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REVIEW ARTICLE

Fluid Balance and Hydration Considerations for Women: Review and Future Directions

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Abstract
Although it is well understood that dehydration can have a major impact on exercise performance and thermoregulatory physiology, the potential for interactions between female sex hormone influences and the impact of dehydration on these variables is poorly understood. Female reproductive hormonal profiles over the course of the menstrual cycle have significant influences on thermoregulatory and volume regulatory physiology. Increased insight into the interactions among dehydration and menstrual cycle hormonal influences may have important implications for safety, nutritional recommendations, as well as optimal mental and physical performance. The purpose of this review is to summarize what is known in this area and highlight the areas that will be important for future work.

Key Points

Dehydration and female sex hormone variation both independently impact facets of everyday health and sport performance.

It is unknown whether female sex hormone variation adds to or exacerbates the effects of dehydration on health and well-being.

Much research is still needed to understand the interaction or relationship between female sex hormone variation and dehydration.

1 Introduction

Hydration has a significant impact on a variety of factors related to health and well-being, including mental and physical capacity [1], mood [2, 3], exercise performance [4, 5], among others. The importance of hydration for various types of physical performance has been the topic of numerous published discussions and some controversy [6–9], highlighting the complexity of making hydration recommendations for a variety of populations.

A significant proportion of the physically active population are women—from athletes at all levels, to military personnel, and occupational workers—highlighting the need to understand the impact of changes in hydration in women for optimization of health, safety, and performance. However, research investigating the impact of hydration status and dehydration stress on human health and performance has largely been conducted in men, leaving sex-specific influences of hydration variation, interventions, and supplementation unclear. In this context, menstrual cycle hormones have specific and quantitative influences on both thermoregulation (notably heat dissipation via cutaneous vasodilation and sweating) [10–13] and volume regulation [14]. Therefore, it will be important for future work to more specifically quantify whether or not the added influences of dehydration have additive, synergistic, or no additional influence when combined with reproductive hormone effects.

The purpose of the present review is to synthesize the existing literature and summarize important areas for future work regarding female reproductive hormones, thermoregulation, exercise performance, and hydration in premenopausal women.

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2 The Changing Hormonal Profile of Females Throughout the Menstrual Cycle is Related to Variation in Body Fluid Regulation

The menstrual cycle is, on average, a 28-day cycle, composed of hormonal peaks and nadirs that have been associated with changes in physiological responses to stress, fluid loading, exercise, sleep, mood, behavior, and many other variables [15–19]. The follicular phase is defined as the period from the onset of menstrual bleeding (menses, usually categorized as day 0 or day 1 of the cycle) to ovulation. The middle of the cycle can be identified by estrogen, luteinizing hormone, and follicle stimulating hormone peaks that occur just prior to ovulation [20]. Ovulation usually occurs around day 14 [21]. The luteal phase is the period from the end of ovulation until menses begins (approximately days 14–28) and is characterized by high concentrations of both estrogen and progesterone in circulation. Both of these hormones have been associated with variation in body fluid regulation and may have independent impacts on hydration and body fluid balance [22, 23]. Menstrual cycle hormone fluctuations have been related to changes in nutritional needs [24], sport performance [16], temperature regulation [25], and others.

Female sex hormones are related to body fluid balance via a number of mechanisms. Estrogen and progesterone appear to influence shifts in transcapillary fluid dynamics, thus affecting the relationship between intra- and extracellular fluid balance [26]. Additionally, variation in sex hormones during the menstrual cycle is linked to shifting set points and thresholds for synthesis, release and activity of volume regulatory hormones, including arginine vasopressin [26, 27]. Figure 1 highlights the relationship between characteristic hormonal profiles within the phases of the menstrual cycle and their interaction with body fluid regulatory hormones.

