British Journal of Nutrition (2012), **107**, 1673–1681
doi:10.1017/S0007114511004776

Water balance throughout the adult life span in a German population

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(Submitted 4 February 2011 – Final revision received 27 July 2011 – Accepted 27 July 2011 – First published online 16 September 2011)

Abstract

Mild dehydration, defined as a 1–2 % loss in body mass caused by fluid deficit, is associated with risks of functional impairments and chronic diseases. Whether water requirements change with increasing age remains unclear. Therefore, the aim of the present investigation is to quantify hydration status and its complex determining factors from young to old adulthood to analyse age-related alterations and to provide a reliable database for the derivation of dietary recommendations. Urine samples collected over a 24 h period and dietary records from 1528 German adults (18–88 years; sub-sample of the first National Food Consumption Survey) were used to calculate water intake (beverages, food and metabolic water) and water excretion parameters (non-renal water losses (NRWL), urine volume, obligatory urine volume) and to estimate hydration status (free-water-reserve) and 'adequate intake (AI)'. Median total water intake (2483 and 2054 ml/d, for men and women, respectively ($P<0·0001$)), decreased with increasing age only in males ($P=0·001$). Obligatory urine volume increased in both sexes ($P<0·0001$) due to decreased renal concentration capacity. The latter was balanced by a decrease of NRWL ($P<0·05$), leaving the free-water-reserve and therefore hydration status almost unchanged. Calculated 'AI' of total water was the same for young (18–24 years) and elderly (≥65 years) adults (2910 and 2265 ml/d, for men and women, respectively). The present study is the first population-based examination showing that total water requirements do not change with age although ageing affects several parameters of water metabolism. Reduced sweat loss with increasing age appears to be primarily responsible for this observation.

Key words: **Hydration status: Elderly: Adequate water Intake: Urine osmolality**

Water constitutes approximately one-half of human body weight[1] and is essential for human life and health. Total body water is tightly regulated and there is increasing evidence that even mild dehydration (defined as a 1–2 % loss in body mass caused by fluid deficit) may play a role in various morbidities like urolithiasis, constipation and hypertension[2]. Especially the elderly (≥65 years) are at an increased risk of dehydration because they experience a decrease in thirst sensation and at the same time have an impaired capacity of their kidneys to concentrate the urine[3–5].

However, the scientific basis for water intake recommendations for the elderly is scarce and the recommendations from different nutrition societies are not consistent. The German Nutrition Society, for example, recommends a lower total water intake with increasing age[6]. In contrast, the US Institute of Medicine provides constant water intake recommendations (adequate intake (AI)) for younger and older adults. These AI values were based on the median total water intake of young adults to ensure an adequate amount of consumption in the elderly[7]. The European Food Safety Authority is trying to develop a European standard at present[8]. However, until now, detailed and representative data on water intake and hydration status of a population, which is the requirement to derive a reliable basis for intake recommendations, are missing.

Some years ago, we presented a concept of estimating individual 24 h hydration status[9]. It complies with the concept of Dietary Reference Intakes from the US Institute of Medicine[7], i.e. that the AI of a nutrient is the observed or experimentally determined estimated intake at which the risk of inadequacy is very low – only 2–3 %[7]. The 24 h hydration status of a subject is inadequate if the 24 h urine osmolality is above the mean (−2 SD) value of experimentally determined maximum urine osmolality (for the respective life-stage group)[10]. The difference between the 24 h urine volume and the obligatory urine volume (i.e. the hypothetic volume necessary to excrete

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Abbreviations: AI, adequate intake; NRWL, non-renal water losses; VERA, Verbundstudie Ernährungserhebung und Risikofaktoren-Analytik.

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the actual 24 h urine solutes) is called the free-water-reserve[9] – measuring the individual 24 h euhydration (calculations in detail are described in the Methods section).

Free-water-reserve is determined by various parameters of water metabolism: beverages and food water intake, metabolic water, non-renal water losses (NRWL), urine volume and obligatory urine volume. It is widely known that nearly all of these parameters undergo changes with increasing age. Elderly people show lower sweat losses[11,12], and therefore NRWL decreases; at the same time renal concentration capacity becomes impaired[10], resulting in an increased obligatory urine volume.

