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Water- the forgotten nutrient: revisiting its role in health and disease

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Water- the forgotten nutrient: revisiting its role in health and disease

El agua, el nutriente olvidado: revisión de su papel en la salud y la enfermedad

Água, o nutriente esquecido: análise de seu papel na saúde e na doença

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ABSTRACT

INTRODUCTION: Water intake has arguably been one of the least-studied topics in nutrition science and is often described as the 'forgotten nutrient'. Despite its importance, it has been largely overlooked in dietary guidance. **DEVELOPMENT:** A Recommended Dietary Allowance for water has yet to be established. Adequate Intake guidelines of 3.7 and 2.7 L of water per day have been suggested for sedentary adult men and women (> 18 y), respectively. Even though these values are based on population consumption data, they are also supported by recent scientific evidence. Body fluid balance is regulated by fluid balance homeostatic mechanisms. Arginine vasopressin (AVP; also known as anti-diuretic hormone) is regulated by osmoreceptors and baroreceptors and among many functions, it mainly reduces urinary output. It has been suggested that thirst might be an adequate signal for water intake when the body is in a deficit. However, inadequate water intake and underhydration can occur in the absence of thirst. There are many deleterious health effects related to elevated AVP and underhydration. Low water intake and elevated AVP significantly and negatively impact cardiovascular health, mood, kidney function, glucose regulation, chronic disease development, accelerated aging, and increased mortality. Water intake is particularly important during physical activity, especially in warm environments. Replacing fluids lost through sweating is essential for maintaining fluid and electrolyte balance during thermoregulation. **CONCLUSION:** Increasing water consumption through palatable non-sugar-sweetened beverages represents a simple, cost-effective strategy with the potential to produce sustained improvements in population health.

KEYWORDS: drinking, thirst, essential nutrients, health.

RESUMEN

INTRODUCCIÓN: Se ha demostrado que la ingestión de agua ha sido uno de los temas menos estudiados en la ciencia de la nutrición, y con frecuencia se la describe como el "nutriente olvidado". A pesar de su importancia, en general ha sido pasada por alto en la orientación dietética. **DESARROLLO:** Todavía no se ha establecido una cantidad dietética recomendada

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(CDR) para el agua. Se han sugerido los parámetros de Ingesta Adecuada (IA) de 3.7 y 2.7 L de agua por día para hombres y mujeres adultos sedentarios (> 18 años), respectivamente. Si bien esos valores se basan en datos de consumo de la población, también son respaldados por evidencias científicas recientes. El equilibrio de fluidos corporales es regulado por mecanismos homeostáticos de equilibrio de fluidos. La vasopresina arginina (AVP, conocida también como hormona antidiurética) es regulada por osmorreceptores y barorreceptores y, entre muchas funciones, reduce principalmente la producción de orina. Se ha sugerido que la sed podría ser una señal adecuada para la ingestión de agua cuando el cuerpo está en déficit. Sin embargo, la ingestión insuficiente de agua y la subhidratación pueden darse en ausencia de sed. Hay muchos efectos deletéreos para la salud relacionados con la AVP elevada y la subhidratación. La baja ingestión de agua y la AVP elevada causan impactos significativos y negativos en la salud cardiovascular, el estado de ánimo, la función renal, la regulación de la glucosa, el desarrollo de enfermedades crónicas, el envejecimiento acelerado y el incremento en la mortalidad. La ingestión de agua es particularmente importante durante la actividad física, especialmente en ambientes cálidos. El reemplazo de los fluidos perdidos al sudar es esencial para mantener el equilibrio de ellos y de los electrolitos durante la termorregulación. **CONCLUSIÓN:** Aumentar el consumo de agua mediante bebidas sabrosas no azucaradas constituye una estrategia sencilla y económica con el potencial de producir mejoras sostenidas en la salud de la población.

PALABRAS CLAVE: beber, sed, nutrientes esenciales, salud.

RESUMO

INTRODUÇÃO: A ingestão de água tem se mostrado um dos tópicos menos estudados na ciência da nutrição, sendo frequentemente descrita como o "nutriente esquecido". Apesar de sua importância, geralmente é negligenciada nas orientações dietéticas. **DESENVOLVIMENTO:** A ingestão diária recomendada (IDR) de água ainda não foi estabelecida. Os parâmetros de Ingestão Adequada (IA) de 3,7 e 2,7 L de água por dia foram sugeridos para homens e mulheres adultos sedentários (> 18 anos), respectivamente. Embora esses valores sejam baseados em dados de consumo da população, eles também são corroborados por evidências científicas recentes. O equilíbrio dos fluidos corporais é regulado por mecanismos homeostáticos de equilíbrio de fluidos. A arginina vasopressina (AVP, também conhecida como hormônio antidiurético) é regulada por osmorreceptores e barorreceptores e, entre muitas funções, reduz principalmente a produção de urina. Foi sugerido que a sede pode ser um sinal apropriado para a ingestão de água quando o corpo está com déficit hídrico. No entanto, a ingestão insuficiente de água e a desidratação podem ocorrer mesmo na ausência de sede. Existem muitos efeitos nocivos à saúde associados a níveis elevados de AVP e à desidratação. A baixa ingestão de água e o nível elevado da AVP causam impactos significativos e negativos na saúde cardiovascular, no humor, na função renal, na regulação da glicose, no desenvolvimento de doenças crônicas, no envelhecimento acelerado e no aumento da mortalidade. A ingestão de água é particularmente importante durante a atividade física, especialmente em ambientes quentes. A reposição dos fluidos perdidos na transpiração é essencial para manter o equilíbrio hidroeletrolítico durante a termorregulação. **CONCLUSÃO:** Aumentar o consumo de água por meio de bebidas saborosas e sem açúcar é uma estratégia simples e barata com potencial para produzir melhorias sustentáveis na saúde da população.

PALAVRAS-CHAVE: beber, sede, nutrientes essenciais, saúde.

