Review

Hydration at the Work Site

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When performing physical work, sweat output often exceeds water intake, producing a body water deficit or dehydration. Specific to the work place, dehydration can adversely affect worker productivity, safety, and morale. Legislative bodies in North America such as the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) recommend replacing fluids frequently when exposed to heat stress, such as one cup (250 ml) every 20 minutes when working in warm environments. However, the majority of legislative guidelines provide vague guidance and none take into account the effects of work intensity, specific environments, or protective clothing. Improved occupational guidelines for fluid and electrolyte replacement during hot weather occupational activities should be developed to include recommendations for fluid consumption before, during, and after work.

Key teaching points:

- Total body water approximates ~60% of body mass and normally varies by ±3%.
- Maintaining normal total body water (euhydration) is important, as deficits >2% of body mass can adversely impact on aerobic performance, orthostatic tolerance and cognitive function.
- Studies of occupational accidents report the lowest rates in cold months and highest rates in hot months when sweat losses would be greatest.
- Physical activity level, clothing / equipment and weather are important in determining fluid needs. Work places that are either in warm environments, involve high level of physical activity, or both will require greater fluid replacement.
- Measures of body weight and urine color are used in combination with the subjective sense of thirst, can help to provide an assessment of hydration state.
- Fluid replacement guidelines should take into account work intensity, environment and work-to-rest cycles.

INTRODUCTION

While "normal" hydration is achieved with a wide range of water intakes by sedentary and active people across the life-span, homeostasis of body water can be difficult to maintain when challenged by strenuous physical work and heat stress. Athletes and industrial workers comprise the populations that are most often challenged by hydration issues; however, industrial workers are another often-overlooked population sharing these concerns. These individuals may perform intense physical labor in warm-hot environments, which can induce dehydration on a daily basis. Hydration in the work place is a specific concern because dehydration can affect productivity, safety, cost, and morale. The purpose of this review is to discuss factors that play a role in body water maintenance, review these factors relative to the workplace, and offer guidance regarding workplace hydration.

BODY WATER

Water is the principal chemical component of the human body and represents 50% to 70% of body weight [1] for the

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average young adult male. While the workforce includes individuals of varying ages, body composition, and physical fitness, it is important to note that variability in total body water is mostly accounted for by body composition where lean body mass contains ~73% water and fat body mass consists of ~10% water [2]. Therefore, obese individuals with the same body weight as their lean counterparts will have markedly smaller total body water volumes. For example, a lean adult who is 70 kg and has 10% body fat would have ~48 liters of total body water compared to an obese adult of 70 kg and 35% fat who would have ~36 liters of total body water, so an absolute fluid deficit will have more severe consequences for in the latter.

Approximately 5–10% of total body water is turned over daily [3] via obligatory (non-exercise) fluid loss avenues. Respiratory water loss is influenced by the inspired air and pulmonary ventilation; however, respiratory water losses are offset by the metabolic water formed by oxidation of substrates. Urine output approximates one to two liters per day, but may be larger or small depending on daily fluid consumption and activity. This ability to vary urine output represents the primary means to regulate net body water balance across a broad range of fluid intake volumes and losses from other avenues [4]. Sweat losses, and ultimately fluid needs, can vary widely and depend upon the amount and intensity of physical activity and environmental conditions [5].

Net body water balance (loss = gain) is regulated remarkably well day-to-day as a result of thirst and hunger, coupled with *ad libitum* access to food and beverage to off-set water losses [4]. Although acute mismatches between fluid gain and loss may occur due to illness, environmental exposure, exercise, or physical work, it is a reproducible phenomenon that intakes are generally adequate to offset net loss from day-to-day [6]. It is recognized, however, that after significant body water losses like those associated with physical work or heat stress, wherein substantial water deficits are incurred, many hours of rehydration and electrolyte consumption may be needed to reestablish body water balance [7]. For example, if dehydrated by more than about 4% of total body weight, it may take >24h to fully rehydrate via water and electrolyte replacement [8–10]. While daily strenuous activity in a hot environment can result in mild water balance deficits even with unlimited access to food and fluids [7,11], adherence to recognized water intake guidance [11–13] under similar conditions minimizes water deficits, as determined by daily body mass stability [14].

