levels of energy intake for soldiers training in the Panamanian jungle, they addressed the question: "Would a minimal planned daily ration of 600 kcal, if consumed, be more beneficial to the soldier than the remnants of a 3600 kcal ration, the majority of which was indiscriminately discarded because of its heavy weight" (18). They concluded that if mineral supplements were included in the limited-energy provision, health and performance could be reasonably sustained over a short period of time.

Even when food consumption is restricted, sustained energy expenditures of soldiers in the field are typically about 4000 kcal/day for men in a variety of training scenarios (Table 4) (49). In shorter-term, high-intensity operations ($<$3–5 days) these rates may be higher. Estimated expenditures of 8000 kcal/day or more in soldiers participating in the Norwegian Ranger training course (13) await confirmation by the doubly labeled water method. Typical values for women may be lower. Energy expenditures of women in Army basic training were 2800 kcal/day over the eight-week course, based on food intake/energy balance estimations (110). Thus, the energy deficits produced by subsistence on restricted rations clearly limit their use.

The RLW—a compact, calorically dense, light-weight ration containing 2000 kcal/day—is intended to be used during short-term missions when resupply is not expected. A study was conducted with Special Forces soldiers on a field-training exercise at Camp Ethan Allen, VT, in temperate weather (7). Soldiers subsisting on the RLW lost 11.5 lb (6.3% of initial body weight) compared with 4 lb (2.2% of body weight) lost by soldiers fed three MREs/day during

Table 4 Studies of total daily energy expenditures (TDEE) in military personnel, as measured by the doubly labeled water method[a]

TDEE (mean ± SD) (kcal)	n	Duration (days)	Subjects and military duty/environment	Reference
3540 ± 510	8	28	Special Forces soldiers consuming MREs	23
3330 ± 850	8	28	-consuming RLWs	
4750 (4150–5390)	4	7	Australian soldiers, jungle warfare training	30
3310 ± 600	11	7	Australian sailors on shore duties	31
4920 ± 910	23	11	Marine cold weather field exercise	44
4320 ± 927	10	10	Canadian infantrymen in the arctic	51
4070 ± 840	6	63	Army Ranger students, summer 1991	46
4090 ± 470	6	65	Army Ranger students, summer 1992	
3937 ± 550	12	12	Israeli soldiers in summer training	14
4280 ± 720	18	12	Israeli soldiers in cool-weather training	15
4560 ± 570	6	6	Special Forces soldiers on Mt. Rainier	42
3550 ± 610	11	10	US soldiers in Bolivia (3500- to 4000-m elevation)	26

[a]Note: 1 MJ = 239 kcal.

the 30-day study. Aerobic capacity was decreased for both groups (10–14% decrease); muscle strength and endurance demonstrated modest declines in the RLW group but not in the MRE group. Hematuria and proteinuria were detected primarily in the RLW group. The RLW group had more symptomatic complaints and cognitive disturbances (e.g. weakness, dizziness, and visual, motor, and cognitive performance). Good hydration was maintained, and except for energy and protein intakes in the RLW group, the MRDAs were met for all nutrients (7). These results strongly suggest that the RLW ration impairs mission performance if used for a full month.

In contrast, the RLW was used successfully in two short-term studies where it was provided either as a double ration or with a carbohydrate supplement. Marines receiving two RLWs per day in a 10-day cold-weather study had food intakes and weight changes similar to those of the groups consuming four MREs per day or RCW rations (79). Ten Special Forces soldiers consumed the RLW with a liquid carbohydrate supplement during a six-day winter exercise on Mount Rainier (52). They maintained good hydration, with fluid intakes of 3.6 liters/day, but had an energy deficit of nearly 2000 kcal/day. These studies demonstrated that the RLW could support short-term, high-altitude operations if used as a double ration or in conjunction with a carbohydrate supplement.

Previous studies have indicated that up to 10% of weight loss produces little decrement in performance. Crowdy et al found that 12 days of energy restriction with large deficits (1700 kcal/day) did not affect physical performance, vigilance, cognitive tests (arithmetic, coding), or marksmanship performance

(21). In the 1950s, Taylor et al (106) studied weight loss in the laboratory with exercise and food restriction and concluded that up to 10% loss of initial body weight could be tolerated without significant impairments of physical performance. In the 1970s, Consolazio et al (18) again examined the problem in their elegant field study in the Panamanian jungle. They demonstrated that foot soldiers could subsist on extremely limited energy intakes for 10-day periods without adverse effects on mission success.

