Fluid Balance, Hydration, and Athletic Performance

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Louise M. Burke

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7.1 INTRODUCTION

There is irony in the observation that endurance sports have received the most attention from sports science and nutrition experts in terms of the development of guidelines for fluid intake, yet they remain the focus of controversy and continued discussion. For the purposes of this chapter, endurance sports are defined as continuous activities of greater than 90 min duration that can potentially span into ultra-endurance events (>4 h) and multiday competitions. The mode of locomotion can include running, cycling, swimming, skiing, or padding/rowing, and sometimes combinations of several of these within the same event, and the field of play is usually outdoors with exposure to the prevailing environmental conditions. In line with the duration of these sports, the majority of the work-rate is undertaken at submaximal intensities. However, it should be remembered that in many events, critical pieces that shape the outcome of the event involve high-intensity exercise: for example, the breakaway, the surge up a hill, and the sprint to the finish line. Furthermore, in some events there is an element of skill and technique that requires good coordination of central and peripheral function.

As is the case with other sporting activities, the goal of drinking fluids is to prevent the fluid deficit that accrues due to sweat losses from reaching avoidably problematic level. However, other considerations for consuming fluids during endurance sporting event include the ingestion of common drink ingredients known to enhance performance such as carbohydrate, electrolytes and caffeine, as well as the contribution of cool or icy fluids to comfort and thermoregulation during exercise. In multiday endurance events, fluids consumed during the activity may contribute a substantial proportion of the energy, protein, and micronutrients needed for general health, as well as specific guidelines for optimal performance and recovery. A common element to endurance sports is that fluid intake during an event is primarily achieved *on the run*—or while the athlete is actually exercising. This feature means that the *cost* of achieving the activity must be balanced against the *benefits* of its effects. These costs include the effort to have drinks available to consume, the time lost in slowing down to obtain and consume them, and the risk of incurring gastrointestinal discomfort or upsets as a result.

Guidelines for hydration practices in endurance sports have evolved from prescriptive recommendations to consume a certain fluid volume during exercise to the adoption of a practiced and individualized plan that can partially replace sweat losses as well as provide other ingredients or characteristics previously mentioned. This advice is not universally embraced; however, alternative views are that thirst should dictate the need for, and volume of, fluid replacement during exercise and that *ad libitum* drinking is sufficient to address fluid needs during sport. This chapter will review the background to the debate over fluid needs for endurance events, covering the evolution of the guidelines and the points of differences in current views. In proposing recommendations to find some common and practical middle-ground, the literature on self-chosen fluid intakes of competitors in a variety of endurance sports will be presented. While such data do not necessarily always represent optimal practice, at least they show what is logistically possible and valued by athletes under real-life competition conditions (Garth and Burke 2013).

The nutritional strategies that can be of benefit to endurance sports involve the integration of a number of elements including the intake of nutrients and evidence-based ergogenic aids, and the manipulation of stomach comfort and temperature regulation. The science behind these strategies and practical ways to achieve them are covered in a number of sections and chapters in this book. The principle focus of the current chapter is to consider how they can be incorporated into a plan in which the intake of fluid is the dominant or binding factor. This plan must be underpinned by an understanding of both the specific issues around hydration and the practical issues of achieving this within endurance sports.

7.2 EVOLUTION OF GUIDELINES FOR FLUID INTAKE DURING ENDURANCE SPORTS

Since the 1970s, expert groups have issued guidelines for fluid intake during sport and exercise. These guidelines have evolved over the years due to our increasing knowledge as well as some justifiable criticisms of previous ideas and education messages. The first position stands on fluids for exercise were focused on distance running and were mostly targeted to race organizers and medical support teams (American College of Sports Medicine [ACSM] 1975, 1987). They were prepared in response both to the increased community participation in marathons and fun runs with the running boom of the 1970s and a desire to update the prevailing rules of the IAAF (the international governing body of athletics) that no aid stations should be provided prior to the 15 km mark of a distance race.

Although these guidelines recommended more access to aid stations throughout races, they proved to be problematic in several ways: First, they continued to prescribe water as the only fluid that should be available (ACSM 1975, 1987), failing to recognize the accumulating evidence of the benefits of consuming carbohydrate during exercise of >1 h duration (see Chapter 19). Importantly, the recommendations were prescriptive and impractical to translate into the varying characteristics of distance running, let alone other endurance sports. Although many athletes like the simplicity of prescriptive advice, even apparently simple guidelines often fail the test of scrutiny. For example, suggestion that "distance runners should drink 100–200 ml of water at aid stations provided every 2–3 km in a race" (ACSM 1987) sounds reasonable. However, if taken literally, it could span the intake of 330 ml/h by a slow runner to 2 L/h by a fast runner. This would range from inadequate to suitable for slower runners depending on their actual sweat rates, but the high rate would be impossible to achieve when running at high speeds and any such attempt would be likely to cause gastrointestinal discomfort and substantial time loss at aid stations.

The updated ACSM guidelines published in 1996 increased the general scope of interest to fluid intake during exercise and recognized the benefits of including carbohydrate and electrolytes in beverages for endurance sports. However, they continued to promote a formulaic intake of fluid with the goal of minimizing the mismatch between fluid intake and sweat losses: "During exercise, athletes should start drinking early and at regular intervals in an attempt to consume fluids at a rate sufficient to replace all the water lost through sweating (i.e., body weight loss), or consume the maximal amount that can be tolerated" (ACSM et al. 2007). Concern that these guidelines could be interpreted out of context as "consume the maximal amount of fluid possible" and contribute to observations of hyponatremia/water intoxication caused by the excessive intake of fluids by some (usually recreational) participants in endurance/ultra-endurance sports activities (Noakes et al. 2005; Noakes and Speedy 2006) is an important factor in later guidelines.

The most recent guidelines by groups such as the ACSM (ACSM et al. 2007), the National Athletic Trainers Association (Casa 2007), and the International Olympic Committee (Shirreffs and Sawka 2011) have tried to accommodate the specificity of needs and opportunities to hydrate during exercise across a range of sports, as well as the unique needs of each participant. They recommend that each athlete develop an individualized fluid plan based on an appreciation of his or her likely sweat rates and knowledge of opportunities to drink during the exercise session. They typically maintain the goal of defending, where possible, a *gold standard* of hydration, suggested as loss of <2% body mass (BM) over the event, but warn against overdrinking as shown by a gain in BM. However, even these recommendations have been subjected to the (often vitriolic) criticism of being unnecessary, complicated, and driven by commercial interests (Beltrami et al. 2008; Noakes 2012). Instead, it has been argued that athlete should simply drink according to their thirst (Noakes 2007).

7.3 ISSUES AND CONTROVERSIES

There are two different considerations involved in setting guidelines for fluid intake during endurance sport. The first consideration is the level of hydration that is needed to achieve optimal performance (or from the obverse point of view, what is the largest level of fluid deficit that can be tolerated before performance is impaired?).

Second, the guidelines need to consider how the athlete can be educated to achieve this hydration level/avoid a fluid deficit larger than this. Both of these considerations have been the focus of challenge and discussion over the recent decade.