WATER NEEDS AND PHYSICAL ACTIVITY

The National Academy of Sciences has established an adequate intake (AI) for daily total water as 3.7 L and 2.7 L for adult males and females, respectively [4]. However, daily water intake varies greatly for individuals and between groups. For example, the daily water needs of sedentary men are ~1.2 L or ~2.5 L [15,16] and increase to ~3.2 L if performing modest physical activity [17,18]. Compared to sedentary adults, active adults who live in a warm environment are reported to have daily water needs of ~6 L [19], and highly active populations have been reported to have markedly higher values (>6L) [20]. Limited data are available on fluid needs for women, but they generally exhibit lower daily water turnover rates than their male counterparts.

The magnitude of sweat losses incurred during work in a warm environment is dependent primarily on work intensity and duration [21]. Metabolic heat production is balanced by both dry and evaporative (sweating) heat loss, but very high metabolic rates coupled with warm weather demand a larger thermal requirement for evaporative cooling [22], leading to greater sweat losses and subsequently larger water requirements. However, it is important to note that sweat rates can differ between various work activities and between individuals [21].

Fig. 1 [4] depicts generalized modeling approximations for daily sweating rates as a function of daily metabolic rate (activity level) and air temperature. Note that metabolic rate and air temperature both have marked effects on water needs. In addition to air temperature, other environmental factors such as relative humidity, air motion, solar load, and protective clothing will influence heat strain and thus water needs.

CONSEQUENCES OF DEHYDRATION

Dehydration results in an increased core temperature during physical work in temperate [23–25] or hot environments [26–28]. The typical reported change in core temperature with dehydration is an increase of 0.1–0.2°C with each 1% of dehydration [29]. The greater heat storage associated with dehydration is mediated by reduced heat loss via sweating

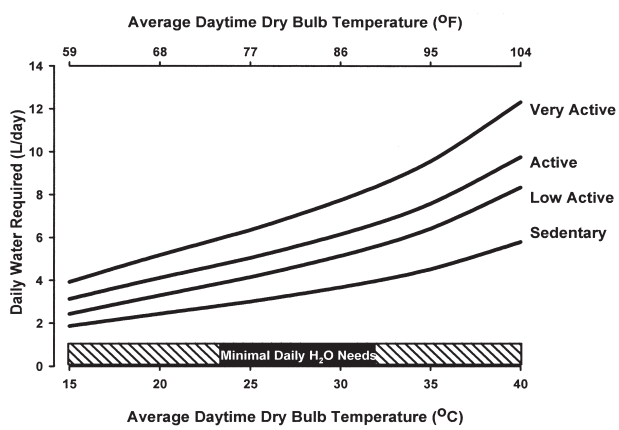

Fig. 1. Water needs estimated from sweat loss predictions due to changes in physical activity and air temperature. From IOM (with permission) [4].

(evaporative heat loss) and cutaneous blood flow (dry heat loss) [30–32]. In warm or hot environments, sweat evaporation is the primary mechanism for heat dissipation when the relative humidity is low. When dehydrated, the sweating rate is lower for any given core temperature and heat loss via evaporation is therefore reduced [33].

During sub-maximal work in or out of the heat, dehydration results in an increase in cardiovascular strain. Heart rate has been shown to increase four beats per minute for each percent loss in body weight [34]. Individuals who may come to work in a dehydrated state and/or become further dehydrated while working could expect to see an increase of 16 to 20 beats per minute with a 4–5% loss in body weight. This increase in heart rate is typically accompanied by an increase in an individual's subjective rating of perceived exertion to perform an exercise task, which may play a role in alterations in work performance when dehydrated.

Dehydration has also been shown to adversely impact aerobic work performance. The magnitude of performance decrement is related to environmental temperature, exercise task, and the individual's physiological characteristics such as fitness, acclimatization state, and tolerance to dehydration. The National Academy of sciences reviewed a number of studies regarding the influence of dehydration on endurance exercise performance and physical work capacity [4]. This review concluded that when dehydration exceeds 2% of body weight, endurance performance and work capacity are degraded, and the decrements in performance were accentuated when working in the heat.

