Caffeine, Body Fluid–Electrolyte Balance, and Exercise Performance

Lawrence E. Armstrong

Recreational enthusiasts and athletes often are advised to abstain from consuming caffeinated beverages (CB). The dual purposes of this review are to (a) critique controlled investigations regarding the effects of caffeine on dehydration and exercise performance, and (b) ascertain whether abstaining from CB is scientifically and physiologically justifiable. The literature indicates that caffeine consumption stimulates a mild diuresis similar to water, but there is no evidence of a fluid-electrolyte imbalance that is detrimental to exercise performance or health. Investigations comparing caffeine (100–680 mg) to water or placebo seldom found a statistical difference in urine volume. In the 10 studies reviewed, consumption of a CB resulted in 0–84% retention of the initial volume ingested, whereas consumption of water resulted in 0–81% retention. Further, tolerance to caffeine reduces the likelihood that a detrimental fluid-electrolyte imbalance will occur. The scientific literature suggests that athletes and recreational enthusiasts will not incur detrimental fluid-electrolyte imbalances if they consume CB in moderation and eat a typical U.S. diet. Sedentary members of the general public should be at less risk than athletes because their fluid losses via sweating are smaller.

Key Words: methylxanthine, total body water, diuresis, sweat, fluid balance

Background

The amount of body water lost during exercise depends on the intensity and duration of exercise, the clothing worn, environmental conditions, fitness level, and the extent of heat acclimatization. An average person, running at 180 m/min (i.e., a 9-min pace per mile), produces 550–1000 ml of sweat per hour. A heat acclimatized athlete or laborer, exercising strenuously, may produce 2–3 times this amount (5). Large losses of body water clearly impose significant stress on the circulatory and other organ systems, and reduce physical performance. For example, laboratory studies suggest that normal heart rate and core body temperature responses to exercise are exaggerated when fluid losses reach only 1 or 2% of body weight. Unequivocal decrements in cardiovascular endurance performance and maximal aerobic power (VO_{max}) appear at a weight decrease of approximately 3% as water. Muscular strength and power reductions begin to appear at a body weight loss of 5%.

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Further, the risk of heat illness such as heat exhaustion or heatstroke increases as dehydration progresses without adequate fluid replacement (3). For these reasons, regular fluid intake is widely recognized as a means to avoid performance decrements and safeguard health. The American College of Sports Medicine, for example, provides active individuals with specific recommendations regarding the volume, timing, and composition of fluids (21).

However, the aforementioned facts do not necessarily mean that every factor that causes minor body water loss is detrimental. Some factors may be inconsequential, and concern about them may represent a waste of effort and time. The caffeine content of beverages is a case in point. The author undertook this review after several years of anecdotal observations that ran contrary to the common recommendation (44) that athletes should not consume caffeinated beverages (CB). The remainder of this manuscript will evaluate whether abstaining from CB is scientifically and physiologically justifiable.

Consumption of Caffeine

Caffeine is the most widely used behaviorally active drug in the world (36), with 82–92% of adults in North America regularly consuming caffeine. In the U.S., an average adult coffee drinker consumes 200–400 mg of caffeine (2–4 cups of coffee) each day and 20–30% of these adults consume up to 600 mg per day (15). Worldwide, the per capita caffeine consumption of all residents is approximately 70 mg per day, which is equivalent to one small cup of ground coffee per person (36, 46). Of this amount, dietary caffeine intake is derived overwhelmingly from beverages: 54% from coffee, 43% from tea, and 3% from other sources. Chocolate and confectionery items account for only a few mg per 100 g of total daily adult intake. Caffeine also is consumed in the form of prescription drugs and over-the-counter analgesics (e.g., Anacin®, Vanquish®, Midal®, Excedrin®; 44).

The amount of caffeine in a cup of coffee or tea obviously varies with the strength of the beverage and volume of the cup. Table 1 presents the caffeine content of various beverages. Although soft drinks provide a fraction of the amount of caffeine found in coffee and tea, 98% of Americans aged 5 to 18 consume some caffeine each day, due largely to the popularity of soft drinks among children (36).

Caffeine Pharmacology

The active agents in coffee, tea, and soda are classified chemically as methylxanthines. Caffeine (in coffee, tea, and soft drinks) is 1,3,7-trimethylxanthine; theophylline (in tea) is 1,3-dimethylxanthine; and theobromine (in tea, chocolate, and cocoa) is 3,7-dimethylxanthine. All three compounds are central nervous system and cardiac stimulants. Theophylline also acts as a mild diuretic and serves to mobilize lipids as metabolic substrates. In the U.S., the daily consumption of these three compounds consists of 83.2% caffeine, 16.7% theobromine, and 0.1% theophylline (48).