Optimal performance in endurance sports requires the integration of the muscle's ability to produce the power needed to achieve optimal movement patterns and the central nervous system's role in choosing appropriate pacing strategies and execute optimal technique, decision making, and skill. Historically, it has been considered that impairments of *aerobic* performance undertaken in a hot environment can be detected when there is a fluid deficit of ~2% or greater, with the magnitude of effects increasing as the degree of dehydration increases. Furthermore, the effects of dehydration are less obvious when aerobic exercise is undertaken in a cool environment and it may take a fluid deficit of 3%–5% before they are detectable (Sawka 1992; Cheuvront et al. 2003, 2010; Sawka and Noakes 2007; Cheuvront and Kenefick 2014). However, in recent times, there have been debates about whether these concepts are correct, with arguments in both directions that they are too simplistic to capture the real essence of the effects of dehydration on sports performance.

The case that endurance athletes can tolerate larger fluid deficits without problem includes the following ideas:

- The evidence that dehydration impairs endurance performance is mostly based on studies conducted in laboratory sessions which don't adequately replicate real-life conditions of sport, including factors such as the cooling effect of the air movement from outdoors (Saunders et al. 2005) or the effect of motivation and reward for successful outcomes.
- Some reviews of laboratory-based studies have concluded that dehydration of <4% is unlikely to impair the performance of time-trial type protocols (Goulet 2013).
- Studies and anecdotal observations show that successful athletes can tolerate high levels of dehydration (Beis et al. 2012), with the winners in a race often being the most dehydrated.
- Competitive athletes learn to accommodate the physiological decrements associated with laboratory-based observations of dehydration.
- Successful performance does not always require optimal outputs; rather, the athlete only needs to be better than his or her competitors.

There are counter-arguments to these suggestions, including the following:

- Laboratory studies of graded levels of dehydration show that the effects on a range of physiological factors and perceived effort of exertion increase in a continuum (Montain and Coyle 1992); it is also likely that the effect on performance gradually increases until the point when, according to the sensitivity of the protocol, it becomes measurable. Failure to see a performance impairment in a study may represent a Type II error due to underpowering of sample size or poor reliability of monitoring performance.
- Some field-based studies have reported that mild fluid deficits of even 2%–3% impair performance in the heat (Casa et al. 2010; Bardis et al. 2013).

- In many outdoor sports, athletes deliberately reduce the potential for convective cooling by adopting aerodynamic positions (riding/running in slipstream of other competitors, choosing special equipment and clothing).
- The margins of winning and losing in sport are typically very small, making it unlikely that we can measure all the factors that make meaningful changes in the outcomes.
- The effort required to overcome the physiological and psychological decrements associated with dehydration may manifest in ways other than a measurable drop in work-rates: for example, loss of concentration during the event and greater difficulty with recovery between events.
- Not all studies report that the race winners are the most dehydrated. Some studies show no correlation between loss of mass over event and performance (Speedy et al. 1999) and others show an inverse relationship with most successful athletes being the best hydrated (Ross et al. 2014). In any case, observations cannot tell cause or effect, or how an athlete would have performed with a different fluid intake strategy.

In summing up these views, this author feels that endurance athletes should make a calculated risk about how much of their relative or absolute performance is needed on the specific day of any race after undertaking a cost-benefit analysis of their potential opportunities for fluid intake in the event. In other words, they should counterbalance the time loss or risk of gut discomfort associated with drinking at the available opportunities with the impairment of perception of effort and performance associated with a fluid deficit. The outcome of this analysis is likely to vary according to factors such as the individual athlete, the environmental conditions, the logistics of drinking, and the type of event. This will be discussed further in the conclusion of this chapter.

The second topic of recent debate has been the need for guidelines for fluid intake. Although the expert position stands have moved away from prescriptive guidelines to favor the development of an individualized fluid intake plan, some sports scientists have heavily criticized even this approach. Instead, they argue that humans can optimize their performance and health during a sporting event by drinking according to behavior that is innate and spontaneous rather than planned. They advocate that hydration can be managed by *drinking to thirst* or *ad libitum fluid intake* (Noakes 2010). The hypothesis that drinking to thirst is the best way to approach education around fluid intake is based on several assumptions (Noakes 2010) given as follows:

- That the human thirst response is highly developed in guiding athletes to the need to drink in the short-term and long-term and that the athlete can respond to thirst by drinking appropriate volumes of fluid
- That humans have evolved to tolerate a certain level of thirst and fluid deficit in the short-term without impairment of health or performance
- That this behavior will err on the side of allowing a fluid deficit rather than overload, thus preventing the development of hyponatremia in individuals and groups

Concern about over-hydration during exercise has been at the forefront of the revisions and concerns over guidelines for fluid intake during sport. This is rare, at least historically, in non-endurance sports where athletes exercise at high intensities with commensurately high sweat rates. However, observational studies of endurance and ultra-endurance sports over the past two decades have found that some individuals are overzealous with their fluid intake and drink at a rate that substantially exceeds their sweat losses and their ability to excrete fluid via urine. Excessive fluid intake is a major contributor to the potentially fatal condition of hyponatremia, although other factors include the retention of excess fluid because of inadequate suppression of antidiuretic hormone secretion (Noakes et al. 2005; Siegel et al. 2007). Risk factors for over-hydrating include undertaking endurance and ultra-endurance events at a slow pace (lower sweat rates and greater likelihood of stopping to drink at aid stations) and being female (smaller body size with lower sweat rates) (Almond et al. 2005). Mathematical modeling also shows that mild levels of hyponatremia may also occur as a result of large salt losses in individuals who excrete sweat that is salty or simply high in volume (Montain et al. 2006). However, overdrinking underpins the development of severe hyponatremia and the sequelae of encephalopathies that have caused several unfortunate and preventable deaths among athletes and military personnel. As a result, new fluid intake guidelines are clear in their warnings against overdrinking during exercise (ACSM et al. 2007; Casa 2007; Shirreffs and Sawka 2011).

Although this author believes that thirst provides a reasonable starting point or contribution to the development of fluid plan for endurance sports, there are some problems in making this a universal or single approach. First, it is unclear what *drinking to thirst* really means, since it can be interpreted in different ways which would require different behavior and lead to different outcomes in terms of fluid intake and fluid balance. For example, interpretations include (1) drink every time you are thirsty; (2) when presented with fluids, only drink if you are thirsty; or (3) drink during the opportunities in sport so that thirst doesn't develop. Although some people use *drinking to thirst* interchangeably with the term *ad libitum fluid intake*, this is not strictly true since the latter implies that fluid intake can be undertaken whenever and in whatever volumes the athlete desires.

In addition to the potential confusion around what the term actually means, there are several types of athletes or situations, however, where there may be benefits from building a more calculated approach than *drinking if you are thirsty*. It is noted that the following conditions apply to many endurance and ultra-endurance sports:

- In events where opportunities for fluid intake are limited, the athlete may need to drink at the available opportunities early in an event (i.e., *ahead of their thirst*) to better pace the total fluid intake over the session.
- In events where performance can benefit from the regular intake of other nutrients that can be delivered in fluids—in particular, carbohydrate. As long as it doesn't require an excessive fluid intake, athletes may develop a plan to consume beverages such as sports drinks to contribute to refueling targets.
- For athletes who are unable to respond to thirst or hunger due to personal characteristics or the confusion about appropriate volumes to consume due to exposure to a food environment with continually upsized food portions.