Work tasks that are predominantly anaerobic have sometimes been shown to be adversely affected by dehydration, however this is not clear-cut as body water deficits do not appear to alter muscular strength [4]. The Institute of Medicine's report on dietary references intakes reviewed five studies concerning the influence of dehydration on anaerobic exercise performance. Half of the reviewed studies reported reduction in anaerobic performance; however, most of the studies reported no effect of dehydration on muscular strength.

Occupational work typically employs a variety of work components, so it cannot always be categorized as totally aerobic, anaerobic, or muscular strength dependent. Aerobic work represents occupational tasks that are ongoing over a number of hours and include work done in foundries, construction, agriculture, landscaping, and forestry. Work performance for these tasks may be seriously impacted by dehydration, especially for individuals who perform heavy work in warm or hot environments and have high rates of water flux. However, these tasks may periodically involve a predominantly anaerobic or strength component. Likewise, some tasks that may be sedentary but have occasional strength and anaerobic components such as heavy lifting, sledge hammering, or throwing bales of hay, might be less impacted by body water deficits.

DEHYDRATION IN THE WORK PLACE

During physical work in the heat, sweat output can often exceed water intake, which can lead to body water deficits or dehydration. Bishop et al. [35] observed that, in simulated industrial work conditions, encapsulated protective clothing increased sweat rates up to 2.25 L/h. Likewise, wearing protective equipment such as full or half face masks can make fluid consumption more difficult and can further contribute to dehydration in the work place. Firefighters, for example, wear heavy protective clothing and are exposed to intense heat. Rossi [36] reported that firefighters wearing protective clothing and equipment, performing simulated work tasks in the heat can have sweat rates up to 2.1 L/h. Brake et al. [37] observed fluid losses and hydration status of mine workers under thermal stress working extended shifts (12 hours). They stated that 60% of the miners reported to work dehydrated and that their hydration status did not improve throughout the 10 to 12 hour shift. Therefore, it is not surprising that maintaining fluid balance can be a difficult problem during the workday. It is well documented that workers often not only become dehydrated on the job, but may also start the workday with a fluid deficit.

While many studies have observed the effect of dehydration on physical work capacity, few studies have observed dehydration's impact on manual labor productivity. Wasterlund and Chaseling [38] studied forest workers in a 14.7°C environment in two scenarios, one where subjects consumed fluid sufficient to maintain a normal hydration state and a second where subjects consumed limited fluid which resulted in 0.7kg body weight loss (>1% body weight). The measure of productivity was the amount of time to stack and debark 2.4 cubic meters of pulpwood. When subjects were dehydrated, productivity of stacking and debarking pulpwood was reduced by 12%.

Dehydration also has been shown to adversely influence decision-making and cognitive performance, which may contribute to a decline in productivity and could be associated with an increased risk of work-related accidents. Gopinthan et al. [39] dehydrated subjects passively by 1, 2, 3, and 4% of body weight and found that visual motor tracking, short-term memory, attention, and arithmetic efficiency were all impaired at 2% or more dehydration. Cian et al. [40] observed the effect of <3% dehydration achieved by exercise or heat exposure on cognitive function. They reported that, compared to a well-hydrated state, dehydrated subjects exhibited impairments in short-term memory and reported greater fatigue for up to two hours following dehydration. Szinnai et al. [41] examined the effect of 2.6% dehydration on the cognitive-motor function of 16 subjects. They reported that dehydrated subjects reported greater tiredness, reduced alertness, and higher levels of perceived effort and concentration compared to their normally hydrated state.

Fig. 2 depicts the 23% change in reaction time observed by

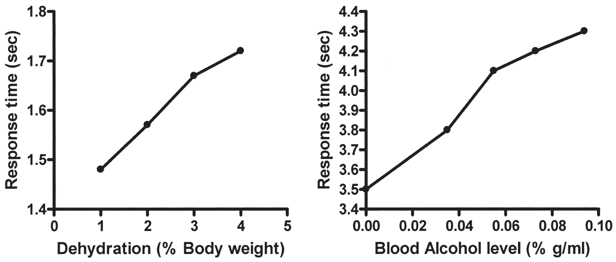

Fig. 2. Effect of dehydration on response time [39] and the effect of blood alcohol content on response time [42].