The principal pharmacological actions of acute caffeine administration are to stimulate the central nervous system, increase urine output from the kidneys, stimulate cardiac muscle, decrease peripheral resistance in blood vessels, increase gastric secretions, and relax smooth (e.g., bronchial) muscle (46). Caffeine is most commonly derived from the following plants: coffee (coffee arabica), tea (thea sinensis),
Table 1  Caffeine Content of Common Beverages

<table>
<thead>
<tr>
<th>Beverage</th>
<th>Caffeine content / Serving size</th>
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<tbody>
<tr>
<td>Instant coffee</td>
<td>66–74 mg / 150 ml</td>
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<tr>
<td>Brewed coffee</td>
<td>146 mg / 150 ml</td>
</tr>
<tr>
<td>Decaffeinated brewed coffee</td>
<td>3–9 mg / 150 ml</td>
</tr>
<tr>
<td>Weak tea (1-min brew)</td>
<td>19–28 mg / 140 ml</td>
</tr>
<tr>
<td>Strong tea (5-min brew)</td>
<td>38–70 mg / 140 ml</td>
</tr>
<tr>
<td>Green tea</td>
<td>15 mg / 140 ml</td>
</tr>
<tr>
<td>Iced tea</td>
<td>22–36 mg / 240 ml</td>
</tr>
<tr>
<td>Cola soft drink</td>
<td>47 mg / 360 ml</td>
</tr>
<tr>
<td>Cocoa</td>
<td>0–16 mg / 217 ml</td>
</tr>
</tbody>
</table>

Note. Serving sizes represent commercial containers, traditional cups, and mugs as defined by authors. Sources: Nagy (59), Bunker and McWilliams (13), and Graham (40).

chocolate (theobroma cocoa), and kola (cola nitida). Caffeine is extracted from these plant sources and is very soluble in boiling water (39).

Caffeine is readily absorbed and freely diffusible, thus an oral dose is a reliable predictor of tissue levels when a bolus is consumed with an empty stomach. Ingesting caffeine with a meal causes lower levels in plasma and urine (24). The mean time to reach peak caffeine concentration is 30–60 min (range, 15–120 min; 46, 76) in plasma and 2.2 h (range, 1–3 h; 78) in urine. Although caffeine metabolism occurs mainly in the liver, the brain and kidney also may participate (71). Urinalysis is the most effective means of detecting consumption of large quantities. Several studies have demonstrated that between 0.5 and 3.0% of the administered dose of caffeine is recovered in urine (76, 78). By-products of caffeine metabolism (e.g., theophylline, theobromine, paraxanthine) also appear in urine.

**Metabolic and Ergogenic Properties**

Exercise physiologists have long suspected that caffeine might improve endurance performance and, as a central nervous system stimulant, caffeine has been used for many decades in an attempt to improve human performance. For example, a widely published report described the purported use of caffeine suppositories by the U.S. Olympic Cycling Team in 1984 (67). Indeed, the general consensus of research evidence indicates that caffeine improves endurance time to exhaustion in prolonged events (18, 25, 43); this ergogenic effect increases as the duration of exercise extends beyond 30 min (41). The literature suggests that a dose of 9 mg caffeine/kg body weight, taken 1 h prior to exercise, enhances performance at intensities of about 80–85% VO$_{2}$max in well-trained endurance athletes and recreational cyclists.

The exact metabolic mechanism of this ergogenic effect is unknown, but plasma epinephrine rises after caffeine intake (23, 32, 51, 65), independent of plasma
norepinephrine, which may or may not rise (32, 43, 77). The absence of elevated plasma norepinephrine is consistent with specific stimulation of the adrenal medulla (43) rather than a general increase in sympathetic nervous system activity (66).

Research does not support an ergogenic effect of caffeine for all types of exercise. The majority of studies demonstrate that caffeine does not enhance performance during incremental exercise tests lasting 8 to 22 min, or during sprints lasting less than 90 s (10, 41, 62, 64). However, a few research groups report that caffeine enhances short-term intense exercise lasting about 5 min (74), as well as maximal muscular power (40). These discordant findings suggest that different caffeine-induced effects may be at work in different types of exercise. In fact, Conlee (20) recently listed a number of other experimental factors that influenced these studies, including caffeine dose, type of exercise, pre-exercise feedings, subject training status, previous caffeine use, and individual variation. Therefore, it may be best to view caffeine as a compound that can alter the function of many body tissues, and to acknowledge that some of the influences may not be metabolic but rather may be direct effects on excitation-contraction coupling in skeletal muscle (41).

**Tolerance to Caffeine**

With regular consumption of caffeine, tolerance develops to many of its effects in only 4 or 5 days, in most adults. When tolerance occurs, a typical physiological response requires a greater amount of caffeine (23, 66). Development of tolerance to caffeine has been observed in the responses of urine formation, blood pressure, heart rate, sleep onset, salivary secretions, and hormone metabolism (66, 77). In a classic study, Eddy and Downs (27) determined that the average minimal effective dose (i.e., the amount that caused an obvious diuretic effect) was 0.48 mg/kg body weight, when subjects abstained from drinking coffee for 2 months. After habituation to caffeine, the minimum effective dose was 1.12 mg/kg body weight. Similar tolerance was observed in tests that involved theobromine (from 0.44 to 1.39 mg/kg) and theophylline (from 0.29 to 0.45 mg/kg).