In these situations, there may be benefits from developing a personalized plan that can be manipulated according to circumstances or characteristics of each event.

7.4 WHAT DO ENDURANCE ATHLETES CURRENTLY DRINK?

A range of factors that influence the intake of fluids during competitive endurance events; these include thirst, genetic predisposition to be avid or reluctant drinker, beliefs regarding dehydration or over-hydration, access/availability of fluids, opportunity to drink, palatability of drink, gastrointestinal comfort, wish to avoid the need to urinate, desire to reduce BM over the race, and the desire for other ingredients (e.g., carbohydrate and caffeine) or characteristics (e.g., temperature) of fluid. The available literature on observed practices of athletes in endurance competitions is now summarized (Tables 7.1 through 7.3), to discuss the apparent importance of these factors.

7.4.1 Single-Day Endurance Events (Events Lasting <~3 h for Top Competitors)

An unusual characteristic of many endurance events (marathons and Olympic distance triathlons) is that elite and recreational athletes often compete in the same race, meaning that the event will include participants with a large range of finishing times. As in all sports, the rates and total volume of sweat loss vary with the intensity and duration of the event, with potential for large differences between athletes, even those in the same race. The outdoor setting increases the potential for large differences in sweat losses between events of the same type, according to specific characteristics such as the event terrain and environmental conditions (heat, humidity, altitude, and wind).

We have previously identified a range of features that influence fluid intake during competitive endurance events (Garth and Burke 2013). A key characteristic of the hydration opportunities in endurance events is that athletes must drink while *on the move*. Access to fluids during the majority of events is typically governed by a network of drink stations/feed zones, although this can be supplemented or replaced in other endurance sports by the transport of fluids by the individual athlete. Elite athletes are often able to provide themselves their own specific race supplies at aid stations, while in mass participation events, the provisions at feed stations available to general competitors are governed by the race organizer. Opportunities to drink must consider the time lost in obtaining and consuming fluid, and the potential for gut discomfort due to drinking while exercising at relatively high intensities. Practicing drinking during event-simulating training sessions may facilitate the development of appropriate skills and gut tolerance in some athletes. Devices such as fluid containing backpacks and spill-proof bottles may also enhance access to fluid and opportunities to drink during some endurance sports. However, in other sports, technique requirements such as bike handling during downhill mountain bike riding or maintaining an aerodynamic position during road cycling time trials may interfere with opportunities to obtain or consume fluids. Similarly, pacing strategies and race tactics may interfere with the athlete's opportunities to drink, since they may choose to surge past the aid stations. Some endurance athletes may deliberately or subconsciously restrict fluid intake

TABLE 7.1
Fluid Balance Characteristics of Single-Day Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Beis et al. (2012)	10 M Elite	13 Olympic and Big City Marathons	126 ± 1	Air: 0–30 Humidity: 39–89	N/A	N/A	0.55 ± 0.34[c]
Kipps et al. (2011)	53 M, 35 F Mixed caliber	London Marathon	252 ± 43 (Nor) 266 ± 48 (EAH)	Air: 9–12 Humidity: 73 Raining	NR	N/A	0.45 (Nor) 0.84 (EAH)
Tam et al. (2011)	12 M, 9 F Mixed caliber	Two Oceans Half Marathon, South Africa	129 ± 24	Air: 18–24 Humidity: 50–70	NR	−1.9 (−1.4 ± 0.6 kg)	0.33 ± 0.18
Zouhal et al. (2011)	560 M, 83 F Mixed caliber	Mont Saint-Michel Marathon France	NR	Air: 9–16 Humidity: 60–80	NR	−2.3 (All) [range −8 to +5] −3.1 (finish <3 h) −2.5 (finish 3–4 h) −1.8 (finish >4 h)	N/A
van Rooyen et al. (2010)	4 M, 5 F Elite	Athens Olympic Marathon	NR	Air: 30–33 Humidity: 31–39	N/A	N/A	*Range:* 0.43–1.30[c] (F) 0.30–0.35[c] (M)
Au-Yeung et al. (2010)	240 M, 32 F Mixed caliber	Hong Kong Marathon	255	Air: 12–19 Humidity: 59–88 Raining	NR	N/A	0.40

(*Continued*)

TABLE 7.1 (*Continued*)
Fluid Balance Characteristics of Single-Day Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Mettler et al. (2008)	128 M, 39 F Mixed caliber	Zurich Marathon	220 ± 32 (M) 245 ± 23 (F)	Air: ~10 Humidity: NR Raining	NR	−0.8 ± 0.8 (M) −0.2 ± 0.8 (F)	0.47 (M) 0.36 (F)
Hew (2005)	63 M, 54 F Mixed caliber	Houston Marathon	269 ± 45 (M) 303 ± 54 (F)	NR	NR	−2.1 (M) (−1.7 ± 1.8 kg) −1.0 (F) (−0.6 ± 1.1 kg)	0.74 (M) 0.68 (F)
Myhre et al. (1982)	3 M Mixed caliber	Marathon Southern United States	216	Air: 15.5–24.5 Humidity: NR Raining	1.24 (1.06–1.17)	−4.7 (range: −3.4 to −6.7%)	1.33 (range: 0.65–1.90)

Source: Garth, A.K., and Burke, L.M., *Sports Med.,* 43(7), 539–64, 2013.

M, male; F, female; N/A, data excluded from the table due to use of inappropriate methodology; NR, not reported.

[a] Data are reported as mean ± SD (if provided) unless otherwise stated.

TABLE 7.2
Fluid Balance Characteristics of Single-Day Ultra-Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
				Multisport			
Schwellnus et al. (2011)	209 M + F Mixed caliber	South Africa IM	759 ± 96 (CR) 795 ± 93 (NC)	Air: 20 Humidity: 70	NR	−3.1 ± 1.9 (CR) −2.8 ± 1.8 (NC)	NR
Pahnke et al. (2010)	26 M, 20 F Mixed caliber	Hawaii IM	NR	Air: 27.6 Humidity: NR	Race day data NR	−2.1 ± 2.1	1.00 ± 0.30 (All) 0.85 ± 0.30 (M) 1.05 ± 0.30 (F)
Laursen et al. (2006)	10 M Mixed caliber	Busselton IM	611 ± 49	Air: 23.3 ± 1.9; Water: 19.5; Humidity: 60	NR	−3.0 ± 1.5	NR
Sulzer et al. (2005)	20 M + F Mixed caliber	South Africa IM	661 ± 78 (CR) 685 ± 49 (NC)	Air: 20.5; Water: 16 Humidity: 68	NR	−3.4 ± 1.3 (CR) −3.9 ± 2.0 (NC)	NR
Sharwood et al. (2002)	311 M, 45 F Mixed caliber	South Africa IM	757 ± 100	Air: 20.5; Water: 16 Humidity: 68	NR	−5.2 ± 2.2	NR
Speedy et al. (2002) (*data* = *median*)	11 M, 7 F Mixed caliber	New Zealand IM	738	Air: 21; Water: 20.7 Humidity: 91	0.81 (bike) 1.02 (run)	−3.5 [−6.1 to +2.5%] −1.0 kg (swim): +0.5 kg (bike); −2.0 kg (run)	0.72 0.89 (bike) 0.63 (run)
Speedy et al. (1999)	292 M, 38 F Mixed caliber	New Zealand IM	734	Air: 21; Water: 20.7 Humidity: 91	NR	−4.3 ± 2.3 (M) −2.7 ± 3.1 (F)	NR
O'Toole et al. (1995)	26 M, 4 F Mixed caliber	Hawaii IM	711 ± 105	Air: 22–31; Water: 26 Humidity: 40–85	NR	−2.6 (Nor) −0.6 (EAH)	NR