Gopinathan et al. [39] when subjects were 4% dehydrated. In comparison, a study by Moskowitz et al. [42] reported on the effects of blood alcohol content and driving skills and indicated that blood alcohol levels at the legal limit of 0.08 yielded a 17% slowing of drivers' response time. While these two studies [39, 42] are not equivalent as different tests were used to measure reaction time, a point of comparison can be made. A blood alcohol content at or above the legal limit in all U.S. will result in significant impairment in the ability to operate a vehicle; it is possible that the changes in reaction time reported with dehydration may also cause similar impairment.

Dehydration may mediate job-related accidents by causing orthostatic intolerance. Adolph [2] reported that dehydrated subjects fainted more quickly when faced with a change in body posture (orthostatic challenge test). Likewise, Carter et al. [43] reported that subjects who were dehydrated by 3% of body weight from heat exposure exhibited a significant reduction in cerebral blood flow velocity when going from a seated to a standing posture. While there are no reported links, it is possible that dehydration mediated reductions in cognitive function and reaction time may be indirectly connected. In a classic study by Vernon [44], accident rates were shown to be at their lowest in temperatures of ~20°C and increased by 30% in environments of ~24°C, illustrated in Fig. 3. As stated previously, it is in warm-hot environments that fluid turnover would be highest and workers most likely to become dehydrated.

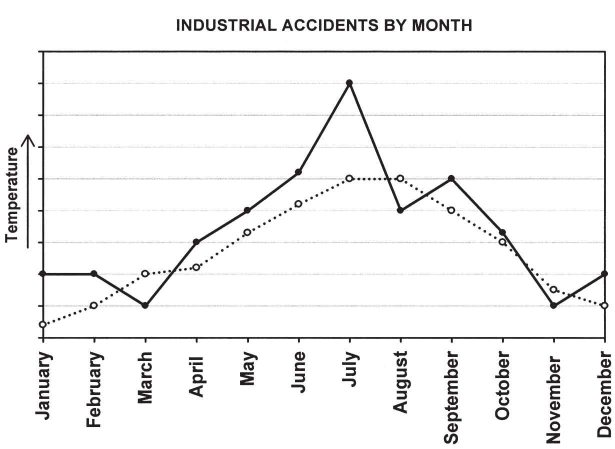

Fig. 3. Industrial accidents by month, redrawn from [42].

HYDRATION ASSESSMENT AND RECOMMENDATIONS

Alleviating dehydration should involve a combination of strategies that include assessment, education, and the inclusion of practices that encourage fluid intake. As discussed earlier, Brake et al. [37] reported that, in their assessment of hydration status of mine workers, over half reported to their work shift in a hydration state that would not be considered suitable for work in hot conditions. Assessing hydration state has proven challenging given the difficulty in providing an accepted definition of normal body water status. Despite this difficulty, measuring total body water or plasma osmolality has been purported to be the standard for hydration assessment [45]. However, methods of measuring these variables such as isotopic dilution, bioelectrical impedance, and analysis of blood and/or plasma can be invasive, expensive, and difficult to employ in a workplace setting. Less invasive and expensive methods of hydration assessment such as urine specific gravity (USG) and urine color have been employed but have limitations. Urine specific gravity has been shown to be somewhat effective in determining hydration status. USG of $\leq$1.020 has been reported to be indicative of normal hydration state [11] and has been used to determine dehydration state in the workplace [37]. However, urine values can be misleading regarding hydration status. If dehydrated individuals drink a large volume of hypotonic fluid, they will produce copious amounts of urine before normal body water levels have been achieved. In addition, the urine will be light in color and have USG values comparable to well-hydrated individuals. In the proper context, if measures of body weight and urine color are used in combination with the subjective sense of thirst, a more meaningful assessment of hydration state can be made [45]. By determining if morning body weight has fluctuated by $>$1% compared to the previous morning, if morning urine is a darker color, and if thirst is present, it is likely that an individual is in a dehydrated state.

Education is a vital component to help workers maintain their hydration state during and after a work shift. Informing individuals, especially those who work in a hot environment, about hydration assessment, signs and dangers of dehydration, and strategies in maintaining hydration while working can reduce dehydration in the workplace. Brake et al. [37] reported that individuals working in a thermally stressful environment were better able to maintain hydration when they were educated about dehydration, assessed their hydration state and used a fluid replacement program while working.