One of the influences of the menstrual cycle on fluid regulatory dynamics is a buildup of interstitial fluid during the luteal phase [26] and an increase in the possibility of edema. During dehydration and loss of total body water, body fluid compartments adjust to maintain homeostatic osmotic pressure [28]. An influence of sex hormones to favor buildup of interstitial fluid, such as may occur in the luteal phase, could cause a shift in body water compartments, possibly leading to decreased plasma volume and increased osmolality [29]. This could complicate potential conclusions regarding the effects of a given exercise or heat stress intervention on hydration or fluid shifts when women are studied in the luteal phase. Additionally, while plasma osmolality (P_{osm}) is the most valid metric for hydration assessment in a laboratory setting [30], it is not a feasible measure of acute hydration status in a field setting. Urine specific gravity (USG) is often utilized in a field setting and may be affected by behavioral and physiological phenomenon (acute increase in fluid ingestion, increased urine output) which may vary with changes in female sex hormone concentration, as discussed later in this review.

2.1 Menstrual Cycle Phase and Dehydration Could Result in Cumulative Decrements in Exercise Performance

Dehydration (> 2% body mass loss) has been shown to have a negative impact on aerobic exercise performance [31, 32]. Anaerobic performance decrements have also been observed in dehydrated individuals, with body weight-dependent exercise being particularly affected by greater levels of dehydration and body mass loss [5, 33]. Endurance performance is thought to be affected by dehydration via decreased blood volume associated with fluid loss during prolonged exercise

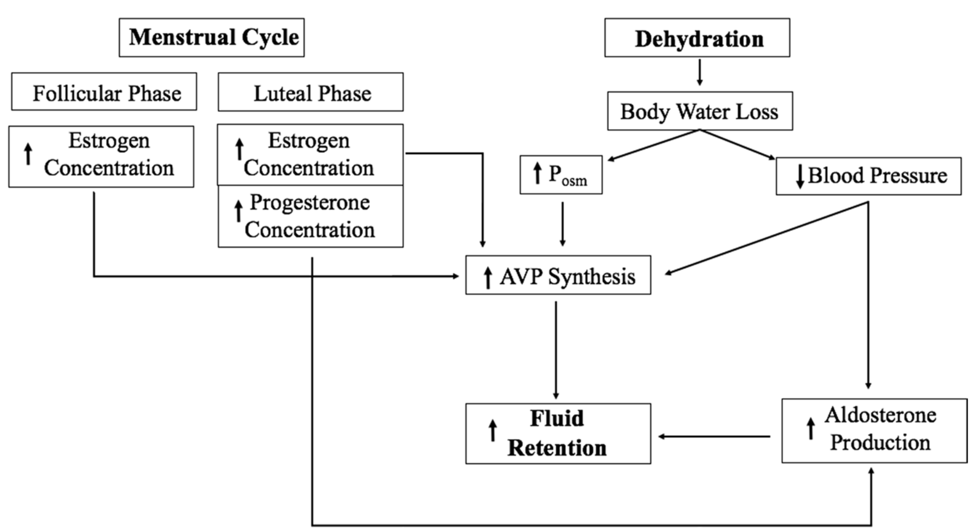

Fig. 1 Relationship between dehydration and female sex hormones associated with fluid retention (P_{osm}: plasma osmolality, AVP: arginine vasopressin). Up arrows signify increases, down arrows signify decreases. Arrows from one variable to another signify relationships between the two

[34]. The decrease in blood volume results in decreased stroke volume and an increase in heart rate for a given cardiac output resulting in increased cardiovascular strain for a given exercise workload which can serve to diminish exercise capacity; particularly when exercise is performed in the heat where more blood volume will be lost due to total body water loss from sweat [35]. Dehydration has a more substantial impact in warm or hot conditions due to the impairment of blood delivery needed to maintain exercise performance (blood flow to the skeletal muscle) and heat dissipation mechanisms (skin blood flow), putting further strain on the cardiovascular system [36, 37]. Since a majority of hydration research has been done in men, [38], further research is necessary to understand the interaction between menstrual cycle phase, contraceptive status, and dehydration.

Menstrual cycle phase has also been associated with variation in exercise performance, but results appear to be dependent on type of exercise and existing reports are conflicting [16, 39, 40]. Previous reviews have examined the impact of menstrual cycle phase on exercise performance [16, 41]; however, none have prospectively assessed performance in varying menstrual cycle phase as a function of hydration status. While interactions between female sex hormones and fluid regulatory mechanisms exist, the impact of that interaction has yet to be investigated with respect to exercise performance.