(*Continued*)

TABLE 7.2 (*Continued*)
Fluid Balance Characteristics of Single-Day Ultra-Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Speedy et al. (1997)	46 M + 2 F Mixed caliber	Coast to Coast New Zealand	879 ± 83	Air: 7.5–19.6 Humidity: 56–94	NR	−3.1 ± 2.1	NR
Rogers et al. (1997)	13 M Mixed caliber	South Africa IM Ultra-triathlon	620 ± 64	Air: 28.0 ± 4.9 Humidity: 48	0.94 ± 0.16	−4.6 ± 1.8	0.74 ± 0.14
van Rensberg et al. (1986)	23 M Mixed caliber	Rand Daily Mail-Nutri-Sport Triathlon	687	Air: 24.7–33.8 Humidity: NR	NR	−4.5	NR
Stuempfle et al. (2003)	17 M, 3 F Mixed caliber	Susitna 100 mile alpine multisport (run, cycle, or ski) Alaska	2292	Air: −14 to −2 Humidity: NR Snow	NR	−1.6	0.30
			Ultra-Running				
Bracher et al. (2012)	50 M Mixed caliber	"100 km Lauf Biel" Switzerland Start time 2200	All finished within 735	Air: 15.6–21.7 Humidity: 52–69	NR	−2.5	0.58
Tam et al. (2011)	9 M, 3 F Mixed caliber	Two Oceans 56 km South Africa	340 ± 64	Air: 18–24; Humidity: 50–70	NR	−3.5 (−2.5 ± 1.1 kg)	0.54 ± 0.36
Knechtle et al. (2011b)	27 M Mixed caliber	"100 km Lauf Biel" Switzerland	689 ± 119	Air: 8–18; Humidity: NR; Start time 2200	NR	−2.6 (−1.9 ± 1.4 kg)	0.52 ± 0.18
Knechtle et al. (2011c)	145 M Mixed caliber	"100 km Lauf Biel" Switzerland	640 ± 74 (EAH) 710 ± 120 (Nor)	Air: 8–28; Humidity: NR; Start time 2200	NR	−2.4 ± 1.8[c] (All) −2.6 (EAH) −2.4 (Nor)	0.58 ± 0.23 (EAH) 0.65 ± 0.30 (Nor)
Knechtle et al. (2010)	11 F Mixed caliber	"100 km Lauf Biel" Switzerland	All finished within 762 ± 91	Air: 8–18; Humidity: NR; Start time 2200	NR	−2.4 (−1.5 ± 1.1 kg)	0.30 ± 0.10

(*Continued*)

TABLE 7.2 (*Continued*)
Fluid Balance Characteristics of Single-Day Ultra-Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Lebus et al. (2010)	35 M, 10 F Mixed caliber	Rio Del Lago 100 mile California	1547 ± 190	Air: 12.2–37.6 Humidity: NR	NR	−2.9[c]	NR
Kao et al. (2008)	17 M, 1 F Mixed caliber	Soochow University International 12 h	720 (89.7 ± 11.7 km)	Air: 11.5–14.6 Humidity: 55–60	NR	−2.9 ± 1.6	NR
Kao et al. (2008)	19 M, 4 F Mixed caliber	Soochow University International 24 h	1440 (199.4 ± 37 km)	Air: 11.5–14.6 Humidity: 55–60	NR	−5.1 ± 2.3	NR
Kruseman et al. (2005)	39 M, 3 F Mixed caliber	44 km Mountain Marathon Switzerland	423 ± 77	Air: 18–30 Humidity: 34–92	NR	−4.0 (−2.9 ± 1.1 kg)	0.55 ± 0.16
Glace et al. (2002)	13 M + F Mixed caliber	160 km trail run Start time 0430	1572 ± 216	Air: 21–38 Humidity: NR	NR	−0.5 (−0.5 ± 1.5 kg)	0.74
Fallon et al. (1998)	7 M Mixed caliber	100 km road run	629 ± 113	Air: 2–17 Humidity: 45	0.86 ± 0.15	−3.3 ± 1.1	0.54 ± 0.21
Rehrer et al. (1992)	158 M, 12 F Mixed caliber	Swiss Alpine Marathon (67 km)	498 (M) 536 (F)	Air: 7–11 Humidity: 64–72		−3.3 (M) −4% (F)	0.40 (M) 0.31 (F)
			Cycling				
Armstrong et al. (2012)	42 M, 6 F Mixed caliber	164 km cycle event USA	546 ± 72 (M) 540 ± 12 (F)	Air: 34.5 ± 5.0 Humidity: 53	1.13 (n = 20 M)	N/A	0.65 (M) 0.52 (F)
Hew-Butler et al. (2010)	26 M, 7 F Mixed caliber	109 km cycle race South Africa	296	Air: 24.9 Humidity: 50	NR	−1.5	0.44
Knechtle et al. (2009)	37 M Mixed caliber	Swiss MTB Bike Masters 120 km	540 ± 80	Air: 11 (at start) Humidity: NR	NR	−1.9 ± 1.6	0.7 ± 0.2

(*Continued*)

TABLE 7.2 (*Continued*)
Fluid Balance Characteristics of Single-Day Ultra-Endurance Events

Study	Subjects	Event	Duration (min)[a]	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
			Swimming				
Wagner et al. (2012)	25 M, 11 F Mixed caliber	26.4 km swim Switzerland	528 (M) 599 (F)	Air: 18.28; Humidity: 42–93; Water: 23–24	NR	−0.5 ± 1.1 (M) −0.1 ± 1.6 (F)	0.56 ± 0.22 (M) 0.44 ± 0.17 (F)

Source: Garth, A.K., and Burke, L.M., *Sports Med.,* 43(7), 539–64, 2013.

M, male; F, female; IM, Ironman triathlon; N/A, data excluded from the table due to use of inappropriate methodology; NR, not reported; Nor, normotremic; EAH, exercise associated hyponatremia; CR, cramps reported; NC, no cramps.

[a] Data are reported as mean ± SD (if provided) unless otherwise stated.