An education and hydration program at work should stress the importance of consuming meals. De Castro [46] observed food and fluid intake of 36 adults over seven consecutive days and concluded that the amount of fluid ingested was primarily related to the amount of food ingested and that fluid intake independent of eating was relatively rare. In addition, Maughan et al. [47], among others, reported that meals play an important role in helping to stimulate the thirst response causing the intake of additional fluids and restoration of fluid balance. Using established meal breaks in a workplace setting, especially during longer work shifts (10 to 12 hours), may help replenish fluids and can be important in replacing sodium and other electrolytes.

One recommendation that may enhance hydration at the work site involves improving access to bathroom facilities. Anecdotal statements and interviews have revealed that individuals, particularly women, will purposefully not drink fluid when bathroom facilities are not available. While logistical factors may complicate access to facilities, providing access may be a simple means of improving workplace hydration and reducing the practice of voluntary dehydration.

At present there are no specific national industry standards regarding fluid replacement that take into account environment, protective clothing, and work intensity. In North America, occupational health and safety associations use guidelines established by the American Conference of Governmental Industrial Hygienists (ACGIH), Occupational Safety & Health Administration (OSHA), the National Institute of Occupational Safety & Health (NIOSH). The ACGIH and OSHA both recommend that fluids be replaced by providing cool water or any cool liquid (except alcoholic beverages) to workers and that they be encouraged to drink small amounts frequently, such as one cup (250 ml) every 20 minutes. NIOSH recommends that drinking water should be readily available to workers exposed to a hot work environment. It is important that these organizations have made recommendations regarding fluid intake and hydration. However, these recommendations may recommend too much or too little fluid depending on the environment, the individual, and the work intensity.

The U.S. Army has developed fluid replacement and work pacing guidelines that incorporate work intensity, environment, work-to-rest cycles, and fluid intake as shown in Fig. 4 [49]. These guidelines use wet bulb globe temperature (WBGT) to mark levels of environmental heat stress. The WBGT takes environmental variables such as solar radiation, humidity, and ambient temperature into account in its calculation; automated systems for WBGT measurement are commercially available. Occupational safety communities may want to include WBGT measures relative to work intensity in any recommendations they make regarding fluid intake in the workplace.

		Easy Work		Moderate Work		Hard Work	
Heat Category	WBGT Index, F°	Work/Rest (min)	Water Intake (qt/hr)	Work/Rest (min)	Water Intake (qt/hr)	Work/Rest (min)	Water Intake (qt/hr)
1	78° - 81.9°	NL	½	NL	¾	40/20 min	¾
2 (green)	82° - 84.9°	NL	½	50/10 min	¾	30/30 min	1
3 (yellow)	85° - 87.9°	NL	¾	40/20 min	¾	30/30 min	1
4 (red)	88° - 89.9°	NL	¾	30/30 min	¾	20/40 min	1
5 (black)	> 90°	50/10 min	1	20/40 min	1	10/50	1

* Fluid Intake should not exceed 1.5 qts per hour or 12 qts per day.

Fig. 4. Fluid replacement and work/rest guidelines for warm weather training conditions used by the U.S. Army during training in hot weather [49].

Employers have sometimes not promoted drinking, as this would require more rest breaks and thus decrease employee productivity. It is more likely that sustaining hydration will maintain worker productivity sufficiently to offset any work breaks, particularly during hot weather. In addition, the decrease in health care costs associated with possibly reducing accidents or illnesses in the workplace could further help the small decline in productivity from rest breaks.

SUMMARY

This review has presented information on the importance of hydration in the workplace and the effects hydration state can have on cognitive function, productivity, health, and safety. Current workplace hydration guidelines and possible needs to incorporate factors such as environment and work intensity into recommendations for fluid intake have also been reviewed. Despite specific challenges, improving hydration in the workplace should increase productivity, decrease accidents, and boost employee morale.