The aim of the present investigation was to quantify hydration status and its complex determining factors from young to old adulthood to analyse possible age-related alterations and provide a reliable basis for the derivation of dietary recommendations. We used data from the public use file and new results from the analysis of stored urine samples from the Verbundstudie Ernährungserhebung und Risikofaktoren-Analytik (VERA) study population of the National Food Consumption Survey of Germany in 1986–8[13].

Methods

Between 1986 and 1988, a representative sample of 24 632 persons of the Federal Republic of Germany living in 11 141 households took part in the first National Food Consumption Survey[14,15], documenting and analysing nutrition behaviour and physical activity by 7 d records and personal interviews. From this population, a representative sub-sample of 2006 persons aged 18–88 years was taken randomly and 24 h urine samples were collected from each subject (Cooperative Study: Nutrition Survey and Risk Factors Analysis, VERA)[15,16]. The original diet and health survey from which the information used in the present study was obtained had ethical approval from the commissioning Federal Ministry of Research and Technology, the Institutional Review Board of the Faculty of Nutritional Sciences, Justus-Liebig-University Giessen, Germany, and the Scientific Advisory Council of the VERA study. Urine collection, over a 24 h period, was carried out on one of the days of dietary recording; subjects were instructed by the interviewer how to perform 24 h urine collection. Completely collected frozen urine samples were directly transported to the laboratory for analysis. Remaining samples were stored at <-80°C. Urine osmolality was analysed (Osmometer OM 802-D; Vogel, Giessen, Germany) in the year 2003 from stored urine samples (<-80°C). Stability of urine osmolality was previously checked by remeasurements of 24 h urine samples after 15 years of storage. Recovery rates of more than 95 % ensured no disturbing effects of storage duration on urine osmolality. Measurements of 24 h urine osmolality were combined with previous measurements of urine volume and creatinine (Jaffé method) as well as data from the dietary record of the day of urine collection as available in the public use files of the VERA study[17]. In 115 subjects, single urine data were missing. In 269 subjects, the urine collection time was not in the range of 1200–1560 min. In ninety-one subjects, 24 h urine creatinine was below 0·1 mmol/kg per d in males and 0·09 mmol/kg per d in females[18]. In two subjects, 24 h urine volume was below 300 ml and in one subject, body weight was missing. The final data sets included the data of 1528 subjects (women: 58·2 %; proportion of women in the initial VERA sample: 57·0 %; in the German population (1986–8, ≥ 20 years): 52·7 %).

Hydration status

Total water intake corresponds to the sum of beverages, metabolic water and water in food (including milk and milk products) taken from the dietary record of the day of urine collection. All foods and beverages consumed were recorded, using food scales for weighing or standardised containers and templates to estimate the consumed amounts.

In water balance, total water intake corresponds to total water losses, which is the sum of NRWL and 24 h urine volume. Thus, NRWL correspond to the difference of calculated total water intake and measured 24 h urine volume:

$$\text{NRWL (litres/d)} = \text{total water intake (litres/d)} - \text{24 h urine volume (litres/d)}. \quad (1)$$

Renal solutes excretion (mOsm/d) corresponds to the product of urine osmolality (mOsm/kg) and 24 h urine volume (litres/d, assuming 1 kg water corresponds to 1 litre). Obligatory urine volume is defined as the water volume necessary to excrete 24 h urine solutes at the age-related lower limit of maximum urine osmolality (mean (-2 SD)). Based on literature data of standardised tests of renal concentration capacity in subjects in industrialised countries, the lower limit of maximum urine osmolality has been estimated to be 830 mOsm/kg minus 3·4 mOsm/kg per year starting from an age of 20 years[10]. The calculation of obligatory urine volume for an age above 20 years is:

$$\text{Obligatory urine volume (litres/d)} = \text{24 h urine solutes (mOsm/d)}/(830 - 3{\cdot}4 \times (\text{age} - 20)) \ \text{(mOsm/l, assuming 1 kg water corresponds to 1 litre)}. \quad (2)$$

Free-water-reserve corresponds to the difference of the 24 h urine volume and the obligatory urine volume

$$\text{Free-water-reserve (litres/d)} = \text{24 h urine volume (litres/d)} - \text{obligatory urine volume (litres/d)}. \quad (3)$$

It quantifies individual 24 h hydration status[9]. If the value is positive, the subject is euhydrated. If it is negative (due to a 24 h urine osmolality above the mean (-2 SD) value of maximum urine osmolality), the subject is hypohydrated or in a hydration status in the range at risk of hypohydration.