TABLE 7.3
Fluid Balance Characteristics of Multiday Stage Events

Study	Subjects	Event	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Ross et al. (2012)	5 M: Elite Australian National Road Series team	Tour of Gippsland cycling stage race (9 stages in 5 days)	Air: 15.8 ± 1.4 Humidity: 54 ± 12	1.1 ± 0.3	−1.5 ± 0.3 (road) −1.1 ± 0.2 (crit)	0.41 ± 0.19 (road) 0.24 ± 0.19 (crit)
Ross et al. (2012)	5 M: Elite Australian National Road Series team	Tour of Geelong cycling (6 stages over 5 days)	Air: 13.2 ± 2.1 Humidity: 80 ± 8			0.56 ± 0.14 (road) 0.27 ± 0.21 (crit)
Rust et al. (2012)	65 M: Mixed caliber	Swiss Cycling Marathon (720 km in ~3 days)	Air: 9–25 Humidity: NR	NR	−1.5 ± 1.7[c]	0.67 ± 0.23
Ebert et al. (2007)	8 M: Elite Professional team	Tour Down Under cycling stage race (719 km in 6 days)	Air: 20.2–32.9 Humidity: 14–69	1.60 ± 0.10	−2.8	1.00 ± 0.10
Ebert et al. (2007)	6 F: Elite Australian national squad	Tour De L'Aude (788 km in 10 days)	Air: 7.7–27.8 Humidity: 29–76	0.90	−2.6	0.40 ± 0.06
Garcia-Roves et al. (1998)	10 M: Elite Professional team	3 × 24 h periods during the 3-week Tour of Spain	NR	NR	NR	1.26 ± 0.55L[b] =1.03 L/h W =0.23 L/h SD
Rose et al. (2010)	18 M: Mixed caliber	Sani2C MTB race (248 km over 3 stages)	Air: 9–22 Humidity: 43–100 Rain stage: 1	NR	−1.4 (Stage 1) −2.0 (Stage 2) −1.0 (Stage 3)	0.34 (Stage 1) 0.41 (Stage 2) 0.55 (Stage 3)
Schenk et al. (2010)	25 M: Mixed caliber	Transalp MTB (665 km in 8 stages)	Air: 4–32 Humidity: NR Rain stage: 2, 3, 8	NR	−0.17 to −1.44	0.49 to 0.75[b] (range)

(Continued)

TABLE 7.3 (*Continued*)
Fluid Balance Characteristics of Multiday Stage Events

Study	Subjects	Event	Environment (°C, %)	Sweat Rate (L/h)[a]	Δ Body Mass (%)[a]	Fluid Intake (L/h)[a]
Singh et al. (2012)	5 M, 7 F: Mixed caliber	Three Cranes Challenge (95 km trail run over 3 stages)	Air: 11.5–22.8 Humidity: 54–97	NR	−3.1[b] (−2.06 ± 0.57 kg)	NR
Knechtle et al. (2011a)	25 M: Mixed caliber	Swiss Jura Marathon (350 km in 7 stages)	Air: Not stated Humidity: NR	NR	−1.4 ± 2.0[c]	0.54–0.75[c] (range)

Source: Garth, A.K., and Burke, L.M., *Sports Med.,* 43(7), 539–64, 2013.

M, male; F, female; NR, not reported; road, road race stage; crit, criterium race stage; W, water; SD, carbohydrate-electrolyte sports drink.

[a] Data are reported as mean ± SD (if provided).

[b] Per stage.

[c] Total event.

during events in the belief that accrual of a fluid deficit may enhance performance, particularly in hilly terrain, due to the effect of a lower BM in increasing the economy of movement and improving power to weight ratio. Finally, fluid intake by some endurance athletes may be driven by their desire to consume other ingredients found in everyday drinks or specialized sports beverages such as carbohydrate, caffeine, and electrolytes, or by the desire to regulate body temperature via the intake of cool drinks.

The available literature on fluid intake during endurance sports has been limited to marathon and half-marathon running races conducted in mild to warm environments (Table 7.1).

Notwithstanding the limitations of methodologies used in such studies, which have been previously acknowledged (Garth and Burke 2013), studies in which data were collected immediately pre- and post-race showed that the typical change in BM across the event was a deficit of ~1%–2%; however, the range across the subjects in the same race spanned a deficit of >2% BM to a gain in mass. Indeed, in the study which involved the largest number (>600) of participants, individual BM changes over the marathon ranged from −8% to +5% (Zouhal et al. 2011). Although the authors noted a relationship between finishing time and BM losses, with the faster runners incurring a greater fluid deficit, BM change only accounted for 4.7% of the variance in race time, suggesting a complex relationship. Several studies in this category noted drinking behavior between the group who were characterized as having normal plasma sodium concentrations and those who developed mild/asymptomatic hyponatremia, with the hyponatremic group drinking more fluid and losing less BM (or gaining) over the course of the event (Hew 2005; Kipps et al. 2011).

The only observations on fluid intake by elite marathon runners were gathered by an innovative but largely unvalidated technique of retrospectively examining television footage of the behavior of the leading runner at the race drinking stations at the 2004 Athens Olympics (van Rooyen et al. 2010) and at 13 Olympic or Big City marathons (Beis et al. 2012). The footage revealed that they spent a total of 2–51 s, representing less than 1% of race time, engaged in drinking activities. The estimated (maximum) intake of fluid by male marathon winners, the majority of which are likely to be East African athletes, was claimed to be an average of 550 ± 340 ml/h with a range of 30–1090 ml/h (Beis et al. 2012). There were no correlations between fluid intake and either ambient conditions or running speed among these observations. Indeed, in similar environmental conditions, runners can behave differently in different races as illustrated by the athlete who ran the Berlin marathon in 2006 (12°C) and 2008 (16°C) with an estimated fluid intake of 1839 ml for the first year (2:03:59 finishing time) and 1098 ml for the second (2:06:08).

7.4.2 Single-Day Ultra-Endurance Events (Top Competitors Finish in >3 h)

Events such as ultra-marathons, 50 km race walking, cycling road races, and half Ironman and Ironman triathlons also involve mass participation with a mixture of elite to recreational competitors. They also share the characteristics of endurance sports with regard to opportunities for fluid intake during the event, and the variable effect of the outdoor environment on sweat rates. Since the intensity of the event is reduced compared with endurance events, sweat rates are theoretically lower and there may be increased opportunity for fluid intake. However, the extended duration of the race may also increase the absolute fluid deficit or gain if there is a mismatch between sweating and fluid intake. Fluids may contribute a substantial amount of the carbohydrate needed to meet sports nutrition recommendations for extended events: for example, Speedy and colleagues reported that ~2/3 of the fluid consumed by Ironman triathletes contained carbohydrate (sports drink and cola drinks) and can contribute ~50% of the carbohydrate consumed during the race (Speedy et al. 2001; Kimber et al. 2002).

Table 7.2 summarizes the results of studies of ultra-endurance events involving running, cycling, and multisport combinations conducted over 5–24 h as a single-day race. Observations of fluid intake during ultra-endurance events noted mean intakes ranging from 300 to 1000 ml/h with large individual variations in these rates. Factors contributing to differences in fluid intake include the mode of activity: greater rates of intake were typically observed during cycling activities (400–900 ml/h) than running events (300–700 ml/h).