Some physiologists have hypothesized that the effects of caffeine on exercise performance may be attenuated in consumers of caffeine because they develop tolerance to the pharmacological effects of caffeine (61). This hypothesis exists because some physiological responses indicate desensitization to caffeine use. For example, plasma epinephrine levels decrease (6), and changes occur in respiratory variables and plasma free fatty acid levels (31), during the development of tolerance and withdrawal from caffeine. However, these observations were made on steadystate exercise, not maximal performance. In contrast, direct measurements of running and cycling time to exhaustion, as well as muscle torque output, show that tolerance to caffeine does not alter its possible ergogenic effects (77).

The difference between experimental caffeine dosage and daily habitual caffeine intake also is important. The aforementioned studies contained obvious differences in experimental designs. In some, experimental dosage was less than daily habitual caffeine intake, whereas in other studies it was greater. Also, the time allowed for the development of tolerance to caffeine was different among these studies. The critical question is, “Does caffeine tolerance alter the ergogenic effects of caffeine?” Tarnopolsky’s (77) thorough review of caffeine and endurance performance addressed this question. He concluded that habitual caffeine consumption
(a) does not have a significant effect on variables that may be ergogenic to endurance performance, and (b) does not alter the ergogenic effect of large doses of caffeine (9 mg/kg body weight) on endurance running or cycling performance. Similar conclusions were drawn by Spriet (74) in an extensive review of caffeine effects on performance.

**Large Doses of Caffeine**

Tolerance to caffeine may be overcome when daily consumption is very large. Denaro and colleagues (23) observed that daily consumption of 12 mg caffeine/kg body weight (6–11 cups of coffee per day) produced pharmacologic effects that are not completely compensated by the development of tolerance. Apparently, the mechanism(s) of tolerance are overwhelmed by accumulation of caffeine in blood and tissues, when metabolic caffeine removal is saturated. This effect would not occur in the average adult, who consumes 1 to 2 cups of coffee per day (36, 46).

Further, large doses of caffeine induce stress-like neuroendocrine responses that are characterized by increased serum corticosterone and β-endorphin, decreased serum growth hormone and thyroid-stimulating hormone, and no change in prolactin (73). A person must consume 500 mg caffeine (equivalent to approximately 5 cups of coffee) in one sitting for this endocrine response to occur (e.g., slight elevations in plasma ACTH, β-endorphin and cortisol). Typical oral doses of caffeine (e.g., 1–2 cups of brewed coffee) have small or no endocrine effects of this type. Unfortunately, no direct measurements of exercise performance have been made in studies examining the effects of stress-like responses, or tolerance, to large doses of caffeine.

**Regulations of Sport Governing Bodies**

Presently, both the National Collegiate Athletic Association (NCAA) and the International Olympic Committee (IOC) classify caffeine as a banned substance, due to its ergogenic properties. To achieve a plasma concentration that has no ergogenic properties, athletes would have to abstain from caffeine intake for 48–72 h prior to competition. Because the ergogenic effects of caffeine have been observed with as little as 3 mg/kg body weight, it is easy for endurance athletes to enhance performance "legally" with caffeine. Even moderate doses (5–6 mg/kg body weight) enhance exercise performance.

Concentrations of 15 and 12 μg caffeine/ml urine are defined as "positive tests" by the NCAA and IOC, respectively (72). It is reasonable to ask whether these limits can be produced by the social intake of CB. A team of South African investigators examined this question by measuring urinary caffeine levels for 24 h after 9 healthy males drank a volume of about 4 cups (600 ml) of brewed coffee, tea, and Coca Cola® on separate days (78). To exceed the limit of 15 μg/ml, subjects had to consume 918–999 mg caffeine (equivalent to about 7–8 cups of coffee or tea). These investigators concluded that (a) participants in competitive sport will not exhibit illegal urinary concentrations by mere social intake of CB, and (b) if the urine concentration exceeds 15 μg/ml, officials can be confident that large amounts of caffeine were taken purposefully, shortly before a competitive event. In support of these conclusions, Wagner (81) subsequently observed that only 3 of 9 study participants had urinary caffeine levels greater than 12 μg/ml, after consuming 13.5 mg/kg body weight.
Abuse of Diuretics in Sport

Although the effects of methylxanthine consumption are usually minor compared to prescription medications, research has clearly shown that diuretic-induced dehydration hampers exercise performance (1). Five previous studies (4, 8, 15, 17, 80) have utilized the commonly prescribed diuretic medication Lasix™ (furosemide). Ingestion of 40–126 mg of this compound induced dehydration ranging from −2 to −4% of body weight. The results demonstrated that running performance (1500, 5000, and 10,000 m), cycling performance, and maximal isometric leg strength decreased. Physiological responses such as heart rate and heat storage also increased.