Mechanisms may be related to changes in fluid volume regulation over the course of the menstrual cycle [41], which is possibly responsible for the observed decrement in absolute and relative oxygen consumption during maximal exercise in the luteal phase [41, 42]. In this context, the specific influences of menstrual cycle hormones on the relationships between dehydration and exercise performance have not been investigated. Further research is needed to determine the impact of dehydration over the course of the menstrual cycle in terms of exercise, thermoregulation, and other performance variables. The relationship and interaction between hydration and menstrual cycle variation are unknown but any negative impacts of hormonal variation may compound the decrements in females who are dehydrated.

2.2 Hydration and the Menstrual Cycle have Independent Impacts on Internal Body Temperature

Internal body temperature during exercise in the heat is affected by hydration status prior to, and during exercise. Body temperature has been shown to increase (~ 0.22 °C) for every 1% loss in body mass during exercise in the heat [43–45]. The increase in internal body temperature associated with dehydration has led to the consideration of dehydration as a risk factor for developing exertional heat illnesses (e.g., heat exhaustion, exertional heat stroke) by organizational governing bodies [46–48]. The increased risk is based on the mechanisms of increased heat storage (decreased heat dissipation) when dehydrated due to increased competition for blood flow during exercise that limits heat dissipation via decreased sweat rate and skin blood flow [49]. Several previous studies, in a predominantly male population, have observed increases in internal body temperature in dehydrated participants when performing exercise in the heat, showing an exaggerated hyperthermic response with dehydration [50–53].

A characteristic of the luteal phase of the menstrual cycle is a “set-point” shift of internal body temperature resulting in a 0.3–0.5 °C increase in resting and exercise body temperature in the luteal phase, known as a “set-point” shift [13, 54]. Because of this shift, it is possible that women in the luteal phase are at higher risk for heat illness, particularly if the luteal phase is paired with a situation leading to dehydration [55]. This has led to the assertion that females may be at an increased risk for developing exertional heat illnesses over their male counterparts, but there is no direct physiological evidence to support this idea [56, 57]. While recent epidemiological observations suggest that there is no basis for increased risk [56], further investigation is needed to determine the full impact of the menstrual cycle and sex differences with respect to exertional heat stroke risk. Evidence suggesting differences in heat dissipation mechanisms between menstrual cycle phases suggests that the threshold for the onset of dissipation mechanisms is similarly affected by the set-point shift as resting internal body temperature [58–62].

Given the known effect of dehydration and menstrual cycle phase on internal body temperature, it is possible that these factors may compound one another, but any interaction of these factors has not yet been investigated.

2.3 Naturally Cycling Females and Oral Contraceptive Users may have Different Responses to Varying Hydration States

Oral contraceptive (OC) users made up 25.3% of those using contraception in 2014 in the United States [63]. While there are many contraceptive options available to women, the most common contraceptive method in human subjects research is OCs. Researching OCs is highly applicable given the large proportion of females that utilize this method; however, with the varying types and hormonal environment that oral contraceptives provide, it is difficult to control for type and concentration of circulating hormones. OCs increase the concentration of hormones in the body over the values ordinarily found in naturally cycling females [64]. This may alter the responses of women on oral contraceptives compared to naturally cycling females to a variety of different stressors.

The primary finding of oral contraceptives' impact on hydration is a lower osmotic threshold for Arginine vasopressin (AVP) and thirst stimulation. This means that less dehydration is required to elicit fluid retention responses at the level of the kidney and increased fluid consumption via increased thirst in resting females [65]. Variable results in oral contraceptive use have been theorized to be a result of the estradiol content in different OC preparations [66].

Combination (estradiol and progesterone) oral contraceptives in single concentration, or "monophasic," are the most commonly studied in terms of thermoregulation and hydration, combination. These affect thermoregulatory variables, including increased resting internal body temperature [67] and alterations in skin blood flow at rest [25, 60, 68] and during exercise [69]. Influences of other types of hormonal supplementation for contraception (e.g., transdermal patch, intrauterine device, implantable bar) have not yet been investigated.