Overall, mean BM loss over the race ranged from 1.5% to 5.2%, with individual outcomes spanning a loss of >7% to a gain of 5% BM. Correlations between sweat loss and finishing time were unclear, with faster athletes recording a greater total loss of BM over the race in some studies (Lebus et al. 2010; Bracher et al. 2012) while the slowest athletes reported greatest losses in others (Speedy et al. 1999). Again, many investigations were focused on the incidence of hyponatremia, which occurred in 0%–51% of the study participants and occurred mostly in asymptomatic forms. As in the endurance events, weight gain was associated with hyponatremia (Speedy et al. 1999, 2001) particularly in the case of severe decreases in serum sodium concentrations. However, hyponatremia was also reported in individuals who maintained (Speedy et al. 1997) or even lost BM (Speedy et al. 1999, 2001) including substantial changes of a 9% BM loss (Speedy et al. 2001). Thus, the etiology of hyponatremia is complex.

7.4.3 Fluid Balance in Multiday Ultra-Endurance Events

Sports such as cycling, mountain biking, running, and single or multisport adventure racing include multiday competition formats, with events lasting from two days to three weeks. Events can be further divided into those in which competitors are required to complete the course in a continuous manner of their own choosing, where the periods taken to sleep or eat are included in the finishing time, and those in which competitors complete a number of stages each day with these individual performances accumulating to produce the final results. Access to nutritional support may come from a variety and combination of sources including self-sufficiency, official feed zones, sporadic checkpoints for supplies, and assistance from team support crew. The determinants of sweat losses and fluid intake vary as discussed in the previous section on single-day endurance and ultra-endurance sports, with the additional challenges that intake during the event may need to contribute to substantial requirements for fluid, carbohydrate, and energy over the duration of the whole event and that deficits from one day may carry over to the next.

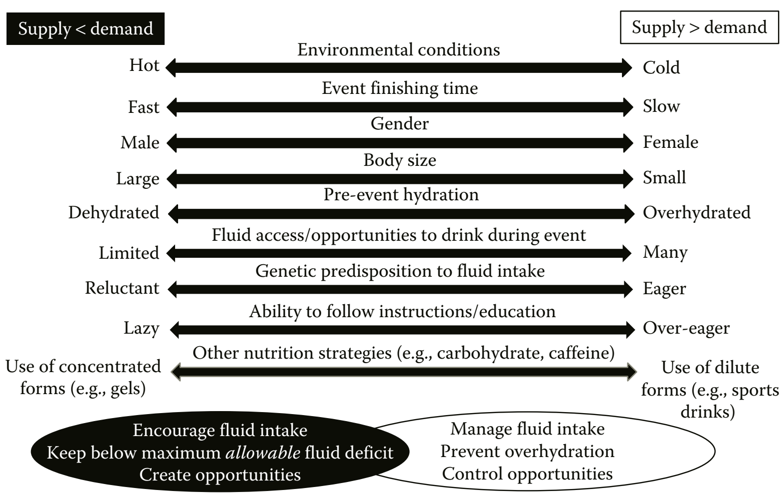
Table 7.3 summarizes observations from 10 separate multiday events, including four involving elite cyclists of international caliber, and formats ranging from a continuous road cycling format to events involving road cycling, mountain biking, or ultra-running with one or more stages each day. Studies reported mean fluid intakes across a stage of ~300–1000 ml/h and mean BM changes of 0.2%–3% BM, with the likelihood that elite athletes recorded a fluid deficit exceeding 3% BM in hot weather races. Fluid intake in some events was correlated to the temperature at the start of the stage (Schenk et al. 2010) and the duration of the stage (Ross et al. 2014). In addition, the format of a cycling race was seen to influence fluid intake, with road cyclists drinking less during criterium and individual time-trial formats than road races (Ross et al. 2014). Explanations for this observation include the briefer length of the race as well as reduced access to fluids (lack of feed zones) and opportunity to drink (the conflict between taking time to drink and the need to ride aggressively or in a streamlined position). However, it was also noted that the rules and culture of road cycling have evolved to promote greater opportunities for fluid and energy intake during the road race format. In addition to feed zones in which all cyclists can obtain food and fluid supplies from their support crews, designated riders within a cycling team (*domestiques*) assume a role of ferrying food and drinks supplies from the team car throughout the race to the cyclists who are in contention to win (Ross et al. 2014). Nevertheless, there are obstacles to drinking during the stage including the need to keep hands on the handlebars during steep ascents and descents in road cycling (Ebert et al. 2007; Ross et al. 2014), difficult terrain in mountain biking (Schenk et al. 2010) as well as aggressive riding tactics and the *breakaway* whereby the lead rider is distant to the support of the domestiques (Ebert et al. 2007; Ross et al. 2014).

There were reports of both a negative correlation between the finishing time within a stage and fluid intake or level of deficit (Ebert et al. 2007) and a lack of association or even positive correlation between success in a race and fluid intake/BM maintenance (Ross et al. 2014). Although it is intuitive that the fastest athletes in a race might incur the greatest fluid deficit as a result of a higher sweat rate and less opportunity or desire to obtain or drink fluids at high speed, in some sports there are unique factors that may change this relationship. For example, in one cycling study, the fastest competitors within each stage were shown to have incurred the smallest losses of BM (Ross et al. 2014). This was explained by the team tactic in road cycling whereby the *protected rider* (cyclists who are deemed to have the best chance of winning) spends much of the race riding within the slipstream of the peloton or their team mates, thus reducing their power outputs (and sweat rates) while allowing them to achieve greater intakes of fluid and energy. Further studies on such events, including those involving elite competitors, may provide further insights into cultural, behavioral, and logistical determinants of fluid intake.

7.5 SUMMARY AND FINDING MIDDLE GROUND ON FLUID GUIDELINES

Further studies of real-life hydration practices during competitive events including information on motives for drinking or not, along with intervention studies that simulate the actual nature of real-life sport, are needed before conclusions can be made about ideal drinking strategies for endurance and ultra-endurance sports (Garth and Burke 2013). In any case, it is likely that a range of drinking strategies may be appropriate and that athletes need to have an individualized and flexible approach to their hydration practices. This approach should also incorporate goals for other nutrition strategies known to enhance fluid palatability and voluntary consumption, thermoregulation, or performance and may dictate a desirable volume and pattern of intake that is independent of thirst. There may be benefits associated with a *paced* approach to drinking during sport, in which the athlete plans to spread their intake of these nutrients as well as a reasonable replacement of their sweat losses across the opportunities that their event provides to consume fluids.

An important step in developing messages about hydration practices in endurance sport is to recognize that a single approach is unlikely to be successful. Rather, it is likely that needs, challenges, and opportunities will vary between athletes within any single event, as well as changing from event to event. Indeed, the range of experiences between and within endurance/ultra-endurance sports is likely to include athletes whose fluid plan needs to increase their habitual/natural intake because sweat rates are likely to greatly exceed opportunities to drink, as well as athletes with the opposite characteristics. We have recently tried to conceptualize a model (Figure 7.1) that explains why a spectrum of approaches needs to coexist. Hopefully, this will help to find middle ground in the current debate about fluid guidelines for competitive sports.



The spectrum of issues that need to be considered in education and event logistics regarding fluid intake during competitive events includes consideration of the balance between supply (fluids) and demand (sweat rates)

FIGURE 7.1 Fluid guidelines for endurance and ultra-endurance sports should recognize that a range of approaches to encouraging or managing drinking behavior is needed. (Adapted from Burke, L.M., *Aspetar Sports Med. J.,* 2, 86–93, 2012.)