Despite these facts, diuretic medications and numerous compounds including caffeine, are abused by athletes in a few sports. Two examples demonstrate the nature of this abuse. First, caffeine use by competitors, who attempt to “make weight” (e.g., wrestlers lose 3–4 kg in 3–4 days) or enhance muscle definition before competition, is a legitimate health concern because any water loss is serious in their dehydrated state. Caffeine is a favorite stimulant of bodybuilders; it is used to stimulate diuresis (29), reducing the water content of the extracellular fluid and improving appearance by making the skin lie closer to underlying muscles. A 1995 case report (75) provides insight regarding the negative consequences of excessive drug use in competition. A 27-year-old male professional bodybuilder utilized diuretic pills (caffeine was not specifically mentioned), potassium supplements, and dietary restrictions. He developed profound muscle weakness, muscle cramps, mild rhabdomyolysis (i.e., muscle fiber damage), abnormal kidney function, and life-threatening hyperkalemia (elevated potassium levels in blood) that caused changes in his cardiac rhythm (ECG). His case closely resembled another bodybuilder who died after employing similar drug and diet strategies. Second, abnormal behaviors were reported in a survey of 371 female athletes who were members of NCAA Division I basketball, softball, and volleyball teams (55). Results indicated that 27% utilized at least one nonprescription weight loss product, such as laxatives, diet pills, and/or diuretic pills (caffeine was not specifically mentioned). Although these examples do not represent all athletes, they emphasize the extraordinary, sometimes illicit, steps that some competitors take.

Because the above examples represent abnormal and unhealthy behavior, it is reasonable for dieticians, exercise physiologists, and clinicians to denounce the use of diuretics to enhance performance or alter body composition. However, these examples should not be interpreted to mean that the average person, who participates in exercise several times each week, is jeopardizing his/her health by consuming one or two CB each day. The determination of safety or risk associated with caffeine consumption depends on many factors, including the amount consumed, body water turnover (i.e., intake versus loss), and the individual’s tolerance to caffeine consumption (see below).

Water is a diuretic when consumed in a large volume in that it acts to increase urine output. This was demonstrated in 1947 by Barclay et al., who observed that urine volume averaged 552 ml (morning trial) and 526 ml (afternoon trial), during the initial 1.5 h after participants had consumed 800 ml of water. Only 31–34% of the ingested water was retained by the body after 90 min. Fluid-electrolyte replacement beverages (FERB) also are diuretics, although a slightly greater percentage of the consumed fluid is retained in the body (versus pure water), due to the sodium content of the FERB. Following the same logic that is applied to CB, does this mean
that active adults should consume no water or FERB? The answer to this question is obviously no, but it illustrates the potential to incorrectly assume that consuming any fluid with diuretic properties is unsafe for active adults. Statements such as these should be examined critically and qualified.

The Diuretic Effect of Caffeine

Of the three methylxanthines described above, theophylline has the most potent diuretic effect, whereas caffeine and theobromine impose weaker influences (34). Theophylline and caffeine exert their primary effect on the kidneys as an increase in blood flow (i.e., increased glomerular filtration rate). Theophylline and caffeine also act to enhance sodium and chloride excretion at both the proximal and distal renal tubules, which secondarily causes an increase in urinary water loss (26, 33, 82).

Because of its diuretic potential, dieticians, exercise physiologists, and clinicians often advise recreational enthusiasts and athletes to abstain from consuming caffeinated beverages (CB; 9, 16, 44, 53, 71, 74). They reason that exercise stimulates sweating and dehydration, and assume that consuming CB exaggerates dehydration and electrolyte loss to the point that it impairs exercise performance and/or health. However, these authorities rarely cite research investigations to support their advice, and virtually no evidence exists in the scientific literature to support this assumption (44, 74). Opposing this viewpoint, other physiologists and physicians view caffeine as a mild diuretic (20, 26, 47, 65). In fact, published reviews by Nehlig and Debry (61) and Sinclair and Geiger (71) concluded that CB and a liquid placebo affect body fluid balance identically during exercise.

In consideration of these opposing viewpoints, the following paragraphs describe the research protocols that evaluated the degree of diuresis induced by caffeine. Table 2 compares CB data to data from water and placebo tests. The initial eight studies were conducted totally at rest; two of these (12, 37) involved rehydration after exercise-induced dehydration. Only one study (82) included urine collections during exercise. The final study has been included to demonstrate the diuretic potential of pure water. The order of presentation matches that in Table 2 and Figure 1.