1. Introduction

It is well documented that water intake has arguably been one of the least studied topics in Nutrition science. In 2003, a series of four papers was published in the Journal of Nutrition that summarized the history of human nutrition and the evolution of our knowledge from 1785 to 1985 (Carpenter, 2003a, 2003b, 2003c, 2003d). Despite coverage of a wide range of nutrients and health outcomes related to nutritional deficiencies, water was scarcely mentioned in this historical account. Water is never mentioned as a nutrient itself, never mind its relation to health and wellness. Instead, the term water typically occurs in other contexts, such as to describe other nutrients (e.g., water-soluble) or as part of the name of one of the founders of Nutrition, Atwater. A nutrient can be defined as, "a component of food useful to an organism for its growth, or functioning (Jew et al., 2015, p.204)". Water plays an essential role in practically all functions of the body and is especially key in thermoregulation (EFSA Panel on Dietetic Products, Nutrition and Allergies, 2010).

Guidance on "water" has likewise been absent across iterations of dietary guidance in the United States. The United States Department of Agriculture (USDA) has provided various forms of dietary guidance since 1894 (Jahns et al., 2018). Consumer-friendly models have been developed to provide nutritional guidance based on food groups (Jahns et al., 2018). Interestingly, countries other than the United States, consumer-friendly models (food pyramids) include water at the base of their pyramids (e.g., France, Indonesia, China). Food group based rather than nutrient-based recommendations are believed to be more practical and easier for consumers to implement. Ultimately, a diet comprising recommended servings of food groups should enable an individual to meet nutrient guidelines, thereby reducing their risk of chronic disease (Jahns et al., 2018).

Variations of the food group models have been introduced over time as nutritional science evolves. Table 1 exemplifies the evolution of the water-related guidance by the USDA dietary guidelines. It illustrates that water has historically been absent from U.S. dietary guidance. More recent guidelines have shifted toward general recognition of hydration but still lack explicit quantitative or structural inclusion. In 1947, USDA introduced "The Basic 7", a wheel diagram evenly divided among seven food groups (i.e., green and yellow vegetables; oranges, tomatoes, and grapefruit; potatoes and other vegetables and fruits; milk and milk products; meat, poultry, fish, or eggs; bread, flour, and cereal; and butter and fortified margarine). "The Basic 4" was introduced in 1956, which simplified "The Basic 7" to four food groups (i.e., milk, meat, vegetables and fruits, and bread and cereal) (Jahns et al., 2018).

Following the establishment of the Dietary Guidelines for Americans in 1980 (Jahns et al., 2018), the Food Pyramid was published in 1992, depicting six food groups (i.e., fats, oils, and sweets; milk, yogurt, and cheese; meat, poultry, fish, dry beans, eggs, and nuts; vegetables; fruits;

and bread, cereal, rice, and pasta) (United States Department of Agriculture, 1992). The recommended number of servings from the top to the bottom of the pyramid increased with each level of food groups. The food groups were condensed once again in 2005 to five groups (i.e., grains, vegetables, fruits, milk, and meat and beans) in the MyPyramid model, where serving sizes were not visually represented. MyPlate was introduced in 2011 (Chang, 2017). MyPlate visually presents four food groups equally within a plate (i.e., fruits, grains, vegetables, and proteins) and a fifth food group in a cup (i.e., dairy) (Chang, 2017). However, for one more time, water was not included. The recent *Dietary Guidelines for Americans*, 2025–2030, emphasize “Eat real food” and visually depict this message using an inverted pyramid. In the graphic, with protein foods, whole dairy, fats, vegetable and fruits are positioned at the top, with whole grains at the base. Although the Guidelines state that “hydration matters”, water is not explicitly represented within the inverted pyramid visual. Instead, hydration guidance is limited to the recommendation to “choose water or unsweetened beverages to accompany meals and snacks”, resulting in no visual emphasis on water’s role in overall dietary patterns (United States Department of Agriculture, 2026). Unfortunately, water is largely positioned as a non-caloric substitute for sugar-sweetened beverages, thereby emphasizing its role in caloric displacement rather than its essential physiological function on well-being and longevity.

While food group models have been updated to account for the latest nutritional evidence, water has never been included. For example, there is no mention of water or its related health benefits throughout the *2015–2020 Dietary Guidelines for Americans,* aside from a suggestion to reduce added sugar intake by replacing sugary drinks with water (United States Department of Health and Human Services & Department of Agriculture, 2015). Only one relevant sub-section was added as a “special consideration” to the *2020 – 2025 Dietary Guidelines for Americans,* which describes the importance of water consumption and hydration in older adults United States Department of Agriculture & United States Department of Health and Human Services, 2020). As stated earlier, food group models are advertised as a way for individuals to meet their nutritional needs (Jahns et al., 2018). However, when water-specific recommendations are repeatedly excluded from dietary guidance over the past 100 years, individuals may be overlooking a critical component of their nutritional needs. Individuals only consume ~20% of their daily water from foods, with the remaining ~80% coming from beverages (Vieux et al., 2020). Fruit juice and milk may contribute to overall water intake, but they are nutrient-dense beverages (Chang, 2017).

Table 1.
Evolution of the water-related guidance by the USDA dietary guidelines.