REFERENCES

Almond, C.S.D., A.Y. Shin, E.B. Fortescue et al. 2005. Hyponatremia among runners in the Boston marathon. *N. Engl. J. Med.* 352: 1550–6.

American College of Sports Medicine. 1975. Position statement of the American College of Sports Medicine: Prevention of heat injuries during distance running. *Med. Sci. Sports Exerc.* 7: vii–ix.

American College of Sports Medicine. 1987. Position stand on the prevention of thermal injuries during distance running *Med. Sci. Sports Exerc.* 19: 529–33.

American College of Sports Medicine, M.N. Sawka, L.M. Burke et al. 2007. American college of sports medicine position stand. Exercise and fluid replacement. *Med. Sci. Sports Exerc.* 39: 377–90.

Armstrong, L.E., D.J. Casa, H. Emmanuel et al. 2012. Nutritional, physiological, and perceptual responses during a summer ultraendurance cycling event. *J. Strength Cond. Res.* 26: 307–18.

Au-Yeung, K.L., W.C. Wu, W.H. Yau et al. 2010. A study of serum sodium level among hong kong runners. *Clin. J. Sport Med.* 20: 482–7.

Bardis, C.N., S.A. Kavouras, G. Arnaoutis, D.B. Panagiotakos, L. S. Sidossis. 2013. Mild dehydration and cycling performance during 5-kilometer hill climbing. *J. Athl. Train.* 48(6): 741–7.

Beis, L.Y., M. Wright-Whyte, B. Fudge et al. 2012. Drinking behaviors of elite male runners during marathon competition. *Clin. J. Sport Med.* 22: 254–61.

Beltrami, F.G., T. Hew-Butler, T.D. Noakes. 2008. Drinking policies and exercise-associated hyponatraemia: Is anyone still promoting overdrinking? *Br. J. Sports Med.* 42(10): 796–501.

Bracher, A., B. Knechtle, M. Gnädinger et al. 2012. Fluid intake and changes in limb volumes in male ultra-marathoners: Does fluid overload lead to peripheral oedema? *Eur. J. Appl. Physiol.* 112: 991–1003.

Burke, L.M. 2012. Fluid facts and fads. *Aspetar Sports Med J.* 2: 86–93.

Casa, D.J. 2007. *Proper Hydration for Distance Running—Identifying Individual Fluid Needs. A USA Track and Field Advisory 2007*. [online]. Available from: http://www.usatf.org/groups/Coaches/library/2007/hydration/ProperHydrationForDistanceRunning.pdf (Accessed April 1, 2015).

Casa, D.J., R.L. Stearns, R.M. Lopez et al. 2010. Influence of hydration on physiological function and performance during trail running in the heat. *J. Ath. Train.* 45(2): 147–56.

Cheuvront, S.N., R. Carter, M.N. Sawka. 2003. Fluid balance and endurance exercise performance. *Curr. Sports Med. Rep.* 2: 202–8.

Cheuvront, S.N., R.W. Kenefick. 2014. Dehydration: Physiology, assessment, and performance effects. *Compr. Physiol.* 4(1): 257–85.

Cheuvront, S.N., R.W. Kenefick, S.J. Montain, M.N. Sawka. 2010. Mechanisms of aerobic performance impairment with heat stress and dehydration. *J. Appl. Physiol*. 109: 1989–95.

Ebert, T.R., D.T. Martin, B. Stephens et al. 2007. Fluid and food intake during professional men's and women's road-cycling tours. *Int. J. Sports Physiol. Perform*. 2: 58–71.

Fallon, K.E., E. Broad, M.W. Thompson et al. 1998. Nutritional and fluid intake in a 100-km ultramarathon. *Int. J. Sport Nutr*. 8: 24–35.

Garcia-Roves, P.M., N. Terrados, S.F. Fernandez et al. 1998. Macronutrients intake of top level cyclists during continuous competition—change in the feeding pattern. *Int. J. Sports Med*. 19: 61–7.

Garth, A.K., L.M. Burke. 2013. What do athletes drink during competitive sporting activities? *Sports Med.* 43(7): 539–64.

Glace, B.W., C.A. Murphy, M.P. McHugh. 2002. Food intake and electrolyte status of ultramarathoners competing in extreme heat. *J. Am. Coll. Nutr.* 21: 553–9.

Goulet, E.D. 2013. Effect of exercise-induced dehydration on endurance performance: Evaluating the impact of exercise protocols on outcomes using a meta-analytic procedure. *Br. J. Sports Med*. 47: 679–86.

Hew, T.D. 2005. Women hydrate more than men during a marathon race. Hyponatremia in the Houston marathon: A report on 60 cases. *Clin. J. Sport Med.* 15: 148–53.

Hew-Butler., T., J.P. Dugas, T.D. Noakes et al. 2010. Changes in plasma arginine vasopressin concentrations in cyclists participating in a 109-km cycle race. *Br. J. Sports Med.* 44: 594–7.

Kao, W.-F., C.-L. Shyu, X.-W. Yang et al. 2008. Athletic performance and serial weight changes during 12- and 24-hour ultra-marathons. *Clin. J. Sport Med.* 18: 155–8.

Kimber, N.E., J.J. Ross, S.L. Mason et al. 2002. Energy balance during an ironman triathlon in male and female triathletes. *Int. J. Sport Nutr. Exerc. Metab.* 12: 47–62.

Kipps, C., S. Sharma, D.T. Pedoe. 2011. The incidence of exercise-associated hyponatraemia in the London marathon. *Br. J. Sports Med.* 45: 14–19.

Knechtle, B., M. Gnadinger, P. Knechtle et al. 2011a. Prevalence of exercise-associated hyponatremia in male ultraendurance athletes. *Clin. J. Sport Med*. 21: 226–32.

Knechtle, B., P. Knechtle, T. Rosemann et al. 2009. No dehydration in mountain bike ultramarathoners. *Clin. J. Sport Med.* 19: 415–20.

Knechtle, B., P. Knechtle, T. Rosemann. 2011b. Low prevalence of exercise-associated hyponatremia in male 100 km ultra-marathon runners in switzerland. *Eur. J. Appl. Physiol.* 111: 1007–16.

Knechtle, B., O. Senn, R. Imoberdorf et al. 2010. Maintained total body water content and serum sodium concentrations despite body mass loss in female ultra-runners drinking ad libitum during a 100 km race. *Asia Pac. J. Clin. Nutr.* 19: 83–90.

Knechtle, B., O. Senn, R. Imoberdorf et al. 2011c. No fluid overload in male ultra-runners during a 100 km ultra-run. *Res. Sports Med.* 19: 14–27.

Kruseman, M., S. Bucher, M. Bovard et al. 2005. Nutrient intake and performance during a mountain marathon: An observational study. *Eur. J. Appl. Physiol.* 94: 151–7.

Laursen, P.B., R. Suriano, M.J. Quod, et al. 2006. Core temperature and hydration status during an ironman triathlon. *Br. J. Sports Med.* 40: 320–5.