1. A group of medical students served as volunteers for a comparison of the diuretic effects of consuming 300 mg of caffeine, 300 mg of theobromine, and placebo (26). Sleep and usual daily activities were maintained; no exercise was involved.
2. Nine healthy, non-coffee drinkers consumed 300 ml of a caffeine-containing fluid (250 mg) and a liquid placebo (65). Subjects did not exercise during the two experiments; supine posture was maintained during 3-h urine collections.
3. On three occasions, 12 female college students consumed 240 ml of either a placebo liquid or a beverage containing caffeine (150 and 300 mg, respectively) while resting for 3 h (57).
4. During three different experiments, 15 healthy males consumed 480 ml of either a placebo liquid or beverages containing caffeine (150 and 300 mg, respectively) while resting for 3 h. Urine volume decreased 8% during the 150-mg condition, and increased 17% during the 300-mg condition (57).
5. Thirty-seven healthy women consumed both a placebo liquid and caffeine (274 mg) in 250 ml of fluid. Urine volume was collected for 2 h at rest (11).
<table>
<thead>
<tr>
<th>Reference, methods</th>
<th>Urine volume change (ml)</th>
<th>Urine Na+ change (mEq)</th>
<th>Urine K+ change (mEq)</th>
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<tbody>
<tr>
<td><strong>Caffeine versus placebo or water</strong></td>
<td></td>
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<tr>
<td>Dorfman and Jarvik (26); p, placebo; c, 300 mg caffeine</td>
<td>+15% (337 p vs. 386 c)</td>
<td>+57% (35 p vs. 55 c)</td>
<td>+10% (10 p vs. 11 c)</td>
</tr>
<tr>
<td>Robertson et al. (65); p, placebo liquid; c, 250 mg caffeine / 300 ml fluid</td>
<td>+28% (366 p vs. 469 c)</td>
<td>+14 (14.4 p vs. 16.4 c)</td>
<td>+10% (8.4 p vs. 9.2 c)</td>
</tr>
<tr>
<td>Massey and Wise (58); p, placebo liquid; c1, 150 mg caffeine; c2, 300 mg caffeine</td>
<td>+14% (463 p vs. 525 c1); +35% (463 p vs. 626 c2)</td>
<td>+90% (2.1 p vs. 4.0 c2); +157% (2.1 p vs. 5.4 c1);</td>
<td>+46% (1.3 p vs. 1.9 c1); +31% (1.3 p vs. 1.7 c2)</td>
</tr>
<tr>
<td>Massey and Berg (57); p, placebo liquid; c1, 150 mg caffeine; c2, 300 mg caffeine</td>
<td>−8% (414 p vs. 381 c1); +17% (414 p vs. 486 c2)</td>
<td>+17% (23.8 p vs. 27.9 c1); +64% (23.8 p vs. 39.0 c2)</td>
<td>0% (14.3 p vs. 14.3 c1); +8% (14.3 p vs. 15.4 c2)</td>
</tr>
<tr>
<td>Bergman et al. (11); p, placebo liquid; c, 6 mg caffeine / kg lean body mass (274 mg)</td>
<td>+34% (332 p vs. 445 c)</td>
<td>+74% (13.7 p vs. 23.8 c)</td>
<td>+21% (8.0 p vs. 9.7 c)</td>
</tr>
<tr>
<td>Grandjean et al. (44); w, water; c1, caffeinated (114 mg) beverage; c2 caffeinated (253 mg) beverage</td>
<td>0% (1424 w vs. 1424 c1); +11% (1424 w vs. 1575 c2)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Experiments involving rehydration and exercise</strong></td>
<td></td>
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<tr>
<td>Gonzalez-Alonso et al. (37); w, water; dc, diet cola (250 mg caffeine)</td>
<td></td>
<td>+18% (600 w vs. 710 dc)</td>
<td>−23% (78 w vs. 60 dc)</td>
</tr>
<tr>
<td>Brouns et al. (12); w, 2.15 L water; c, 2.77 L of caffeinated soft drink (379 mg caffeine)</td>
<td></td>
<td>+4% (960 w vs. 1000 c)</td>
<td>+44% (45.8 w vs. 65.9 c)</td>
</tr>
<tr>
<td>Wemple et al. (82); pr, placebo at rest; cr, caffeine at rest; pe, placebo during exercise; ce, caffeine during exercise; 8.7 mg caffeine / kg body weight (490–680 mg total) was consumed in 2.56 L fluid; all conditions utilized a carbohydrate-electrolyte replacement fluid</td>
<td>0–60 min: −11% (325 pr vs. 290 cr), −1% (380 pe vs. 375 ce); 60–240 min: +31% (1411 pr vs. 1843 cr),</td>
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<tr>
<td><strong>Water only, at rest</strong></td>
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<tr>
<td>Barclay et al. (7); 800 ml pure water was consumed during morning (AM) and afternoon (PM) trials</td>
<td>+494% in AM (93 b vs. 552 a); +662% in PM (69 b vs. 526 a)</td>
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</table>

*Significant difference at *p* < .05 level; †statistical analysis not reported.
Figure 1 — Percentage of water that was retained after consuming caffeinated beverages (CB) versus a placebo liquid (the control trial in all studies). Investigations A through F involved rest; investigations G and H evaluated rehydration after exercise-induced dehydration; investigation I employed 4 h of cycling only. This figure suggests that fluid retention for both CB and water is greater in a dehydrated state. Investigations: A. Dorfman and Jarvik (26); B. Robertson et al. (65); C: Massey and Wise (58); D: Massey and Berg (57); E: Bergmann et al. (11); F. Grandjean et al. (44); G: Gonzalez-Alonso et al. (37); H. Brouns et al. (12); I. Wemple et al. (82).

6. The research of Grandjean et al. (44) is the sole investigation to date that collected urine continuously for 24 h. This is important because it is unlikely that single urine samples will be representative of 24-h urine collections (Lentner, 1981). The authors concluded that, when 18 healthy men consumed 1.75 L of three different fluids at rest, CB did not significantly alter hydration status (44).