YEAR	GUIDELINE	WATER RECOMMENDATION	REFERENCE
1947	Basic 7	No specific recommendation	(Jahns et al., 2018)
1956	Basic 4	No specific recommendation	(Jahns et al., 2018)
1980	Dietary Guidelines for Americans (first Edition)	No specific recommendation	(Jahns et al., 2018)
1992	Food Guide Pyramid (6 groups)	No specific recommendation	(United States Department of Agriculture, 1992)
2005	MyPyramid	No specific recommendation	(Jahns et al., 2018)
2011	MyPlate	No specific recommendation	(Chang, 2017)
2015-2020	Dietary Guidelines for Americans	Recommends replacing sugary drinks with water	(United States Department of Agriculture, 2015)
2020-2025	Dietary Guidelines for Americans	Mentions hydration as a special consideration particularly in older adults	United States Department of Agriculture, 2020)
2025-2030	Inverted Pyramid	States that hydration matters yet water is not explicitly represented	(United States Department of Agriculture, 2026)

Source: the authors

Additional dietary recommendations have been established by the National Academy of Medicine. Recommended Dietary Allowances (RDAs) are guidelines for a given nutrient that correspond to a reduced risk of chronic disease (National Research Council, 1989). Alternatively, Adequate Intake (AI) guidelines are provided for nutrients for which there is inadequate evidence connecting intake levels with disease risk (National Research Council, 1989). International AI values for sedentary adults are listed in Table 2. Adequate Intakes for children ≤ 18 y are classified by age and sex: 1 – 3 y, 1.3 $L{\cdot}d^{-1}$ (both sexes); 4 – 8 y, 1.7 $L{\cdot}d^{-1}$ (both sexes); 9 – 13 y, 2.4 $L{\cdot}d^{-1}$ (boys) and 2.1 $L{\cdot}d^{-1}$ (girls); 14 – 18 y, 3.3 $L{\cdot}d^{-1}$ (boys) and 2.3 $L{\cdot}d^{-1}$ (girls) (National Academy of Medicine, 2005). An important note is that these recommendations represent total water intake (TWI), which encompasses all water consumed from beverages (including plain water) and all foods (National Academy of Medicine, 2005). The dietary guidelines should refer to water as a nutrient, rather than just plain water (tap or bottled), to acknowledge that water can be obtained from sources other than plain water.

Table 2.
*Adequate Intake (AI) values for sedentary adults from international organizations. Values include fluids from foods except China. *In Latin America, AI values for water are not specified in dietary guidelines.*

ORGANIZATION	MEN (L/DAY)	WOMEN (L/DAY)	REFERENCE
US NAM	3.7	2.7	(National Academy of Medicine, 2005)
WHO	None specifically listed	None specifically listed	(World Health Organization, 2003)
EFSA	2.5	2.0	(EFSA Panel on Dietetic Products, 2010)
NHMRC	3.4	2.8	(National Health and Medical Research Council; Australian Government Department of Health and Ageing; New Zealand Ministry of Health, 2006)
CHINA	1.7	1.5	(Zhang et al., 2019)

Note. Abbreviations: US, United States; NAM, National Academy of Medicine; WHO, World Health Organization; EFSA, European Food Safety Authority; NHMRC, National Health and Medical Research Council. Source: the authors

It is not surprising that an RDA has yet to be established for water, given the lack of adequate funding for water research and, consequently, the lack of deliberation on the scientific merits of water in preventing chronic disease. The lack of health awareness for water (as a nutrient) is especially concerning, considering TWI trends among Americans. Recent evidence suggests that 55% of US children (6 – 19 y) are not adequately hydrated based on urine biomarkers (urine osmolality > 800 mmol·kg^{-1}) (Kenney et al., 2015). Moreover, 22% do not drink any plain water, while 72% consume some amount of sugar-sweetened beverages (Kenney et al., 2015). Among adults aged 18 y or older, ~60% failed to meet the AI recommendation for TWI (Drewnowski et al., 2013). Among older adults (≥ 71 y), 95% and 83% of men and women, respectively, failed to meet the AI recommendations (Drewnowski et al., 2013). Under-hydration, as we will highlight, can increase the risk of chronic disease.

Drinking Behavior

Drinking behavior is influenced by a combination of internal and external factors. Many internal factors influence an individual's decision to drink, including motivation and anticipation. External factors include palatability, availability, and water security (Rolls & Rolls, 1982; Young et al., 2021). Drinking is a motivated behavior, and individuals can alter their consumption patterns in response to competing physiological and survival needs (Leib et al., 2016). For example, *Homo erectus* relied on persistent hunting, which involved forcing prey into exhaustion through prolonged pursuit in the heat (Hora et al., 2020). In this situation, the survival need for food outweighed the survival need for water (Hora et al., 2020). Accordingly, *Homo erectus* is estimated to have been able to withstand dehydration up to ~10% body mass loss and hunt without drinking for about 5.5–5.7 hours (Hora et al., 2020). Sex differences may influence the decision to drink more water daily. These differences may be related to elevated thirst and vasopressin in women (Suh et al., 2021). Drinking is also an anticipatory event in relation to eating, as individuals can learn to attribute water needs to specific foods (Rolls & Rolls, 1982). For example, consumption of salty foods may prompt an individual to drink at the same time due to past experiences in which those foods induced a fluid deficit. Additionally, drinking is influenced by palatability (e.g., flavor, sweetness, temperature), as individuals are less likely to consume something that is not desirable to them (Rolls & Rolls, 1982). For plain water specifically, some municipal water treatment methods, such as chlorine disinfection, can negatively affect taste and make tap water undesirable (Zoellner et al., 2012). Flavor appears to be more influential on beverage choice than cost, as some individuals have reported that they would choose a cheaper beverage only if its taste was comparable to that of the more expensive beverage (Zoellner et al., 2012). Other individuals classified their preference for the taste of sugar-sweetened beverages over plain water as an addiction (Rezaei et al., 2025). Individuals may drink less or nothing when their preferred beverages are not readily available. Finally, water security can greatly impact drinking, which refers to the physical availability, accessibility, usability (potability and safety), and stability of water sources (Young et al., 2021).

