The most essential nutrient: Defining the adequate intake of water

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Although water is quantitatively the most import nutrient, there are no recommended dietary allowances (RDA) or adequate intake (AI) values. Based on 718 assessments of 24-hour total water intake, urine volume, and urine osmolality, individual hydration status was characterized in 479 healthy boys and girls of the DONALD study aged 4.0 to 6.9 years and 7.0 to 10.9 years. Mean 24-hour total water intake ranged from 0.90 mL/kcal to 0.96 mL/kcal, and median 24-hour urine osmolality ranged from 683 mosm/kg to 854 mosm/kg. A maximum urine osmolality of 830 mosm/kg (mean – 2 SD) in healthy children with a typical affluent Western-type diet was the physiologic criterion of the upper limit of euhydration. "Water reserve" (24-hour urine volume – hypothetical urine volume to excrete 24 urine solutes at a concentration of 830 mosm/kg) was a quantitative measure of individual 24-hour hydration status and ensuring euhydration in 97% of the subjects in each group; AI values of total water in the 4 age and sex groups ranged from 1.01 mL/kcal to 1.05 mL/kcal. These procedures to quantify 24-hour hydration status may prove valuable in investigating the effects on health of different states of euhydration. (J Pediatr 2002;141:587-92)

Mild dehydration, defined as a 1% to 2% loss of body weight caused by fluid loss, impairs exercise performance, affects overall health in the elderly, and increases the risk of urinary stone disease.[1] Nevertheless, water intake is frequently disregarded. There is no universally accepted laboratory method to characterize individual hydration status, and water requirement depends on several factors (eg, climate, physical activity, renal solute load). In the United Kingdom, water is not included in the list of dietary reference values and in the United States, a total water intake of 1.5 mL/kcal is recommended in infants and 1.0 mL/kcal in children for practical purposes only.[2]

Based on the assumption that hypohydration impairs performance and increases morbidity, data on 24-hour water intake, urine volume, urine osmolality, and water reserve (a new measure to characterize individual hydration status) in 4 age and sex groups of healthy children from Dortmund, Germany, were assessed. Age- and gender-specific adequate intake (AI) values of total water intake, ensuring euhydration (24-hour urine osmolality <830 mosm/kg) in 97% of the subjects of each of the 4 groups, were then calculated.

METHODS

DONALD Study

Healthy children (n = 479, 4.0-10.9 years) taking part in the DONALD (Dortmund Nutritional and Anthropometric Longitudinally Designed) Study[3] had repeated 24-hour studies with measured diet and fluid intakes and urine collections. They were living at home in an industrialized town in Germany with a relatively constant climate, exerting normal physical activity, and consuming a typical affluent Western-type diet. A total of 718 records of 24-hour weighed dietary records and 24-hour urine samples were evaluated. In each age class, data from one day per participant was randomly selected. Parents or the older children and adolescents themselves weighed and recorded all foods and fluids consumed, as well as leftovers, using electronic food scales (± 1 g). Original product information was kept by the participants and collected by a dietician with the diet record. Energy and total water intake (oxidation water, water from food, and beverages) were calculated by using the nutrient database LEBTAB (Research Institute of Child Nutrition) based mainly on

AI	Adequate intake
RDA	Recommended dietary allowance
Vh	Hypothetical volume
Vm	Urine volume

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Table I. Data of actual age, weight, energy, total water intake and urine parameters, water reserve, AI of total water, and predicted urine osmolality at AI of total water in 236 boys and 243 girls from the DONALD Study

				Intake			
		Actual age	Weight	Energy	Total water*		
Age group (y)	Data sets (n)	Mean ± SD (y)	Median 3P, 97P† (kg)	Median 3P, 97P (kcal/24 h)	Mean ± SD (mL/24 h)	Median 3P, 97P (mL/24 h)	Mean ± SD (mL/24 h)
Boys							
4.0-6.9	189	5.6	21.1	1495	1326	1310	0.90
		± 0.9	15.5, 29.3	931, 2264	± 333	768, 2006	±0.20
7.0-10.9	174	8.8	30.6	1834	1696	1640	0.93
		± 1.1	21.1, 47.4	1156, 2877	± 468	882, 2727	±0.24
Girls							
4.0-6.9	181	5.5	19.5	1302	1225	1209	0.94
		± 0.9	14.6, 29.0	797, 1906	± 292	761, 1874	±0.20
7.0-10.9	174	9.0	31.1	1646	1526	1483	0.96
		± 1.2	21.5, 46.2	983, 2484	± 402	915, 2327	±0.23