We revisited the question in the 1990s with studies in Ranger students who lost an average of 16% of their body weight within an eight-week period (77). These soldiers were fed only one MRE per day (1300 kcal) for up to 10 days at a time when energy expenditures averaged 4000 kcal/day and deficits averaged 1000–1200 kcal/day for the duration of the eight-week course (77). This time, physical and cognitive impairments were evident, with 20% reduction in maximal lifting strength (48) and large decrements in decoding, memory, and reasoning tests (72). The resilience of the human body was evident in that biochemical parameters of vitamin and health status remained entirely within normal limits, even for individuals (77, 78). For example, one lean individual lost an extreme 23% of body weight during the eight-week period (37), yet a comprehensive panel of tests indicated that hematological and nutritional biochemical levels remained normal (77, 78). Only the regulators of this physiological compensation revealed the severity of the stress in this individual, who had low serum levels of testosterone and interleukin 6 and extraordinarily high cortisol levels, mobilizing tissue stores to meet the energy deficit.

In a second Ranger study, total energy intake was increased by 15% by exchanging the higher-calorie Long-Life Ration Packet for the single MRE/day (29). The individual biochemical results were again remarkable for their lack of abnormality. However, the modest increase in energy intake in the second Ranger study, with all other major variables such as sleep deprivation and heat exposure remaining constant, was associated with an improvement in indices of immune function (56) and a dramatic reduction in infection rates.

These studies have all involved individuals who were well nourished at the start of the study. A study conducted by Rai et al (91) at the Defense Institute of Physiology and Allied Sciences in Delhi, India, considered the question of what happens to nutritional status in repeated military operations involving energy deficits and without adequate recovery. An experiment group received 2400 kcal/day (including 440 g of carbohydrates) for three separate 7- to 10-day patrols in rugged mountainous terrain, with estimated average energy expenditures of 3800 kcal/day. Each of these patrols was separated by one week of recovery feeding. Compared to a control group fed 4100 kcal/day throughout the study, there were no observed deficits for physical performance, including maximal aerobic performance, psychomotor and vigilance tasks, military performance test scores, nitrogen balance, and vitamin excretion rates.

Muscle Metabolism and Physical Performance

Carbohydrates are readily oxidized, support twice the rate of power production possible when fat alone is combusted, and are needed for peak physical performance (20, 96). However, body carbohydrate reserves are very limited; thus, when carbohydrate intake is inadequate, body fat stores form the primary source of energy. In this ketotic environment, military performance may be compromised.

Nearly every field-training study examining energy balance has demonstrated inadequate intakes. A review of 19 study groups in 11 different ration studies (52) showed average energy expenditures of 3670 ± 680 (standard deviation) kcal but intakes averaging only 2510 ± 440 kcal. Body weight loss averaged 2.4 ± 1.1 kg over the course of the field studies, which were usually of a 10-day duration. Carbohydrate intakes were only 290 ± 70 g/day (range: 190–410 g/day), well below the NATO panel recommendation of >450 g/day needed for glycogen resynthesis (25). The depletion of muscle glycogen stores appears almost inevitable, even with substantial carbohydrate intakes, as noted in a study by Jacobs et al with Canadian commandos (47). Even when the men were administered a carbohydrate supplement, muscle biopsies revealed no difference in the diminished glycogen stores between groups, although the effect on hepatic glycogen stores is not known.

A double-blind crossover study of the effects of liquid carbohydrate supplement on exercise endurance of Special Operations Forces soldiers was conducted at the metabolic ward facility at the Pennington Biomedical Research Center (82). The ingestion of 450 g of carbohydrate/day did not prevent the transition to a fat-predominant fuel metabolism in these physically active soldiers. Nevertheless, endurance-exercise performance improved significantly when supplemental carbohydrate was consumed at mealtime (+6%); the improvement in endurance-exercise capacity was even more pronounced when the carbohydrate was consumed during the exercise (+16%).

Thus, soldiers in the field are characteristically in negative energy balance and do not ingest enough carbohydrates to optimally sustain high-intensity physical performance. This deficit is in part attributable to high energy requirements during sustained periods of work and limited consumption of field rations. Although body fat reserves can meet the energy deficit, carbohydrate intakes fall far short of the recommendations from several expert panels (25, 64–66). Field studies have demonstrated that maltodextrin-based carbohydrate supplements are an effective means of increasing the carbohydrate intakes of soldiers (52). Incorporation of an easily consumed maltodextrin-based carbohydrate beverage base into the military field ration systems would help to solve this problem.

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