In addition to external influences, drinking is regulated by homeostatic mechanisms of fluid balance. Although thirst contributes to the regulation of fluid intake, evidence suggests that it does not fully compensate for body water deficits (Greenleaf, 1992). Both osmoreceptors and baroreceptors activate thirst, which drives individuals to drink (Robertson, 2013). Osmoreceptors detect changes in cellular volume induced by the osmotic gradient of the extracellular fluid, whereas baroreceptors sense mechanical stretch of the vascular walls as a proxy for arterial blood pressure (Robertson, 2013). Those receptors also affect the hormones that regulate water balance (Robertson, 2013). Both receptors primarily stimulate arginine vasopressin (AVP; also known as antidiuretic hormone), which reduces urinary output (greater concentration, smaller volume) by increasing water reabsorption in the kidney (Robertson, 2013). Accordingly, the amount of water released from the body is reduced, and, in response, water is conserved within the body, delaying the onset of dehydration. Copeptin is often used as a surrogate marker of AVP because it is a precursor of AVP, produced at a 1:1 ratio, and is more stable and therefore easier to measure than AVP (Heida et al., 2017). Baroreceptors also stimulate the release of the vasoconstrictor hormone angiotensin II (Le et al., 2013). Angiotensin II stimulates aldosterone, which decreases urinary sodium excretion and promotes water reabsorption in the kidney (Le et al., 2013).

Arginine Vasopressin, Underhydration, and Renal Function

Plasma osmolality typically ranges between 275 and 295 mmol·kg^{-1} (Najem et al., 2022). There is a positive linear relationship between plasma osmolality and stimulating AVP release and thirst activation (Robertson, 1984). Elevated plasma osmolality results from insufficient water consumption, triggering each (AVP release and thirst activation) at different plasma osmolality thresholds (Figure 1).

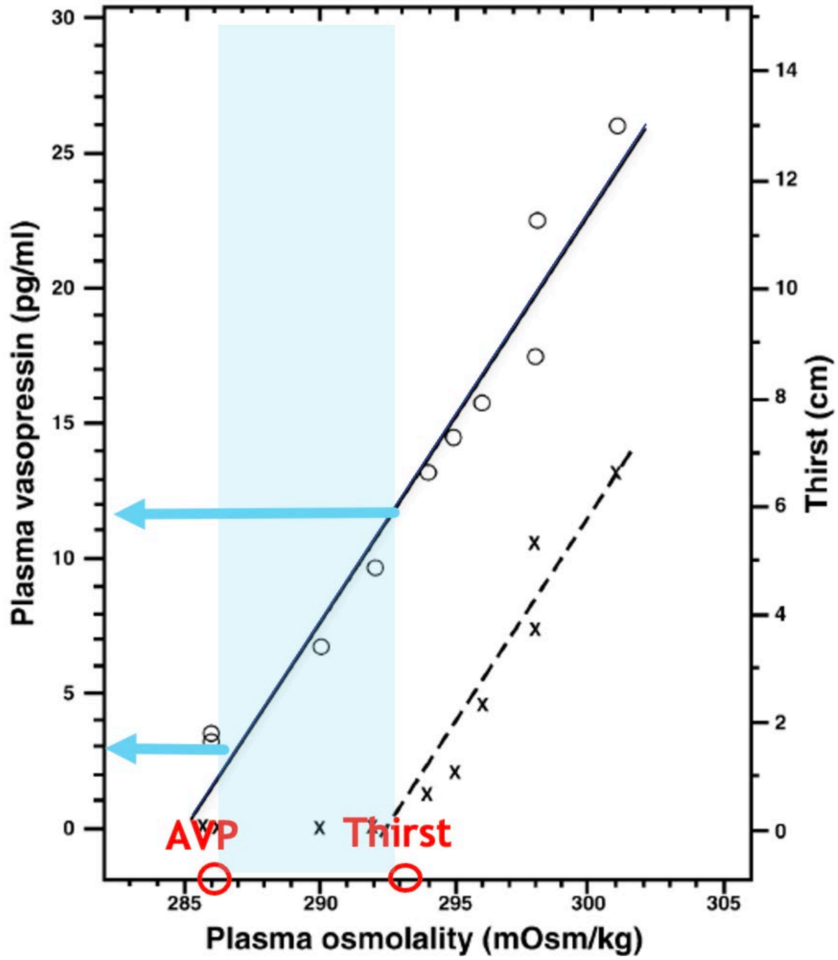


Figure 1. The relationships among plasma osmolality, plasma vasopressin, and thirst. Modified from reference (Robertson, 1984). The blue-shaded area represents the difference between the osmotic threshold of AVP and thirst. The blue arrows indicate the range of AVP within normal physiological levels for plasma osmolality, in the absence of thirst. In this state, the fluid homeostatic mechanism is activated but not thirst. Thirst intensity was estimated by means of a geometric rating scale. © 1984 by the International Society of Nephrology.

AVP is stimulated around ≥ 280 mmol·kg$^{-1,}$ while thirst is not activated until slightly higher osmolality, around ≥ 291 mmol·kg^{-1} (Robertson, 1984). This lag in the onset of thirst describes the in-between "under-hydration" – i.e., between appropriate hydration and dehydration. While thirst is an important signal for water consumption, it appears to be more of a survival instinct rather than a sufficient homeostatic mechanism for fluid balance (Kavouras, 2013). Differences in plasma osmolality thresholds for AVP and thirst distinguish dehydration from underhydration. Clinical dehydration (plasma osmolality > 295 mmol·kg^{-1}) represents a water deficit induced by fluid losses and/or low TWI, accompanied by thirst activation and fluid balance homeostatic mechanisms for water conservation (e.g., AVP) (Kavouras, 2019). Underhydration (slight elevated plasma osmolality but below 295 mmol·kg^{-1}) represents low TWI and activation of fluid balance homeostatic mechanisms in the absence of thirst or water deficit (Kavouras, 2019). Without thirst, individuals are less inclined to drink water despite elevated circulating AVP levels. Specifically, significantly elevated AVP and cortisol have been observed in individuals with low (≤ 1.2 L·d^{-1}) compared to high (2 – 4 L·d^{-1}) habitual TWI (Perrier et al., 2013).