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REFERENCES

1. Altman P, Katz D: “Blood and Other Body Fluids.” Washington, DC: Federation of American Societies for Experimental Biology, 1961.
2. Van Loan M: Age, gender, and fluid balance. In Buskirk ER and Puhl, SM. (eds): Body Fluid Balance: Exercise and Sport. Boca Raton: CRC Press, pp. 215–230, 1996.
3. Raman A, Schoeller DA, Subar AF, Troiano RP, Schatzkin A, Harris T, Bauer D, Bingham SA, Everhart JE, Newman AB, Tylavsky FA: Water turnover in 458 American adults 40–79 yr of age. Am J Physiol Renal Physiol 286:F394–F401, 2004.
4. Institute of Medicine: Dietary reference intakes for water, potassium, sodium, chloride, and sulfate. Washington, DC: The National Academies Press, 2005.
5. Shapiro Y, Pandolf KB, Goldman RF: Predicting sweat loss response to exercise, environment and clothing. Eur J Appl Physiol Occup Physiol 48:83–96, 1982.

6. Johnson RE: Water and osmotic economy on survival rations. J Am Diet Assoc 45:124–129, 1964.
7. Shirreffs SM, Maughan RJ: Volume repletion after exercise-induced volume depletion in humans: replacement of water and sodium losses. Am J Physiol 274(5 Pt 2):F868–F875, 1998.
8. Adolph EF, Dill DB: Observations on water metabolism in the desert. Am J Physiol 123:369–499, 1938.
9. Nielsen B, Hales JR, Strange S, Christensen NJ, Warberg J, Saltin B: Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. J Physiol 460:467–485, 1993.
10. Morimoto T: Thermoregulation and body fluids: role of blood volume and central venous pressure. Jpn J Physiol 40:165–179, 1990.
11. Armstrong LE, Maresh CM, Castellani JW, Bergeron MF, Kenefick RW, LaGasse KE, Riebe D: Urinary indices of hydration status. Int J Sport Nutr 4:265–279, 1994.
12. Convertino VA, Armstrong LE, Coyle EF, Mack GW, Sawka MN, Senay LC, Sherman WM: American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc 28:i–vii, 1996.
13. Casa DJ, Armstrong LE, Hillman SK, Montain SJ, Reiff RV, Rich BS, Roberts WO, Stone JA: National Athletic Trainers' Association Position Statement: Fluid Replacement for Athletes. J Athl Train 35:212–224, 2000.
14. Cheuvront SN, Carter R 3rd, Montain SJ, Sawka MN: Daily body mass variability and stability in active men undergoing exercise-heat stress. Int J Sport Nutr Exerc Metab 14:532–540, 2004.
15. Adolf EF: The metabolism and distribution of water in body and tissues. Physiol Rev 13:336–371, 1933.
16. Newburgh, LH, Woodwell JM, Falcon-Lesses M: Measurement of total water exchange. J Clin Invest 8:161–196, 1930.
17. Greenleaf JE, Bernauer EM, Juhos LT, Young HL, Morse JT, Staley RW: Effects of exercise on fluid exchange and body composition in man during 14-day bed rest. J Appl Physiol 43:126–132, 1977.
18. Gunga HC, Maillet A, Kirsch K, Rocker L, Gharib C, Vaernes R: European isolation and confinement study. Water and salt turnover. Adv Space Biol Med 3:185–200, 1993.
19. Welch BE, Buskirk ER, Iampietro PF: Relation of climate and temperature to food and water intake in man. Metabolism 7:141–148, 1958.
20. Ruby BC, Shriver TC, Zderic TW, Sharkey BJ, Burks C, Tysk S: Total energy expenditure during arduous wildfire suppression. Med Sci Sports Exerc 34:1048–1054, 2002.
21. Sawka MN, Wenger CB, Pandolf KB: Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In Fregly MJ and Blatteis CM (eds): Handbook of Physiology, Section 4, Environmental Physiology. New York: Oxford University Press, pp. 157–185, 1996.
22. Nielsen M: Die Regulation der Körpertemperatur bei Muskelarbeit. Scand Arch Physiol 9:193–230, 1938.
23. Cadarette BS, Sawka MN, Toner MM, Pandolf KB: Aerobic fitness and the hypohydration response to exercise-heat stress. Aviat Space Environ Med 55:507–512, 1984.
24. Neufer PD, Young AJ, Sawka MN: Gastric emptying during exercise: effects of heat stress and hypohydration. Eur J Appl Physiol Occup Physiol 58:433–439, 1989.