**Total water intake*, Water of oxidation + water in food + water from fluid intake.
†3rd percentile and 97th percentile value.
‡*WR*, Vm – Vh; *Vm*, measured urine volume (mL/24 h); *Vh*, hypothetical urine volume (mL/24 h) = measured urine solutes (mosm/24 h)/830 (mosm/1000 g water); assuming 1 g water = 1 mL urine.
§Adequate intake of total water = median total water intake (mL/24 h) – 3rd percentile value of water reserve (mL/24 h).
‖Predicted urine osmolality at AI of total water = urinary solutes excretion (mosm/24 h)/(urinary volume [L/24 h] – 3rd percentile value of water reserve [L/24 h]); the additional water is quantitatively excreted in urine; 1 kg water = 1 L urine.

data from German food tables.[4] The children and their parents were carefully instructed on how to collect a 24-hour urine sample, from about 7:00 AM on the protocol day to 7:00 AM the next day, and how to store samples at –20°C. The timing of voiding was recorded. Before transportation to the institute, the completeness of the urine collection was checked. Only validated dietary records and urine samples were accepted. The two criteria for acceptance were: (1) the age- and sex-related ratio between protein input and nitrogen output was above the 5th percentile and the ratio between energy intake and basic metabolic rate was above 1.06 according to Goldberg,[5] and (2) accepted urine samples showed a urine creatinine excretion value related to body weight above the 5th percentile of the corresponding age and sex groups.[6] The DONALD study is exclusively observational, nonintervening, and noninvasive. It was approved by the International Scientific Committee of the Research Institute of Child Nutrition and the informed consent of the children and parents was given.

Osmolality of urine was calculated from the freezing point depression measured by an osmometer (Knauer, Berlin, Germany). Coefficient of variation was 1.3% at 900 mosm/kg and 0.8% at 350 mosm/kg.

Water Reserve

In a subject, maximum and minimum urine osmolality define the range of euhydration (Fig 1). If, in a particular group of subjects, data on 24-hour urine volume and osmolality but no values of maximum or minimum urine osmolality are known, data of maximum or minimum urine osmolality from a comparable group of similar age and nutrition status can be used to define a range of euhydration and ranges of risk of hypohydration (either between the 3rd percentile and 97th percentile or between the mean -2 SD (2.3 percentile) and the mean + 2 SD (97.7 percentile) of maximum urine osmolality) or hyperhydration. Thus, the mean –2 SD value for maximum urine osmolality was defined as a physiologic criterion for the upper level of euhydration. In healthy children consuming a typical affluent Western-type diet, the upper level of euhydration is 830 mom/kg.[7-12]

Osmolality is a measure of concentration. Thus, the term "water reserve (mL/24 hours)" has been defined as a quantitative measure of individual 24-hour hydration status. It corresponds to the difference between the measured urine volume (Vm; mL/24 hours) and the hypothetic volume (Vh; mL/24 hours) necessary to excrete the actual 24-hour urine solutes (mosm/24 hours) at an urine osmolality of 830 mosm/1000 g water, assuming 1 g water equals 1 mL urine. If almost all subjects (97% based on 97th percentile or 97.7% based on mean +2 SD) of a population show 24-hour urine osmolalities below 830 mosm/kg or positive water reserve

Urine: Volume	Urine: Solutes	Urine: Osmolality	Water reserve‡		AI of total water§		Predicted urine osmolality at AI of total water
Median 3P, 97 (mL/kcal)	Median 3P, 97P (mosm/24 h)	Median 3P, 97P (mosm/kg)	Mean ± SD (mL/24 h)	Median 3P, 97P (mL/24 h)	Median (mL/24 h)	Mean ± SD P (mL/kcal)	Median 3P, 97P (mosm/kg)
497	387	809	54	11	1466	1.01	598
266, 976	222, 645	413, 1146	± 161	–156, 488		± 0.21	340, 830
678	517	854	53	–15	1857	1.05	599
320, 1184	275, 820	402, 1162	± 214	–218, 548		± 0.25	346, 830
487	354	711	95	68	1318	1.03	565
255, 1057	209, 583	417, 1100	± 160	–109, 432		± 0.20	367, 830
651	434	683	159	114	1607	1.04	570
300, 1231	260, 670	358, 1087	± 232	–124, 621		± 0.25	314, 830

values the population is classified as adequately hydrated.[13]