7. Sixteen male and three female college students cycled and ran on three different occasions until they lost 2.5% of body weight. While at rest, they rehydrated fully (1.96 L/2 h) by consuming either water (W) or a caffeinated diet cola (DC) that contained 250 mg of caffeine and 4 mEq Na⁺ (37). Urine volume was statistically similar for both trials.

8. Eight well-trained cyclists exercised in a 28°C environment (12) until they lost 3.2% of body weight. They rehydrated while resting for 2 h at 20°C, by consuming ad libitum either water (2.15 L) or a caffeinated soft drink (2.77 L; 137 mg caffeine/L). Urine volume was statistically similar for both trials during the 6 h following exercise.
9. Wemple and colleagues (82) demonstrated that a large caffeine dose (490–680 mg; 4 males, 2 females), consumed in a large volume (2.56 L) of CES, actually reduced urine losses during some phases of 4 h of cycling (60% \( \text{VO}_{2\text{max}} \)) in a 28–30 °C environment. The authors concluded that caffeine may be consumed, as a part of a CES, without caffeine-induced diuresis or without compromising body hydration status.

10. Water (800 ml) was consumed by healthy males during a 90-min morning rest period. The experiment was repeated during the afternoon of another day. This investigation not only demonstrated that water is a diuretic, it also showed that diuresis is influenced by the volume of fluid consumed. When body water content is normal, a large percentage of pure water will be excreted. When the body is dehydrated, most of the water intake will be retained by the body, up to a state of normal hydration (7).

The findings of the aforementioned studies may be summarized as follows. First, caffeine acted as a mild diuretic in most, but not all, situations. When a low dose (114 to 249 mg caffeine) was consumed, urine volume changed from −8 to +14%, versus placebo. When a dose greater than 250 mg was consumed, urine volume increased 4 to 35%, depending on the experimental protocol. Second, a dose-dependent portion of the water in CB was retained at rest; 0 to 21% was retained for a caffeine dose ≤150 mg and 0 to 10% for a dose of 250–300 mg. Third, 55–64% of the water in a CB was retained during rehydration, after exercise-induced dehydration (12, 37). Fourth, during 4 h of continuous exercise, 70% of a CB was retained (82). Fifth, nine of these studies involved observations of less than 6 h. The amount and effects of subsequent fluid intake are unknown.

Other research has shown that caffeine stimulates glucose absorption in the small intestine. A carbohydrate-electrolyte solution (CES) was compared to a CES + caffeine solution, during 90 min of cycling exercise (70% of maximal watt output). Intestinal glucose uptake was greater in the trial that involved CES + caffeine (79). This positive effect of caffeine may encourage maintenance of blood glucose during prolonged exercise.

Finally, some researchers have hypothesized that exercise in a hot environment may cause harmful dehydration or hyperthermia when accompanied by caffeine intake. This hypothesis arose from two lines of evidence. First, human studies have demonstrated that resting metabolic rate (RMR) is increased by caffeine ingestion (50, 63) in both physically trained and sedentary subjects; this might add to heat production and result in hyperthermia. Second, theophylline directly stimulates eccrine sweat glands (69); this suggested that caffeine might stimulate excessive sweating and dehydration. However, two human experiments employing exercise (29, 38) observed no significant differences (caffeine versus placebo) in core body temperature, sweat loss, or change in plasma volume. In these two investigations, subjects ran for 1 h (70% \( \text{VO}_{2\text{max}} \)) and 2 h in warm environments (25–29 °C) after consuming 5–7.5 mg caffeine/kg body weight (361–553 mg total). One research group (29) noted that caffeine, unlike the majority of stimulants used for ergogenic purposes, induces dilation of cutaneous blood vessels and may advantageously distribute blood to skin for heat dissipation during exercise. A third study evaluated outdoor running performance during great heat stress in Louisiana during midsummer. Seven experienced distance runners performed three 21-km competitive road races 1 h after consuming either 0, 5, or 9 mg caffeine/kg body weight.
(respectively, 0, 315, 567 mg total). Performance times were not significantly different, suggesting that caffeine ingestion was not detrimental to performance (18).

**Caffeine and Urinary Electrolyte Losses**

Table 2 also presents data regarding changes of urinary sodium (Na+) and potassium (K+) losses that result from caffeine consumption. In all but one instance, CB increased Na+ excretion (range of −23 to +157%). This agrees well with previous observations that theophylline and caffeine act to enhance sodium and chloride excretion at both the proximal and distal renal tubules (25, 33, 82). Potassium excretion was less affected by caffeine at rest (0 to +46%). When a CB was consumed during rehydration, it actually caused less K+ excretion than pure water (−33 to −30%).

The absolute electrolyte losses in Table 2 ranged from 4 to 55 mEq Na+ and 1.7 to 15.4 mEq K+. During rehydration protocols (12, 37), urinary electrolyte excretion ranged from 60 to 65.9 mEq Na+ and 23.1 to 38 mEq K+. When compared to the range of typical adult daily intakes in the U.S. (i.e., 78–218 mEq Na+ and 64–87 mEq K+), these losses are small-to-moderate (National Research Council, 1989) and should be replaced adequately by a normal diet. However, studies have not been conducted to assess the effects of repeated days of caffeine intake.