In a population, euhydration is ensured if at least 97 % of the subjects show positive values of free-water-reserve[7].

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Euhydration may be achieved in a population at risk of hypohydration by a general increase in the level of total water intake (the theoretically required increase is represented by the calculated 3rd percentile value of free-water-reserve). Thus, the AI of total water of a population is the sum of median total water intake minus the 3rd percentile value of free-water-reserve[7,9]:

$$\text{Adequate total water intake (litres/d)} = \text{median total water intake (litres/d)} - \text{3rd percentile of free-water-reserve (litres/d)}. \quad (4)$$

Another reasonable, less practicable concept to ensure euhydration is the reduction of obligatory urine volume (by the amount of the 3rd percentile volume of free-water-reserve) by a decrease of urine solutes excretion:

$$\text{Decrease of urine solutes excretion (mOsm/d)} = \text{3rd percentile free-water-reserve (litres/d)} \times (830 - 3{\cdot}4\,(\text{age} - 20))\,\text{(mOsm/litres)}. \quad (5)$$

The high NRWL in men can be divided into an energy-related part (in accordance with the common approach of relating water intake recommendations to units of energy intake[8,19]) and a male-specific part, accounting for the generally higher NRWL in males than in females, even if the differences in energy intake are taken into account. The energy-related part corresponds to the product of the age-group-specific mean female NRWL and the corresponding ratio of mean male and female energy intakes:

$$\text{Energy-related NRWL} = \text{mean NRWL (women)} \times (\text{mean energy intake (men)}/\text{mean energy intake (women)}). \quad (6)$$

$$\text{Male-specific NRWL} = \text{NRWL (men)} - \text{energy-related NRWL}.$$

Statistical analysis

Anthropometric data, energy intake and results of water balance are given as means and standard deviations, stratified by age groups of 18–24, 25–49, 50–64 and ≥65 years. These age ranges were selected according to the actual age categorisation of the German Nutrition Society[6]. Sex differences were tested by an unpaired *t*-test. To investigate the effects of age on the various parameters of water balance, a linear regression model was calculated for each parameter adjusted for energy intake and physical activity. Physical activity was defined as the sum of daily sports activities + cycling + moderate to vigorous physical activities (such as cleaning or gardening) and was expressed in hours. All regression models were run sex-stratified. Concerning free-water-reserve, the effects of the following factors were additionally included and tested for significance: education (four levels: elementary school, secondary school without diploma, diploma, academic studies), region (*n* 4: north, west, middle, south), size of place of residence (four categories: <2000, <20 000, <500 000, ≥500 000 inhabitants) and mean income per person of a household (five categories: <500, <1000, <1500, <2000, ≥2000 D-Mark (approximately corresponding to € today). To directly compare male and female parameters of water metabolism, differences of mean male and mean female parameters were calculated after adjusting the values of women to the energy intake of men (i.e. after multiplication of the female values with the age-group-specific ratio of mean male and female energy intakes). An effect was accepted as significant if the *P* value (two-tailed) was below 0·05. All calculations were performed by using SAS procedures (version 8.02; SAS Institute, Cary, NC, USA).

Results

Anthropometric data, energy intake and results of the parameters of water balance of males and females from a formerly representative sample (*n* 1528) of the German population in 1986–8 aged 18–88 years (VERA study) are presented in Tables 1 and 2, respectively. Comparison between sexes showed a significance level of $P<0{\cdot}0001$ for most of the presented parameters, except for urine solutes/energy ($P=0{\cdot}0002$) and urine volume ($P=0{\cdot}49$).