3 Thirst and Hormonal Control of Fluid Regulation vary with Hormonal Changes

AVP release and thirst are stimulated by an increase in blood osmolality [70]. AVP release has been shown to be increased within the high estrogen phase of the menstrual cycle [14], and estrogen has been observed to have a significant relationship with copeptin, a stable precursor to AVP [71], suggesting interaction between endogenous menstrual cycle hormones and mechanisms of fluid balance. Additionally, previous investigations have observed inhibition of AVP with progesterone increases, suggesting that women in the luteal phase of the menstrual cycle may be more prone to dehydration as less fluid is being retained via AVP downstream mechanisms [72, 73]. However, the luteal phase also appears to be associated with increased sensitivity to dehydration where AVP secretion and thirst sensation have been observed to occur at a lower P_{osm} thresholds than in the follicular phase [74] and increased sodium retention via increased activity of the renin–angiotensin–aldosterone system [14, 75]. The luteal phase of the menstrual cycle is also associated with increased aldosterone; this relationship is thought to be caused by the increase in progesterone during the luteal phase which independently augments aldosterone production [75]. Thirst onset has also been observed to occur at a lower P_{osm} in the luteal phase compared to the follicular phase with hypertonic infusion, which may be related to inhibition of AVP [74, 76].

While there are several investigations linking AVP concentration, thirst, and osmoregulation with female sex hormones, it remains unclear how estrogen and progesterone may interact in their influences on AVP release, as compared to their influences measured separately [77]. Figure 2 shows the variation in hormone concentration across three prominent menstrual cycle phases and the relationship of the distinct hormonal profiles with fluid regulatory mechanisms.

4 Psychological Variables may be Impacted by Hydration and Menstrual Cycle Phase

Dehydration is often used as a stress intervention and can be established via heat, exercise stress, fluid restriction, diuretic or some combination of these. Decrements in cognitive performance have been observed with as little as mild dehydration (> 1% body mass loss) [3, 5]. The impact of dehydration on psychological and cognitive variables has been investigated and the results of individual investigations into reaction time [78], short-term memory [79], and psychomotor performance [80] yield different results than those of a recent meta-analysis [81]. While it is not clear that dehydration impacts cognitive variables, mild dehydration appears to impact mood [82] in men and women [2, 3]. However, the interaction between influences of menstrual cycle phase and dehydration on mood and psychological variables has not yet been investigated. This interaction may be important as females may experience a greater mood disturbance with mild dehydration in one phase of the menstrual cycle over another, which may independently impact cognitive impairments.

There is a well-documented effect of estrogen in facilitating actions of serotonin, likely affecting mood, cognition, and additional psychological variables in women [83]. While estrogen peaks during the follicular phase, significant mood disturbance has been demonstrated in the late luteal phase when estrogen and progesterone are both low [84]. Influences of variations in female sex hormones across the lifespan on mood, risk of depression and use of antidepressants have been reported [85]. Given the observed independent impacts of dehydration and sex hormones, it is important to understand if an interaction is present that may compound effects and impairments on psychological and cognitive factors. Mood appears to be the only cognitive, psychological, or emotional factor significantly affected by changes in female sex hormone concentration, but further research is warranted to determine the responses of females to dehydration interventions in different cycle phases.