Rehydrating with a CB has a small impact on magnesium and calcium homeostasis after exercise-induced dehydration to −3% of body weight (12; see Table 2). Urinary levels of magnesium increased from 1.8 to 3.5 mEq Mg++, and calcium increased from 1.2 to 2.1 mEq Ca++, when compared to water. Similarly, studies conducted at Washington State University demonstrated that urinary calcium and magnesium losses increase during a 3-h resting protocol (57, 58). However, when compared to typical adult daily intakes in the U.S. (range: 8.5–13.5 mEq Mg++ and 18.5–29.4 mEq Ca++), these losses are small-to-moderate (60). As with Na+ and K+, further studies are needed to compare the effects of repeated days of caffeine intake to water consumption.

**Body Fluid Balance: Interpretive Calculations**

This section illustrates key physiological principles that have been derived from the studies in Table 2. The examples below utilize published values and offer an interpretation of the influence that caffeine has on body fluid balance and exercise performance.

**Given:** The body of an average 70 kg adult male contains approximately 60% water (42 L). His total body water (TBW) is partitioned by cell membranes into extracellular fluid (ECF, 14 L) and intracellular (ICF, 28 L) fluid compartments. The ECF is further compartmentalized into the interstitial fluid (10.5 L) and plasma (3.5 L). The normal concentration of plasma is 280 mOsm/kg water, meaning that the total number of osmotically active particles in the ECF is 3920 mOsm (14 L fluid × 280 mOsm/kg H₂O = 3920 mOsm). The average urine volume for an adult male is 1.3 L per day (Geigy Scientific Tables, 1984).

**Example 1**

A 70-kg male consumed 1.75 L water in 1 day and did not exercise. This resulted in a 24-h urine volume of 1.424 L. On a second day, he consumed the same diet, but
included 1 cup of coffee (114 mg caffeine) as a part of his total daily fluid intake. This resulted in an identical urine volume of 1.424 L/24 h. On a third day, he consumed the same diet (including 1.75 L fluid) but consumed 253 mg caffeine in the form of CB. As a result, daily urine volume increased (vs. water) by 151 ml, to 1.575 L. Fluid retention amounted to 19% and 10% of the initial volume consumed, respectively, for the 114- and 253-mg caffeine tests. They illustrate that (a) consuming approximately 1 cup of brewed coffee or 2.4 soft drinks (114 mg caffeine) had no measurable effect on TBW turnover, and (b) consuming approximately 2 cups of coffee or 5.4 soft drinks (253 mg caffeine) resulted in a net urine loss that was 151 ml greater than on day 1 (water only). The difference in fluid lost (caffeine vs. water) is considerably smaller than that incurred during 1 h of moderate intensity exercise; the average male loses 0.5–2.0 L of sweat per hour (70). At rest, caffeine intake increased electrolyte losses by 2–15 mEq Na+ and by 1–2 mEq K+. This difference (caffeine vs. water) is small in comparison to the amount of total body exchangeable sodium (2870 mEq Na+ and potassium (3150 mEq K+; 34), and in comparison to the daily electrolyte content of a typical American diet (78–218 mEq Na+ and 64–87 mEq K+; 60). These values are modeled after the investigation of Grandjean et al. (44) shown in Table 2.

**Example 2**

During exercise, a 70-kg male lost 3% of his body weight as sweat, on 2 separate days. Following each day, he rehydrated for 2 h by drinking either 2 L of water or 2 L of a diet cola containing 250 mg caffeine. As a result, caffeine increased urine volume by 18% (vs. water) but Na+ losses in urine decreased 23% and K+ excretion decreased 33%. This meant that both water and diet cola rehydration resulted in fluid retention (1.36 and 1.25 L, respectively) and that both Na+ and K+ losses were smaller during the caffeine trial (60 mEq Na+, 38 mEq K+) than the water trial (78 mEq Na+, 57 mEq K+). These values are modeled after the research of Gonzalez-Alonso et al. (37) shown in Table 2.

**Example 3**

None of the studies in Table 2 provide evidence that caffeine induces a state of chronic fluid imbalance that negatively influences exercise performance or health. As noted in the second paragraph of this review, decrements in cardiovascular endurance performance and VO2max appear at a weight change of approximately −3%. Muscular strength and power reductions begin to appear at a body weight loss of approximately 5% (1). For a 70-kg male, these dehydration levels require net fluid losses of 2.1 L (−3%) and 3.5 L (−5%). To reach these levels of dehydration, he would have to exercise for 1.4 to 4.2 h (−3%) and 2.3 to 7.0 h (−5%), without consuming any fluid (70). Under normal circumstances, the thirst mechanism stimulates fluid consumption (i.e., a hypothalamic-regulated drive to drink) when the body weight loss reaches 1–2% (49). This causes sweat losses to be replaced ad libitum as they occur. When the rehydration fluid contains caffeine, urine is produced in quantities that are comparable to, but somewhat greater than, a similar experiment in which water is consumed (Table 2). However, because the scientific literature contains no evidence of chronic or harmful caffeine-induced hypohydration, it is reasonable to assume that renal fluid-electrolyte conservation and normal dietary
intake are adequate to maintain TBW balance indefinitely, even if up to 300 mg caffeine is consumed per day (Table 2). Further, tolerance develops with regular consumption of a low caffeine dose, and the usual mild diuretic response is blunted (27). This suggests that, as tolerance develops, the diuretic response to caffeine becomes less likely to induce a detrimental fluid-electrolyte imbalance.