Recent evidence suggests that numerous deleterious health effects are associated with elevated AVP and underhydration. Specifically, endothelial function, a measure of cardiovascular health, was reduced by 26.8% by exercise-induced dehydration (-2% body mass) (Arnaoutis et al., 2017). Endothelial dysfunction can increase an individual's risk for cardiovascular disease, atherosclerosis, and hypertension. Cellular dehydration induced by hypertonic saline infusion (3% NaCl) has also been observed to negatively impact mood, particularly in women (Suh et al., 2021). Mood disturbance was accompanied by elevated plasma osmolality, copeptin (a surrogate marker of AVP), and thirst perception (Suh et al., 2021). Copeptin (21.3 ± 2.0 vs. 14.1 ± 1.4 pmol·L^{-1}) and thirst were also significantly greater in women than men (respectively) and may have contributed to the greater mood degradation in women (Suh et al., 2021).

Excessive water intake without replacing sodium can lead to hyponatremia. Asymptomatic hyponatremia occurs when blood sodium concentrations fall below 135mmol/L in the absence of clinical symptoms. Symptomatic hyponatremia with encephalopathy typically occurs when blood sodium levels fall below 130mmol/L. The condition is considered mild at 130–135 mEq/L, moderate at 125–130 mEq/L, and severe at <125 mEq/L. Symptoms may include fatigue, nausea, weakness, seizures, and delirium (Rout & Badireddy, 2026). While this potential complication associated with fluid overconsumption exists, there is no significant evidence that habitual consumption of high total water intake poses identifiable hazards in a healthy population. No specific Tolerable Upper Intake Levels were set for water because of the ability to self-regulate water intake (Institute of Medicine, 2005).

Aging and Disease Prevention

Several aspects of aging and longevity may be affected by TWI. This was evaluated in a large cohort of US men and women (45 – 66 y) over a 25-year period using serum sodium as a measure of hydration (Dmitrieva et al., 2023). Serum sodium typically ranges between 135 and 146 mmol·L^{-1}, with higher concentrations indicating lower water intake (Dmitrieva et al., 2023). Investigators proposed that serum sodium 140 – 142 mmol·L^{-1} represents a plasma osmolality of 285 mmol·kg^{-1} (Dmitrieva et al., 2023), which falls within the range in which AVP is stimulated in the absence of thirst (Robertson, 1984). Serum sodium > 142 mmol·L^{-1} was associated with a 39% greater risk for chronic diseases (e.g., heart failure, dementia, chronic lung disease, stroke, diabetes, peripheral vascular disease, and atrial fibrillation) and a 50% greater likelihood of being biologically older (increased speed of aging) (Dmitrieva et al., 2023). Serum sodium > 144 mmol·L^{-1} was associated with a 21% greater risk of premature mortality (Dmitrieva et al., 2023). Another cohort of US men and women (51 – 70 y) was evaluated over a 3 – 6-year period with underhydration identified by serum sodium > 145 mmol·L^{-1}, spot urine volume < 50 mL, and/or spot urine osmolality ≥ 500 mmol·kg^{-1} (Stookey et al., 2020). In this population, underhydration was similarly associated with a 2.33 times greater risk for all-cause mortality and a 4.21 times greater risk for chronic disease mortality (Stookey et al., 2020). In contrast, chronic euhydration (serum sodium < 142 mmol·L^{-1}) is predicted to prevent age-related degenerative disease development in 3 million people in the US (Figure 2) (Allen et al., 2019). In particular, disease prevalence in adults 70 – 85 y was predicted to decrease for dementia (48%), heart failure (24%), chronic lung disease (10%), diabetes (11%), high blood pressure (7%), and stroke (3%) (Allen et al., 2019).