Median total water intake was 2483 ml/d in men and 2054 ml/d in women ($P<0{\cdot}0001$). Free-water-reserve was negative in 40 % of males and 19 % of females. Euhydration would have been ensured in 97 % of German adults, if the water balance had been improved by 427 ml/d in men and 211 ml/d in women by (a) an AI of total water of 2910 ml/d or 1·04 ml/kcal in men and 2265 ml/d or 1·05 ml/kcal in women, (b) a decrease of urine solutes excretion of 319 mOsm/d in men and 158 mOsm/d in women or (c) a mixture of both measures. Free-water-reserve was different in men and women ($P<0{\cdot}0001$). Education, region, size of place of residence, or income per person of a household (except in males, $P=0{\cdot}03$) had no effect on free-water-reserve.

Several parameters of 24 h water metabolism were affected by age (Table 3 and Fig. 1). Urine osmolality decreased with age in both sexes (men −3·0 mOsm/kg per year; women −2·4 mOsm/kg per year, results from the linear regression of age on osmolality, adjusted for energy intake, and physical activity, Table 3). Total water intake remained constant with age in men ($P=0{\cdot}2$); in women it increased ($P=0{\cdot}001$). Comparing men (women) above 65 years with those 18–24 years old, the proportion of beverages at 100 % total water input decreased slightly by 4·1 % (5·0 %; statistically not significant), whereas food water increased by 5·4 % (7·3 %). The proportion of metabolic water decreased slightly with −1·4 % (−2·3 %). The proportion of NRWL at 100 % water output decreased by 22·2 % (10·3 %), whereas the proportion of obligatory urine volume increased by 18·1 % (10·9 %) and the proportion of free-water-reserve remained almost unchanged at +4·0 % (−0·4 %). The excretion of urine solutes

Table 1. Anthropometric data, energy intake and results of water balance of men from a formerly representative sample of the German population (VERA study)

(Mean values and standard deviations and medians)

	18–24		25–49		50–64		≥65		All	
Age (years)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
n	79		308		168		84		639	
Weight (kg)	76	10	80	12	82	12	77	11	80	12
Height (cm)	181	7	178	7	174	6	171	7	176	8
Energy intake										
kcal/d	3180	736	2991	860	2749	665	2570	549	2895	782
kJ/d	13 305	3079	12 514	3598	11 502	2782	10 753	2297	12 113	3272
Median										
kcal/d	3124		2879		2692		2476		2806	
kJ/d	13 071		12 046		11 263		10 360		11 740	
Water intake										
Beverages (ml/d)	1535	632	1618	655	1485	601	1267	455	1526	620
Median	1391		1497		1396		1182		1399	
Food water (ml/d)	709	287	688	319	728	295	757	241	710	300
Metabolic water (ml/d)*	386	90	363	105	333	83	310	67	351	96
Total water intake (ml/d)	2630	754	2669	765	2546	668	2334	538	2588	720
Median	2493		2542		2433		2263		2483	
Total water/energy (ml/kcal)	0·83	0·17	0·91	0·23	0·94	0·22	0·92	0·19	0·91	0·22
Water excretion										
Non-renal water loss (ml/d)	1342	723	1224	838	891	759	673	585	1079	805
Urine volume (ml/d)	1288	571	1444	580	1655	627	1661	487	1509	594
Obligatory urine volume (ml/d)	1110	378	1182	365	1411	418	1408	322	1263	394
FWR (ml/d)	178	487	263	514	244	583	253	528	246	531
FWR 3rd percentile (ml/d)										
Single value	−368		−397		−517		−504		−427	
FWR <0 (ml/d)										
Single value (%)	47		37		45		39		40·4	
Urine solutes (mOsm/d)	915	313	918	283	992	294	928	212	939	283
Urine solutes/energy (mOsm/kcal)	0·30	0·11	0·32	0·12	0·38	0·14	0·37	0·10	0·34	0·13
Urine osmolality (mOsm/kg)	775	238	697	221	652	210	601	196	682	222
AI of total water (ml/d)										
Single value	2861		2939		2950		2768		2910	
AI total water/energy (ml/kcal)										
Single value	0·92		1·02		1·10		1·12		1·04	
Decrease of urine solutes (mOsm/d)										
Single value	304		309		364		332		319	

FWR, free-water-reserve; AI, adequate intake.