25. Sawka MN, Knowlton RG, Glaser RM: Body temperature, respiration, and acid-base equilibrium during prolonged running. Med Sci Sports Exerc 12:370–374, 1980.
26. Claremont AD, Costill DL, Fink W, van Handel P: Heat tolerance following diuretic induced dehydration. Med Sci Sports 8:239–243, 1976.
27. Sawka MN, Gonzalez RR, Young AJ, Muza SR, Pandolf KB, Latzka WA, Dennis RC, Valeri CR: Polycythemia and hydration: effects on thermoregulation and blood volume during exercise-heat stress. Am J Physiol 255 (3 Pt 2):R456–R463, 1988.
28. Senay LC Jr: Relationship of evaporative rates to serum [Na+], [K+], and osmolarity in acute heat stress. J Appl Physiol 25:149–152, 1968.
29. Sawka MN, Francesconi RP, Young AJ, Pandolf KB: Influence of hydration level and body fluids on exercise performance in the heat. JAMA 252:1165–1169, 1984.
30. Fortney SM, Nadel ER, Wenger CB, Bove JR: Effect of acute alterations of blood volume on circulatory performance in humans. J Appl Physiol 50:292–298, 1981.
31. Fortney, SM, Wenger CB, Bove JR, and Nadel ER. Effect of hyperosmolality on control of blood flow and sweating. J Appl Physiol 57:1688–1695, 1984.
32. Nadel ER, Fortney SM, and Wenger CB: Effect of hydration state on circulatory and thermal regulation. J Appl Physiol 49:715–721, 1980.
33. Sawka MN: Physiological consequences of hypohydration: exercise performance and thermoregulation. Med Sci Sports Exerc 24:657–670, 1992.
34. Sawka MN, Young AJ, Francesconi RP, Muza SR, Pandolf KB: Thermoregulatory and blood responses during exercise at graded hypohydration levels. J Appl Physiol 59:1394–1401, 1985.
35. Bishop PA, Pieroni RE, Smith JF, Constable SH: Limitations to heavy work at 21 degrees C of personnel wearing the U.S. Military chemical defense ensemble. Aviat Space Environ Med 62:216–220, 1991.
36. Rossi R: Fire fighting and its influence on the body. Ergonomics 46:1017–1033, 2003.
37. Brake DJ, Bates GP: Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. Occup Environ Med 60(2):90–96, 2003.
38. Wasterlund DS, Chaseling J, Burstrom L: The effect of fluid consumption on the forest workers' performance strategy. Appl Ergon 35:29–36, 2004.
39. Gopinathan PM, Pichan G, Sharma VM: Role of dehydration in heat stress-induced variations in mental performance. Arch Environ Health 43:15–17, 1988.
40. Cian C, Koulmann N, Barraud PA, Raphel C, Jimenez C, Melin B: Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. J Psychophysiol 42:243–251, 2001.
41. Szinnai G, Schachinger H, Arnaud MJ, Linder L, Keller U: Effect of water deprivation on cognitive-motor performance in healthy men and women. Am J Physiol Regul Integr Comp Physiol 289: R275–R280, 2005.
42. Moskowitz H, Burns MM, Williams AF: Skills performance at low blood alcohol levels. J Stud Alcohol 46:482–485, 1985.
43. Carter R 3rd, Cheuvront SN, Vernieuw CR, Sawka MN: Hypohydration and prior heat stress exacerbates decreases in cerebral

blood flow velocity during standing. J Appl Physiol 101:1744–1750, 2006.
44. Vernon HM: Industrial fatigue in relation to atmospheric conditions. Physiol Rev 8:130–150, 1928.
45. Cheuvront SN, Sawka MN: Hydration assessment of athltetes. Gatorade Sports Science Institute: Sport Science Exchange 18:1–5, 2005.
46. de Castro JM: A microregulatory analysis of spontaneous fluid intake by humans: evidence that the amount of liquid ingested and its timing is mainly governed by feeding. Physiol Behav 43:705–714, 1988.
47. Maughan RJ, Leiper JB, Shirreffs SM: Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. Eur J Appl Physiol Occup Physiol 73(3–4):317–325, 1996.
48. Montain SJ, Latzka WA, Sawka MN: Fluid replacement recommendations for training in hot weather. Mil Med 164:502–508, 1999.
49. Departments of the Army and Air Force. Heat stress control and heat casualty management. Departments of the Army and Air Force Technical Bulletin Medical 507 / Air Force Pamphlet 48–152(I). 2003.

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