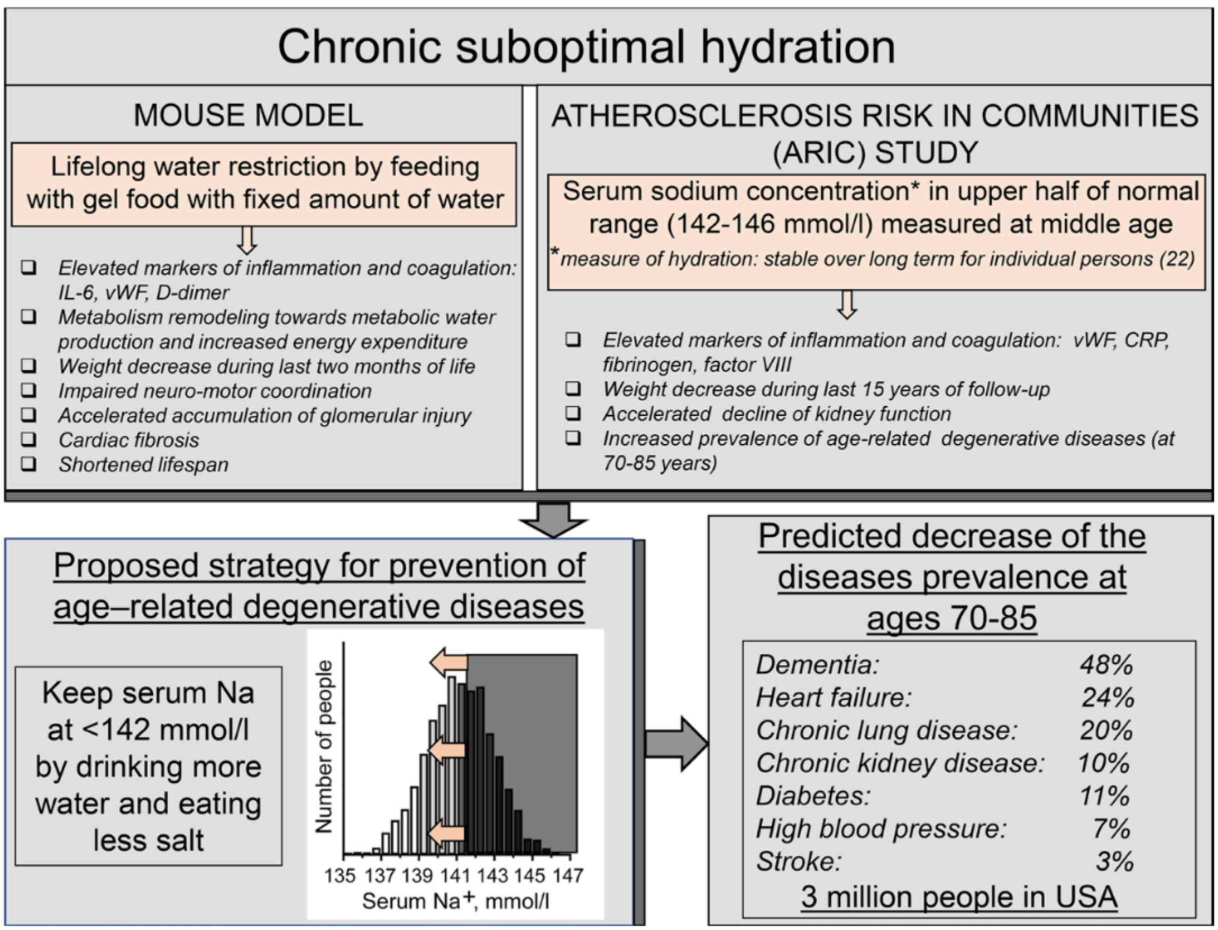
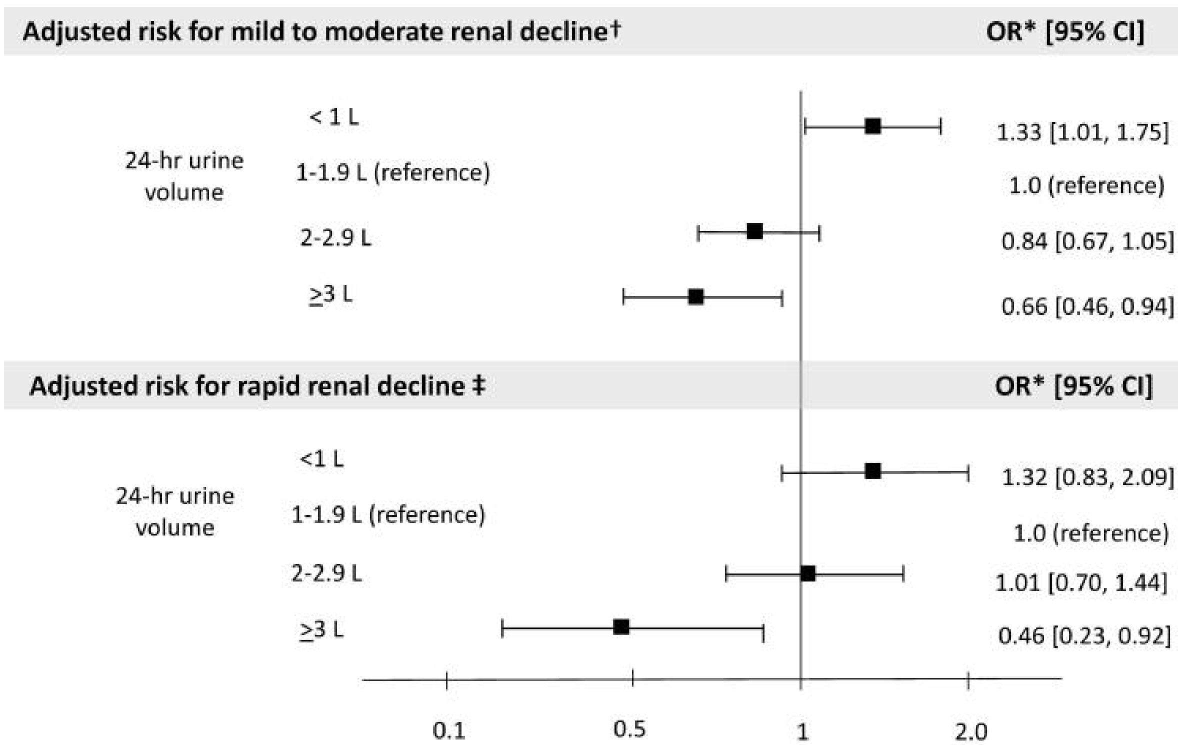


Figure 2. Predicted changes in disease prevalence with chronic euhydration (Allen et al., 2019) © 2019.

Chronic Kidney Disease

Chronic kidney disease is characterized by kidney damage, as indicated by an estimated glomerular filtration rate (eGFR) <60 mL·min^{-1} for >3 months (Vaidya & Aeddula, 2023). A slower eGFR represents a reduced ability of the kidney to filter blood. Men (66 y) and women (65 y) in

Australia with TWI > 3.2 L·d^{-1} had a 30 – 50 % reduced risk of developing chronic kidney disease compared to those drinking 1.7 L·d^{-1} (Strippoli et al., 2011). In another study, percentage annual change in eGFR (renal decline) and 24-h urine volume (another measure of hydration status) were compared in a cohort of Canadian residents (46 y) with eGFR ≥ 60 mL·min^{-1} over a 7-year period (Clark et al., 2011). Renal decline was observed to increase with decreasing urine volumes (Clark et al., 2011). Specifically, adults with urine volume ≥ 3 L·d^{-1} were 34 % less likely to have mild to moderate renal decline (1 – 4.9% eGFR change per year) and 54 % less likely to have rapid renal decline (≥ 5% eGFR change per year) compared to adults with urine volume 1 – 1.9 L·d^{-1} (Clark et al., 2011). As 24-h urine volume is indicative of TWI, this investigation provides additional support for the notion that greater TWI is protective of kidney function.