AI of Total Water

The recommended dietary allowance (RDA) of a nutrient corresponds to "the average daily intake level that is sufficient to meet the nutrient requirement of nearly all (97%-98%) healthy persons in a particular life stage and sex group."[13] AI values of total water were calculated, which correspond to the differences of median observed total water intakes and the 3rd percentile water reserve values (Table I).

Statistical Analysis

SAS procedures (Version 6.12, SAS Institute, Cary, NC) were used for data analysis. To account for the special covariance structure of our data (up to 4 children per family, different frequencies of repeated records, and time intervals between repeated records) and to analyze for the influence of the effects (age, sex) on the outcome variables, the procedure PROC MIXED was used. In each group of boys and girls, only one urine sample per child was randomly selected.

Table II. Influence of the covariance variables sex, age and sex × age on the outcome variables total water intake, urine volume, urine solutes, urine osmolality, and water reserve accounting for the special covariance structure of the DONALD Study

Measurement	Sex *P*	Age *P*	Sex × age *P*
Total water intake (mL/24 h)	< .0001	< .0001	
Urine volume (mL/24 h)		< .0001	
Urine solutes (mosm/24 h)	< .0001	< .0001	< .02
Urine osmolality (mosm/kg)	< .0001		
Water reserve (mL/24 h)	< .01	< .01	< .02

RESULTS

Boys showed significantly higher mean values of total water intake, urine solute excretion, and urine osmolality and lower mean water reserve values than girls, but similar mean values of urine volume (Table II). There was an interaction of sex and age on urine solute excretion and water reserve. Negative water reserve values were observed in 46% and 52% in each age group in boys and 28% and 31% in girls, respectively. In the 4 age and sex groups, a general additional intake of 109 mL/24 hours to 218 mL/24 hours were calculated to be necessary to keep 97% of the children of the respective

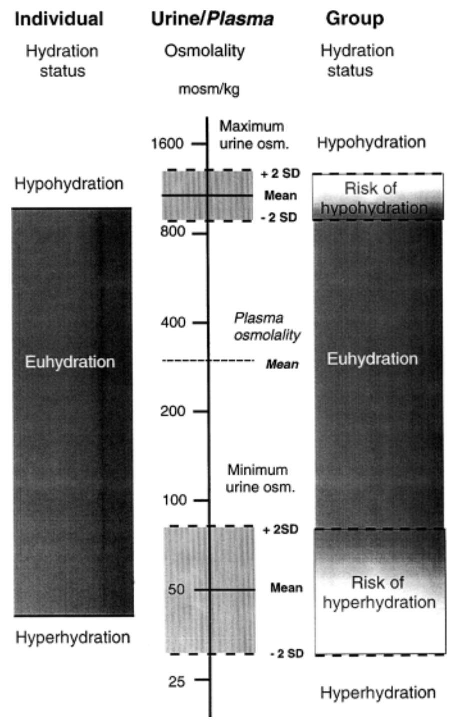

Fig 1. Characterization of hydration status of a subject or a group based on data of urine osmolality.