* Metabolic water (ml) = 0·41 × protein intake (g) + 0·55 × carbohydrate intake (g) + 1·07 × fat intake (g) + 1·17 × alcohol intake (g).

Table 2. Anthropometric data, energy intake and results of water balance of women from a formerly representative sample of the German population (VERA study)
(Mean values and standard deviations and medians)

	18–24		25–49		50–64		≥65		All	
Age (years)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
n	101		468		225		95		889	
Weight (kg)	61	9	65	12	69	12	68	11	66	12
Height (cm)	167	6	165	6	161	6	159	6	164	7
Energy intake										
kcal/d	2271	560	2174	627	2165	557	2072	483	2172	589
kJ/d	9502	2343	9096	2623	9058	2330	8669	2021	9088	2464
Median										
kcal	2260		2146		2165		2006		2149	
kJ	9456		8979		9058		8393		8991	
Water intake										
Beverages (ml/d)	1145	426	1249	524	1210	445	1130	409	1214	484
Meidan	1058		1190		1143		1053		1143	
Food water (ml/d)	529	217	607	221	740	234	724	223	645	235
Metabolic water (ml/d)*	275	68	262	76	259	67	248	58	261	72
Total water intake (ml/d)	1948	483	2118	622	2210	545	2102	516	2120	582
Median	1922		2055		2186		2038		2054	
Total water/energy (ml/kcal)	0·89	0·24	1·02	0·31	1·06	0·31	1·04	0·25	1·02	0·30
Water excretion										
Non-renal water loss (ml/d)	712	577	694	645	612	586	551	612	660	621
Urine volume (ml/d)	1237	656	1423	610	1598	568	1551	556	1460	609
Obligatory urine volume (ml/d)	813	290	977	323	1111	279	1105	309	1006	324
FWR (ml/d)	423	583	446	532	487	468	447	505	454	520
FWR 3rd percentile (ml/d)										
Single value	−163		−233		−201		−143		−211	
FWR <0 ml/d										
Single value (%)	19		20		17		17		18·9	
Urine solutes (mOsm/d)	669	239	754	243	781	212	731	204	749	233
Urine solutes/energy (mOsm/kcal)	0·30	0·11	0·38	0·17	0·39	0·15	0·37	0·14	0·37	0·16
Urine osmolality (mOsm/kg)	619	224	589	207	530	166	507	153	569	197
AI of total water (ml/d)										
Single value	2085		2288		2387		2181		2265	
AI total water/energy (ml/kcal)										
Single value	0·93		1·07		1·10		1·09		1·05	
Decrease of urine solutes (mOsm/d)										
Single value	134		180		141		95		158	

FWR, free-water-reserve; AI, adequate intake.
* Metabolic water (ml) = 0·41 × protein intake (g) + 0·55 × carbohydrate intake (g) + 1·07 × fat intake (g) + 1·17 × alcohol intake (g).

https://doi.org/10.1017/S0007114511004776 Published online by Cambridge University Press

slightly increased with age in both sexes. Concomitantly, an age-related increase in urine volume and a decrease of urine osmolality occurred.

In Table 4, the hydration status of German men and women is compared after adjusting the different parameters for the sex differences in energy intake (by multiplying the female parameters of hydration status with the age-group-specific male-to-female energy ratio). The more unfavourable hydration status of men, indicated by a lower free-water-reserve of 359 ml/d (Table 4), originated from a reduced total water intake of 238 ml/d and a male-specific higher NRWL (mainly sweat loss) of 199 ml/d which was partly compensated by a lower obligatory urine volume of 78 ml/d. The male-specific NRWL were lowest in men ≥65 years (Fig. 1).

Discussion

In the present study, the exceptional combination of dietary weighed records and concomitantly utilisable 24 h urine samples (*n* 1528) was used to estimate individual 24 h hydration status from young to old adulthood in a formerly representative population sample. These data were only available in the earlier, but not the most recent German food consumption survey. For the first time, age-related effects on hydration status and its complex determining factors could be evaluated, allowing us to draw a quite complete picture of the underlying physiological alterations and to derive a reliable basis for water intake recommendations.