*Multinomial logistic regression adjusted for age, sex, baseline eGFR, dipstick protein ≥ 1g/L, medication use for hypertension (including diuretics), diabetes and cardiovascular disease.

†Mild to moderate renal decline: eGFR decline from baseline between 1% and 4.9%.

‡ Rapid renal decline: eGFR decline from baseline ≥5%.

Figure 3. Urine volume and risk for renal decline (Clark et al., 2011). © 2011 by the American Society of Nephrology.

There is also considerable evidence that underhydration contributes to the formation of kidney stones. Low urine volume has been identified as the main risk factor for kidney stones (Dmitrieva et al., 2023; Kavouras et al., 2021; Pak et al., 1980; Robertson et al., 1978). Additionally, increased urine volume via increased TWI has been found to reduce recurrence of kidney stones (Kaid-Omar et al., 2001; Kavouras et al., 2021; Pak et al., 1980; Taylor & Curhan, 2006). Among patients (46 ± 14 y) with recurrent kidney stone formation, the risk of calcium-oxalate kidney stone formation in particular is associated with 24-h urine osmolality > 501 mmol·kg^{-1} and > 577 mmol·kg^{-1} in women and men, respectively (Kavouras et al., 2021).

Type 2 Diabetes

Type 2 diabetes is characterized by hyperglycemia, chronically elevated fasting blood glucose (Galicia-Garcia et al., 2020). Clinically, type 2 diabetes is defined by a fasting plasma glucose concentration ≥126 mg/dL or 7.0 mmol/L (American Diabetes Association, 2026). In healthy individuals, elevated glucose levels stimulate the release of the hormone insulin, which promotes the uptake and metabolism/storage of glucose (Galicia-Garcia et al., 2020). In individuals with type 2 diabetes, several mechanisms contribute to hyperglycemia, including inadequate insulin production, insulin resistance, reduced peripheral glucose uptake in skeletal muscle, and increased endogenous glucose production from the liver, which is a major determinant of fasting hyperglycemia (Defronzo, 2009; DeFronzo et al., 2015; Solis-Herrera et al., 2000).

There is considerable evidence that indicates there is an increased risk of hyperglycemia and type 2 diabetes for individuals with low water intake (Enhörning et al., 2021; Roussel et al., 2011; Wannamethee et al., 2015). Among a cohort of men and women (30–65 y) in France with normal blood glucose, 15.6% developed hyperglycemia over a 9-year follow-up period (Roussel et al., 2011). The risk of developing new-onset hyperglycemia was 32% lower among those with higher (> 1 L·d^{-1}) than lower (< 0.5 L·d^{-1}) daily plain water intake, as assessed via a self-administered questionnaire at baseline (Roussel et al., 2011). A significantly greater risk of new-onset diabetes was observed for those with elevated copeptin in two additional cohorts of adults (Enhörning et al., 2021; Wannamethee et al., 2015). In one cohort, the risk of developing new-onset diabetes was 1.78 times greater among men with plasma copeptin in the top quintile (>6.79 pmol·L^{-1}), and this association appeared to be related to reduced insulin sensitivity (Wannamethee et al., 2015). In the other cohort, the risk of new-onset diabetes was 3.48 times greater for men (>10.7 pmol·L^{-1}) and women (>6.1 pmol·L^{-1}) with plasma copeptin in the top quartile. Elevated copeptin was significantly associated with insulin resistance (Enhörning et al., 2021). The copeptin thresholds observed in these studies (Enhörning et al., 2021; Wannamethee et al., 2015) fall within the range of plasma osmolality where AVP is stimulated in the absence of thirst (Robertson, 1984).

Potential mechanisms underlying these associations have been further explored in adults with type 2 diabetes (Carroll et al., 2003; Carroll et al., 2002; Johnson et al., 2017) and in healthy adults (Jansen et al., 2019). Both studies used oral glucose tolerance tests (OGTTs) to induce hyperglycemia following controlled glucose ingestion (75 g). Men with type 2 diabetes (53 ± 9 y) were removed from diabetic medication and assigned to consume either low (1 L·d^{-1} for 2 days & 0.5 L·d^{-1} for 1 day) or adequate (3 L·d^{-1}) volumes of water for three days (Johnson et al., 2017). Plasma glucose and cortisol levels were significantly greater in response to the OGTT after three days of low water intake (Johnson et al., 2017). While OGTT insulin production was not affected by water intake, fasting insulin resistance, fasting insulin sensitivity, and OGTT glucose clearance from the blood were significantly improved after high water intake (Johnson et al., 2017). These results suggest that cortisol was responsible for differences in glucose regulation (Johnson et al., 2017). Elevated AVP activates a pathway that ultimately induces cortisol production, which can subsequently stimulate glucose production in the body (Johnson et al., 2017). Although AVP was not measured in this study, plasma osmolality was significantly elevated (298±6 mmol·kg^{-1}) after three days of low water intake, which suggests AVP was also elevated (Johnson et al., 2017). Similar results were observed in healthy men and women (39±8 y) when elevated plasma osmolality and AVP were directly induced by hypertonic saline infusion (3% NaCl) rather than by fluid restriction (Jansen et al., 2019). Isotonic saline infusion (0.9% NaCl) was also performed as a control (i.e., no AVP stimulation) (Jansen et al., 2019). OGTT glucose production was significantly greater during hypertonic saline infusion, and insulin production was lower during the first 30 min of the test (Jansen et al., 2019). In contrast to the previous study (Johnson et al., 2017), no differences were observed in cortisol production, insulin sensitivity, or insulin resistance (Jansen et al., 2019). These conflicting findings may be related to differences in methodology between the two studies. In the previous study, elevated plasma osmolality was induced via fluid restriction (Johnson et al., 2017). Hypertonic saline infusion was used in the present study, which increases plasma volume and plasma osmolality (Jansen et al., 2019). Elevated plasma volume loads baroreceptors, which suppresses the renin-angiotensin-aldosterone system (the other hormonal fluid regulation mechanism). The absence of aldosterone and angiotensin II could have minimized their impact on glucose uptake in skeletal muscle (Catena et al., 2006; Cersosimo & DeFronzo, 2006; Cooper et al., 2007). However, the hormone glucagon was significantly elevated during hypertonic saline infusion (Jansen et al., 2019). Similar to cortisol, glucagon stimulates glucose production in the body, and this pathway can be activated by AVP (Jansen et al., 2019). The role of AVP in glucose regulation has been supported by evidence in rats (Taveau et al., 2015). Fasting blood glucose was higher in lean rats with elevated AVP compared to those with low AVP (Taveau et al., 2015). Additionally, four weeks of elevated AVP in obese rats induced elevated blood insulin and glucose intolerance, both of which are associated with diabetes.