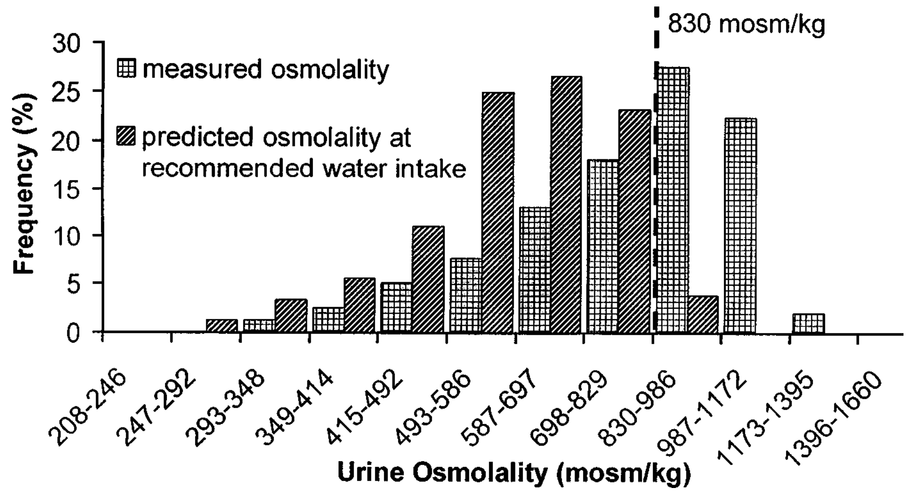

Fig 2. Frequency (%) of measured versus predicted urine osmolality in 236 boys aged 4.0 years to 10.9 years of the DONALD Study at actual and recommended water intake ensuring euhydration in 97% of the children (one randomly selected data per child). Measured urine osmolality (mosm/kg): mean ± SD = 816 ± 212; median = 844; predicted urine osmolality: mean ± SD = 598 ± 136; median = 604.

groups euhydrated. AI of daily total water values referred to energy intake (mL/kcal) were very close to the recommended total water intake of 1.0 mL/kcal in children of the RDA of 1989.[2] Fig 2 shows frequency of measured and predicted urine osmolality in boys at actual intake and AI of total daily water.

DISCUSSION

Based on original data of water intake and output, AI values of total water were calculated in 4 age groups of boys and girls. The high median values of urine osmolality in the children from Dortmund point to an inadequately low water intake. The recommendation of total water intake of 1.0 mL/kcal for children in the United States from 1989[2] is also appropriate for children in Dortmund.

Currently no "gold standard" hydration status marker exists, particularly for relatively moderate levels of hypohydration.[14] Water intake is only a very rough measure of the individual hydration status, because differences in extrarenal water losses are not considered. Serum sodium concentration or hematocrit levels are established clinical measures of severe hypo- or hyperhydration but do not quantify euhydration.[14] Urine volume does not take into account the renal excretion of solutes.[14] Osmolality of a spontaneous urine sample mirrors actual plasma osmolality and is highly influenced by short-term shifts of water between the water pools of the body. In the context of nutrition, the osmolality of a 24-hour urine sample reflecting the self-regulating activity of renal concentration or dilution mechanisms during 24 hours could well be a semiquantitative measure and water reserve a quantitative measure to estimate functional surplus of water and to characterize 24-hour hydration status.

In principle, maximum and minimum urine osmolality are appropriate biomarkers for the physiologic criteria of upper and lower level of euhydration. In renal concentrating capacity tests, maximum urine osmolality is defined as the highest value in a series of values of urine samples from short periods of time. Extrapolated to 24 hours, the maximum urinary osmolality value may appear relatively high. On the other hand, in 24-hour urine samples the scattering of data is lower than in short-period urine samples. The mean –2 SD value of the postulated maximum 24-hour urine samples, therefore, may appear relatively low. The first effect may counterbalance the second.

In standardized tests of renal concentration capacity (intravenous vasopressin, 12-18 hours of fluid restriction with or without intravenous vasopressin or intranasal desmopressin) in 561 healthy children and adolescents from 7 groups of 5 industrialized countries consuming a Western-style diet, mean maximum urine osmolality was 1054 mosm/kg and mean –2 SD 830 mosm/kg.[7-12] There was no sex difference. Minimum urine osmolality in 17 children aged 2 to 12 years was 54 ± 13 mosm/kg.[15]

Gamble set the "average" maximum urine osmolality in adults at 1400 mosm/kg water.[16] Dividing the "mean" daily urine excretion of solutes of a man with an ordinary diet of 1200 mosm/24 hours at 1400 mosm/L he calculated a mean "minimal urine water" volume of 857 mL/24 hours. The difference in urinary volume (mL/24 hours) and minimal urine water volume (mL/24 hours) was classified as functionally disposable or "so-called" free water (mL/24 hours).[16] In retrospect, a mean maximum renal concentration of 1400 mosm/kg water is an extreme value in subjects with a very high protein intake and fluid restriction for more than 18 hours. Urine solute excretion was 1136 mosm/24 hours on a working day and 1365 mosm/24 hours on a rest day in Australian miners.[17] Usually it is about 750 mosm/(24 hours × 1.73 m^2) in adults with a typical Western-style diet.[18-20]