Conclusion

Because caffeine is one of the most widely used drugs on earth, has ergogenic properties, and is banned by sport governing bodies at high dietary levels, a thorough understanding of the physiologic effects of caffeine on fluid-electrolyte balance and subsequent performance is important to anyone who exercises—especially athletes. The foregoing analysis of the scientific literature, spanning 30 years, indicates that the following conclusions are presently warranted.

1. A daily intake of caffeine that is less than 300 mg induces a mild diuresis similar to water, but there is no evidence that this results in a fluid-electrolyte imbalance that is detrimental to exercise performance or health, when a typical U.S. diet is consumed. In the present review, 12 of 15 comparisons of caffeine (100–680 mg) versus water or placebo (Table 2, column 2) found no statistical difference in urine volume.

2. Consumption of a CB resulted in 0–84% retention of the total volume consumed, depending on the experimental scenario (Figure 1). Similarly, consumption of water resulted in 0–81% retention of the initial volume consumed. Apparently, fluid retention is greater when dehydration exists (vs. euhydration) for both CB and water.

3. Direct laboratory comparisons of caffeine (361–567 mg) versus placebo trials, conducted in 25–29°C ambient conditions, revealed no differences in core body temperature, sweat rate, plasma volume shifts, or performance times for 21-km competitive foot races. Thus, no research evidence indicates that caffeine consumption is detrimental during exercise in hot environments, when fluid losses are likely to be maximal.

4. Further research is required to clarify whether a large dose of caffeine (e.g., >680 mg; Table 2) results in fluid-electrolyte imbalances. This is necessary because a large dose (e.g., >9 mg caffeine/kg body weight; 630 mg for a 70-kg person) is required to enhance performance at exercise intensities of 80–85% VO\(_{2\text{max}}\) in well-trained endurance athletes. Future investigations should evaluate fluid-electrolyte balance during chronic, high-dose caffeine use across several days.

5. During 2–6 h of rehydration, consumption of 250–379 mg caffeine may paradoxically result in smaller Na+ or K+ losses (Table 2) than water consumption. Also, during prolonged exercise (e.g., 4 h cycling at 60% VO\(_{2\text{max}}\)), CB may paradoxically result in a smaller urine volume than a placebo fluid. This may be due to the fact that caffeine blocks adenosine-mediated inhibition of renin release from the kidneys and increased levels of angiotensin II (71). Unfortunately, the long-term effects of caffeine consumption have not been adequately investigated. Because, in the present review, only one study observed urine output for a period greater than 6 h (Table 2), future investigations should include 24-h urine analyses across consecutive days.
6. Physiologic tolerance to caffeine reduces the likelihood that a detrimental fluid-electrolyte imbalance will occur. Tolerance to the diuretic effect of caffeine has been observed in response to doses as small as 34 mg for a 70-kg person.

These summary statements suggest that recommendations to entirely avoid consuming CB (16, 53) are unsupported by published investigations. It is unlikely that athletes and recreational enthusiasts will incur detrimental fluid-electrolyte imbalances if they consume CB in moderation and eat a well-balanced diet. Sedentary members of the general public should be at less risk than athletes because their fluid losses via sweating are smaller.

**Addendum**

During the review of this manuscript, Douglas J. Casa, Ph.D., and several graduate students at the University of Connecticut conducted a preliminary experiment that provided further insights (unpublished observations; D.J. Casa et al., *J. Ath. Training* 37:S-33, 2002, abstract). This field study evaluated the influences of *ad libitum* post-exercise rehydration using one of two beverages (either Coca Cola® or Caffeine-Free Coca-Cola®) and a cross-over experimental design. Ten partially heat-acclimated athletes (24 ± 1 years) completed 3 consecutive days of double workouts (4 h/day) on two different occasions, separated by 4 days. Participants played soccer, modified rugby, flag football, and hiked each day, in a specific order and for the same duration of time; they drank only water during workouts. The total water intake during daily exercise was similar in both phases (6.26 ± 0.72 vs. 6.02 ± 0.56 L) and the rehydration beverage volume was similar in both phases (5.60 ± 0.49 vs. 5.39 ± 0.48 L). Caffeine intake was 245 ± 26 mg/day during the Coca-Cola® phase. The results demonstrated no significant differences between the caffeine and non-caffeinated beverages for urine volume, percentage of ingested fluid that was retained, body mass, urine osmolality, urine specific gravity, plasma osmolality, percent change in plasma volume, thirst rating, thermal sensation, and rating of perceived exertion.

**References**


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