Water Intake During Physical Activity

Water intake becomes especially important during physical activity. Muscular contractions produce metabolic heat, elevating core body temperature. This leads to heat loss via increased skin blood flow and sweat evaporation. There is an increase in reliance on sweating for heat loss during heat stress, via stimulation of sudomotor activity (Wingo et al., 2010). Even in tropical regions characterized by high ambient temperatures and relative humidity, resting sweat rates remain substantially lower than those observed during exercise, although they are higher than in temperate climates. In high ambient temperatures and relative humidity, the body's primary mechanism for heat dissipation, evaporative cooling through sweating, can become significantly impaired. Sweat rates of athletes exercising in the heat typically range from 1.0 to 2.0 L/h, but have been observed as high as 4.3 L/h (Armstrong, 2021; Sawka et al., 2001). While observed sweat rates may be similar in tropical climates (Surapongchai et al., 2021), some have reported higher sweat rates in athletes indigenous to tropical climates (Rivera-Brown & Quiñones-González, 2020). With exercise, replacing fluid lost through sweating during thermoregulation is necessary to maintain fluid-electrolyte balance. If sweat losses are not replaced, dehydration can impair performance. Dehydration exacerbates thermal and cardiovascular strain (González-Alonso et al., 2008) and can increase athletes' risk of exertional heat illnesses (Racinais et al., 2015).

The American College of Sports Medicine recommends that athletes start activity euhydrated and with normal electrolyte levels (Sawka et al., 2007). Prevention of excessive dehydration (>2%) is the goal during exercise (McDermott et al., 2017). After exercise, customized fluid replacement based on sweat rate is recommended (Li et al., 2024). Even with access to fluids, humans only replace 2/3 of sweat losses during rehydration (Armstrong et al., 2014). This limitation of the thirst mechanism has been termed involuntary dehydration. Post-exercise ad libitum or voluntary fluid consumption often results in inadequate hydration, as thirst suppression can occur before full rehydration is achieved (Capitán-Jiménez & Aragón-Vargas, 2022). Awareness of fluid losses during exercise alone does not override the dehydration-induced hypothalamic signal for thirst (Capitán-Jiménez & Aragón-Vargas, 2021). Oropharyngeal and gastric signals may suppress thirst before fluid absorption is complete, and plasma osmolality can return to normal values even when fluid intake is considerably lower than fluid loss due to exercise, despite a residual deficiency (Armstrong & Kavouras, 2019; Figaro & Mack, 1997). Structured hydration strategies, particularly in tropical climates, are crucial because environmental stress challenges thermoregulatory efficiency at rest and especially during exercise.

Figure 4 illustrates evidence-based recommendations for water intake, including daily intake guidelines, monitoring tools, and hydration strategies for sedentary individuals and for athletes before, during, and after exercise. Urine color is a practical monitoring tool that can serve as an index of urine concentration and total body water status. Typically, urine color values ≥4 on validated urine color charts are considered indicative of underhydration. In addition, daily urine frequency has been proposed as a user-friendly hydration assessment technique requiring minimal expertise and equipment, with fewer than five voids per day in children and fewer than seven voids per day in adults suggesting inadequate hydration. Together, these tools provide practical approaches for daily hydration assessment in free-living conditions (Adams et al., 2021).

Figure 4. Infographic presenting evidence-based recommendations for water intake, including daily intake guidelines, monitoring tools, and hydration strategies for sedentary individuals and for athletes before, during, and after exercise. Source: Own elaboration based on (Adams et al., 2021; Armstrong, 2021; Institute of Medicine, 2005; Li et al., 2024).

2. Conclusion

Collectively, low water intake and elevated arginine vasopressin are associated with adverse effects across a wide range of health outcomes, including cardiovascular health, mood, kidney function, glucose regulation, chronic disease development, accelerated aging, and increased mortality. Although it has been suggested that thirst might be an adequate signal for fluid needs, a state of underhydration (characterized by AVP stimulation in the absence of thirst) appears to increase the risk of many detrimental health outcomes. Increasing water consumption through palatable non-sugar-sweetened beverages represents a simple, cost-effective approach with the potential to produce sustained improvements in population health.

The origin and scientific support for the recommendation of 8 x 8-oz glasses of water (~2.0 L) per day have been widely debated (Valtin, 2002). However, this recommendation is similar to the National Academy of Medicine's Adequate Intake for total water intake guidelines for women (National Academy of Medicine, 2005). Also, 3.7 and 2.7 L of water per day for sedentary men and women (> 18 y), respectively, are currently recommended (National Academy of Medicine, 2005) and have been supported by scientific evidence (Seal et al., 2023). Individuals are estimated to consume ~80% of their daily TWI from beverages (Vieux et al., 2020), corresponding to 3 and 2.1 L of water per day for men and women, respectively. Ultimately, water needs depend on many factors such as age, physical activity, body composition, body surface area, and environmental conditions (National Academy of Medicine, 2005). While no guideline can accommodate every human in every context, the current guidelines appear to be sufficient at the population level.

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