Maximum Uosm is dependent on age and mainly modulated by the duration of water restriction, the level of protein and sodium intake, and strenuous physical activity. In young adults the prolongation of water restriction from 10 hours to 16 hours and 20 hours to 36 hours increased mean maximum Uosm by 116 mosm/kg to 230 mosm/kg, respectively.[21,22] Fluid restriction for 3 days resulted in an additional increase in mean maximum Uosm of 400 mosm/kg compared with 12-hour fluid restriction after long-term high-fluid intake (5000 mL/24 hours for 3 days).[23] Mean maximum Uosm with a high-protein intake was 300 mosm/kg higher than with a low-protein intake.[24,25] The difference in mean maximum Uosm between a sodium intake of 20 mmol/24 hours and 150 mmol/24 hours was 74 mosm/kg (vasopressin) or 94 mosm/kg (dehydration).[24] In dehydrated soldiers, heavy physical exercise transiently decreased maximum Uosm by as much as 300 mosm/kg.[26] The effect of extreme dietary regimens on maximum urine osmolality is the observed mean maximum urine osmolality of 1362 ± 109 mosm/kg in 9 adolescents who received no fluid, but only dried milk dissolved in half the usual amount of water, for 24 hours.[27] Thus, if we comment on the maximal Uosm of a subject or a group, age and functional status of the kidney should be taken into account.

Accepting the definitions of upper limit of euhydration (mean –2 SD of maximum renal osmolality of 830 mosm/kg in children and adolescents consuming a typical affluent Western-type diet) and AI of water (<3% of 24-hour urine samples with a urine osmolality above the upper limit of euhydration), the 4 groups of boys and girls of Dortmund showed an insufficient hydration status. If we assume that the intake of additional water is quantitatively excreted by the kidneys, ~1 extra cup of water (240 mL) would be enough to meet the postulated daily water needs of the school-aged children in the DONALD study.

Unknown individual deficits or surplus of water balance do not affect median values of AI of total water intake. Days with water deficit in some children were randomly equilibrated by days with water surplus in others.

In the second National Health and Nutrition Examination Survey in the United States from 1976 through 1980, 12- to 19-year-old healthy boys and girls showed a mean 24-hour urine osmolality of 696 mosm/kg.[28] Mean 24-hour urine osmolality was 860 mosm/kg (4-6 years, n = 25) or 804 mosm/kg (3-17 years, n = 49) in Germany,[29,30] 755 mosm/kg in France (3-14 years, n = 46),[31] 676 mosm/kg in Denmark (12-17 years, n = 11),[32] 572 mosm/kg in the United States (11.9 ± 3 years, n = 36),[33] and 560 mosm/kg in The Netherlands (n = 24).[34] Urine osmolality in spontaneous urine samples showed similar results: 964 mosm/kg in Sweden (12-17 years, n = 20),[35] 900 mosm/kg in Japan (3-12 years),[36] 845 mosm/kg in the United Kingdom (3-18 years, n = 322),[37] 791 mosm/kg in Israel (2-6 years, n = 200),[35] and 701 mosm/kg in Italy (7-12 years, n = 40).[39] In several third-world countries, urine osmolality was lower, eg, 523 mosm/kg in the Dominican Republic (3-10 years, n = 30),[40] 498 mosm/kg in Uganda (2-3 years, n = 13),[41] and 392 mosm/kg in Kenya (4-5 years, n = 30).[42] Boys showed a significant higher urine osmolality than girls in Germany (801 mosm/kg vs 729 mosm/kg),[43] the United Kingdom (896 mosm/kg vs 781 mosm/kg),[37] and the United States (649 mosm/kg vs 540 mosm/kg),[28] but not in Italy[39] and Israel.[38]

No data comparing intra- and interindividual variation of urine osmolality were available. However, siblings show smaller differences in 24-hour urine osmolality than nonrelated children[29].

The hydration status of the body is meticulously regulated. The current procedure to analyze water metabolism may prove to be a valuable tool to characterize 24-hour hydration status, to investigate health effects of different states of euhydration, and to calculate the recommended total daily water intake values for homogeneous population groups.

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