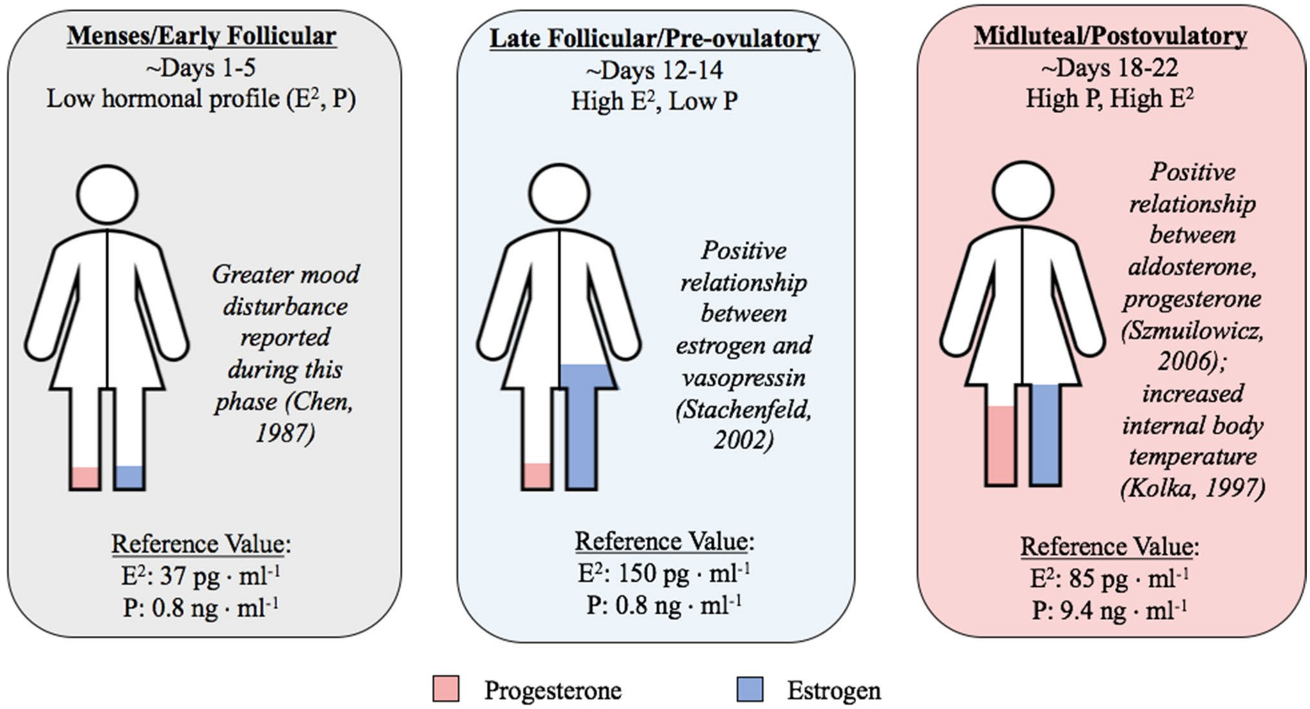

Fig. 2 Variation in circulating female sex hormones (E_2: estrogen, P: progesterone) and physiological variation specific to hydration during the early follicular phase, late follicular, and mid luteal phases. Reference ranges adapted from Stachenfeld [64]

5 Hydration Status and Menstrual Cycle Phase may Impact the Effectiveness of Hyperhydrating Agents in Women

The potential performance-enhancing effects of hyperhydration have primarily been investigated in men—with very little research investigating female-specific responses. Understanding the specific response of females to supplementation is important, particularly as the use of supplementation for athletes is increasingly popular [26]. However, very few investigations assess the effect of supplement use in a female athletic population. Given the known impact of sex hormones on functionality and utilization during exercise, understanding how females respond to supplementation is important for ensuring appropriate supplementation recommendations for safety and performance.

Hyperhydrating agents are supplements that can prompt water retention and an increase in plasma volume, reducing the risk of becoming dehydrated during a short period of exercise [86]. Two common hyperhydrating agents utilized in the athlete population are sodium and glycerol. Sodium supplementation is widely used within the athletic population to prevent the development of hyponatremia and ensure appropriate levels of electrolyte concentrations when performing exercise, primarily in a warm environment [87, 88]. Sims et al. [89] assessed female sex hormone effects on plasma volume and electrolyte loading, and showed that the luteal phase observed greater increases in exercise capacity and decrease in cardiovascular strain with sodium loading possibly due to the increased sensitivity of the body to increased P_{osm} [74]. As previously discussed, the luteal phase of the menstrual cycle is associated with an internal temperature "set-point" shift [54], as well as "set-point" shifts for thresholds associated with increases in P_{osm} [74] increasing the likelihood that the luteal phase of the menstrual cycle may allow for greater enhancement in performance with sodium supplementation than the follicular phase.