Lebus, D.K., G.A. Casazza, M.D. Hoffman et al. 2010. Can changes in body mass and total body water accurately predict hyponatremia after a 161-km running race? *Clin. J. Sport Med.* 20: 193–9.

Mettler, S., C. Rusch, W.O. Frey et al. 2008. Hyponatremia among runners in the Zurich marathon. *Clin. J. Sport Med.* 18: 344–9.

Montain, S.J., E.F. Coyle. 1992. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J. Appl. Physiol.* 73(4): 1340–50.

Myhre, L.G., G.H. Hartung, D.M. Tucker. 1982. Plasma volume and blood metabolites in middle-aged runners during a warm-weather marathon. *Eur. J. Appl. Physiol.* 48: 227–40.

Noakes, T.D. 2007. Hydration in the marathon: Using thirst to gauge safe fluid replacement. *Sports Med.* 37(4–5): 463–6.

Noakes, T.D. 2010. Is drinking to thirst optimum? *Ann. Nutr. Metab*. 57(Suppl 2): 9–17.

Noakes, T.D. 2012. *Waterlogged: The Serious Problem of Overhydration in Endurance Sports*. Human Kinetics Publishers, Champaign, IL.

Noakes, T.D., K. Sharwood, D. Speedy et al. 2005. Three independent biological mechanisms cause exercise-associated hyponatremia: Evidence from 2,135 weighed competitive athletic performances. *Proc. Natl. Acad. Sci. U. S. A.* 102(51): 18550–5.

Noakes, T.D., D.B. Speedy. 2006. Case proven: Exercise associated hyponatraemia is due to overdrinking. So why did it take 20 years before the original evidence was accepted? *Br. J. Sports Med.* 40(7): 567–72.

O'Toole, M.L., P.S. Douglas, R.H. Laird et al. 1995. Fluid and electrolyte status in athletes receiving medical care at an ultradistance triathlon. *Clin. J. Sport Med.* 5: 116–22.

Pahnke, M.D., J.D.Trinity, J.J. Zachwieja et al. 2010. Serum sodium concentration changes are related to fluid balance and sweat sodium loss. *Med. Sci. Sports Exerc*. 42: 1669–74.

Rehrer, N.J., Brouns, F., E.J. Beckers et al. 1992. Physiological changes and gastro-intestinal symptoms as a result of ultra-endurance running. *Eur. J. Appl. Physiol.* 64: 1–8.

Rogers, G., C. Goodman, C. Rosen. 1997. Water budget during ultra-endurance exercise. *Med. Sci. Sports Exerc.* 29: 1477–81.

Rose, S., E.M. Peters-Futre. 2010. Ad libitum adjustments to fluid intake during cool environmental conditions maintain hydration status during a 3-day mountain bike race. *Br. J. Sports Med.* 44: 430–6.

Ross, M.L., B. Stephens, C.R. Abbiss et al. 2014. Observations of fluid balance, carbohydrate ingestion and body temperature regulation during men's stage-race cycling in temperate environmental conditions. *Int. J. Sports Physiol. Perform*. 9(3): 575–82.

Rust, C.A., B. Knechtle, P. Knechtle et al. 2012. No case of exercise-associated hyponatraemia in top male ultra-endurance cyclists: The "Swiss Cycling Marathon." *Eur. J. Appl. Physiol.* 112: 689–97.

Saunders, A.G., J.P Dugas, R. Tucker, M.I. Lambert, T.D. Noakes. 2005. The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. *Acta Physiol. Scand.* 183(3): 241–55.

Sawka, M.N. 1992. Physiological consequences of hypohydration: Exercise performance and thermoregulation. *Med. Sci. Sports Exerc.* 24: 657–70.

Sawka, M.N., T.D. Noakes. 2007. Does dehydration impair exercise performance? *Med. Sci. Sports Exerc.* 39: 1209–17.

Schenk, K., H. Gatterer, M. Ferrari et al. 2010. Bike transalp: Liquid intake and its effect on the body's fluid homeostasis in the course of a multistage, cross-country, MTB marathon race in the central Alps. *Clin. J. Sport Med.* 20: 47–52.

Schwellnus, M.P., N. Drew, M. Collins. 2011. Increased running speed and previous cramps rather than dehydration or serum sodium changes predict exercise-associated muscle cramping: A prospective cohort study in 210 ironman triathletes. *Br. J. Sports Med.* 45: 650–6.

Sharwood, K., M. Collins, J. Goedecke et al. 2002. Weight changes, sodium levels, and performance in the South African Ironman Triathlon. *Clin. J. Sport Med.* 12: 391–9.

Shirreffs, S.M., M.N. Sawka. 2011. Fluid and electrolyte needs for training, competition, and recovery. *J. Sports Sci*. 29(Suppl 1): S39–46.

Siegel, A.J., J.G.Verbalis, S. Clement et al. 2007. Hyponatremia in marathon runners due to inappropriate arginine vasopressin secretion. *Am. J. Med.* 120(5): 461.e11–17.

Singh, N.R., E.C. Denissen, A.J. McKune et al. 2012. Intestinal temperature, heart rate, and hydration status in multiday trail runners. *Clin. J. Sport Med.* 22(4): 311–18.

Speedy, D.B., R. Campbell, G. Mulligan et al. 1997. Weight changes and serum sodium concentrations after an ultradistance multisport triathlon. *Clin. J. Sport Med.* 7: 100–3.

Speedy, D.B., T.D. Noakes, N.E. Kimber et al. 2001. Fluid balance during and after an ironman triathlon. *Clin. J. Sport Med.* 11: 44–50.

Speedy, D.B., T.D. Noakes, I.R. Rogers et al. 1999. Hyponatremia in ultradistance triathletes. *Med. Sci. Sports Exerc.* 31: 809–15.

Stuempfle, K.J., D.R. Lehmann, H.S. Case et al. 2003. Change in serum sodium concentration during a cold weather ultradistance race. *Clin. J. Sport Med.* 13: 171–5.

Sulzer, N.U., M.P. Schwellnus, T.D. Noakes. 2005. Serum electrolytes in ironman triathletes with exercise-associated muscle cramping. *Med. Sci. Sports Exerc.* 37: 1081–5.

Tam, N., H.W. Nolte, T.D. Noakes. 2011. Changes in total body water content during running races of 21.1 km and 56 km in athletes drinking ad libitum. *Clin. J. Sport Med.* 21: 218–55.

van Rooyen, M., T. Hew-Butler, T. Noakes. 2010. Drinking during marathon running in extreme heat: A video analysis study of the top finishers in the 2004 Athens Olympic marathons. *S. Afr. Med. J.* 22: 55–61.

Wagner, S., B. Knechtle, P. Knechtle et al. 2012. Higher prevalence of exercise-associated hyponatremia in female than in male open-water ultra-endurance swimmers: The "marathon-swim" in lake Zurich. *Eur. J. Appl. Physiol.* 112: 1095–106.

Zouhal, H., C. Groussard, G. Minter et al. 2011. Inverse relationship between percentage body weight change and finishing time in 643 forty-two-kilometer marathon runners. *Br. J. Sports Med.* 45: 1101–5.