Glycerol has been extensively investigated as a hyperhydrating agent due to the osmotic qualities that allow for the enhanced retention of fluid [90]. Glycerol has been observed to have performance enhancing effects, particularly when exercising in hot, humid environments [90, 91]. Using glycerol as a supplement for hyperhydration has been investigated including female subjects, but we are unaware of reports of the female sex hormone impact on the efficacy of glycerol [92, 93]. Female sex hormones could theoretically impact the efficacy of glycerol and reduce the effectiveness of the substance as a hyperhydrating agent due to their impact on transcapillary fluid dynamics in the luteal phase [26]. Given the increased osmolality of glycerol, and the increased sensitivity to changes in P_{osm} during the luteal phase, glycerol ingestion may have different effects depending on when it is ingested during the menstrual cycle.

Future research should seek to understand how females may respond to glycerol supplementation as a function of reproductive hormone status.

While sodium-induced hyperhydration appears to be more effective than glycerol hyperhydration [94], when used in conjunction with one another, greater levels of hyperhydration are achieved [95], none of which has been investigated in a female population. Based on the utilization of these supplements to enhance performance, understanding how women may respond differently from men is warranted and important.

6 Hyponatremia Risk and Fluid Needs in Women Across the Menstrual Cycle

Hyponatremia is a rare disorder that arises from dilution of body electrolytes, particularly sodium. It can be fatal if not treated appropriately. People can become hyponatremic due to over-consumption of fluids during prolonged exercise [87], and the risk is greatest in long duration races where time to consume fluid ad libitum may be increased [96]. There has been significant debate on the effectiveness of drinking to thirst (DTT) or utilizing prescribed drinking plans for individuals who are performing exercise particularly in a hot environment [97–100]. A recent meta-analysis observed no difference in performance based on drinking strategy [101]; however, it is important to note that drinking strategy may be subject to interindividual variation. Women were previously thought to be at an increased risk for developing hyponatremia during prolonged physical activity largely based on anthropometric differences [102]. This evidence is up for debate as differences have not been observed when anthropometric variables, fitness status, and exercise duration are controlled [103, 104]; however, more research is still needed in this area. While the most effective method for fluid replacement continues to be debated, determining the impact of the menstrual cycle on maintaining appropriate hydration for an individual's needs is an important consideration.

Fluid needs and optimal hydration plans for females may change depending on the timing of activities in relation to the menstrual cycle. To our knowledge, no investigations have assessed hydration variance across all phases of the menstrual cycle or in varying contraceptive states. A previous investigation seeking to provide normative data for hydration biomarkers in females did so in the placebo pill phase of oral contraceptive use [105], which does not account for variation in female sex hormone concentration either in naturally cycling menstrual phases or with OC use. As previously discussed in this review, circulating estrogen and progesterone may alter the fluid needs over the course of the menstrual cycle or with OCs.

With variation in thirst across the menstrual cycle [74], during prolonged races, hyponatremia may be a risk in one phase over another if athletes are not accounting for variation in fluid losses associated with changes in the menstrual cycle; however, the details of these requirements are currently unclear. Future research should seek to determine if variation exists in hyponatremia risk depending on contraceptive and menstrual status during day-to-day life and physical activity.

7 Conclusion

Existing evidence supports the idea that female reproductive hormone variation across the menstrual cycle has significant influences on thirst and volume regulation in humans, likely impacting hydration status, physiological responses to dehydration, exercise performance, and fluid needs. Independent of reproductive hormone status, hydration status itself can impact exercise performance, risk of heat-related illnesses, mood, and exercise recovery. However, the combined influences of these physiological states (hydration and reproductive hormone status) are not well understood at this time. Investigations assessing factors associated with hydration status variation have largely been completed in men, and subsequent population-wide recommendations made from that body of literature. Increasing information points to the importance of maintaining appropriate hydration for physical and mental health and performance, from endurance exercise to activities of daily living. In this context, it is important to continue to work for understanding potential interactions of reproductive hormone status and hydration/volume regulation, to allow for more comprehensive development of policies and procedures for women athletes and non-athletes alike.

Compliance with Ethical Standards

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