Although ageing affected nearly all parameters of water metabolism, the hydration status itself – as sum of these parameters (water intake, metabolic water, NRWL, urine volume and obligatory urine volume) – did not change with age. Older men and women promoted water supply by the increased consumption of food with a high water and low energy content and counteracted it by an increased sodium intake[20]. Focusing on the side of water losses, the increased demand for obligatory urine volume by the age-related decrease of renal concentrating capacity is well known[10]. In males of our study, the age-related decrease in NRWL predominantly compensated the increase of obligatory urine volume; in females, this NRWL-decrease was less pronounced and did therefore only partly compensate increased obligatory urine volume. However, the remaining 'gap' of water requirements with increasing age in women was balanced by slightly increasing total water intakes – showing the remarkably precise regulation of an adequate hydration status throughout life.

Both overall and maximum sweating rates decreased with age and this was greater in males than females[11,12]. As a general physiological concept, it can be assumed that the difference of NRWL in men and women is the sum of a basic energy-related part and a male-specific part (see Methods – hydration status). In our study, the male-specific NRWL was remarkably lower in men above 50 years of age (114 ml/d) than in men younger than 50 years (about 270 ml/d, Table 4). In men ≥65 years old, energy-adjusted NRWL even fell below the values for women, resulting in negative male-specific NRWL of −10 ml/d. The well-known sex differences in sweating rates between men and women[21] that do not occur until puberty[22] lead to the suggestion that androgen activity may be one important factor involved in the change of the male-specific NRWL coinciding with adrenarche and declining in the elderly. Several authors concluded that male hormones (e.g. testosterone) enhance the sweat response and female hormones (e.g. oestradiol) inhibit it[23,24]. Immunohistochemical studies that detected expression of androgen receptors in eccrine sweat gland cells in adults support this hypothesis[25,26].

Mean 24 h urine osmolality, an indirect parameter of hydration status, was 682 mOsm/kg in men and 569 mOsm/kg in women. Mean osmolalities in spontaneous urine samples of two representative groups in Germany and the USA showed comparable levels[27,28]. Overall, however, mean urine osmolalities from small groups of healthy subjects

Table 3. Effect of age (β) on different parameters of water metabolism in the VERA study population

	Men (*n* 637)*				Women (*n* 884)*			
	β	SE	R^2	*P*†	β	SE	R^2	*P*†
Weight (kg)	0·06	0·03	0·01	0·07	0·16	0·03	0·05	<0·0001
Height (cm)	−0·20	0·02	0·24	<0·0001	−0·17	0·01	0·18	<0·0001
Water intake								
Beverages (ml/d)	−1·67	1·41	0·18	0·24	−0·97	1·05	0·04	0·36
Food water (ml/d)	3·58	0·66	0·22	<0·0001	4·78	0·44	0·30	<0·0001
Metabolic water (ml/d)‡	−0·02	0·02	0·99	0·33	−0·05	0·01	0·99	<0·0001
Total water intake (ml/d)	1·89	1·32	0·46	0·15	3·76	1·13	0·23	0·001
Water excretion								
Non-renal water loss (ml/d)	−7·12	1·61	0·35	<0·0001	−3·12	1·25	0·18	0·01
Urine volume (ml/d)	9·01	1·45	0·06	<0·0001	6·88	1·33	0·03	<0·0001
Obligatory urine volume (ml/d)	8·23	0·92	0·13	<0·0001	6·67	0·68	0·12	<0·0001
Free-water-reserve (ml/d)	0·78	1·33	0·02	0·56	0·22	1·15	0·003	0·85
Urine solutes (mOsm/d)	1·82	0·69	0·05	0·009	1·64	0·51	0·04	0·001
Urine osmolality (mOsm/kg)	−2·99	0·54	0·06	<0·0001	−2·35	0·43	0·04	<0·0001

* For two men and five women, no physical activity record was available.
† Results of the linear regression model with age (in years) as independent continuous variable, adjusted for energy intake and physical activity.
‡ Metabolic water (ml) = 0·41 × protein intake (g) + 0·55 × carbohydrate intake (g) + 1·07 × fat intake (g) + 1·17 × alcohol (g).

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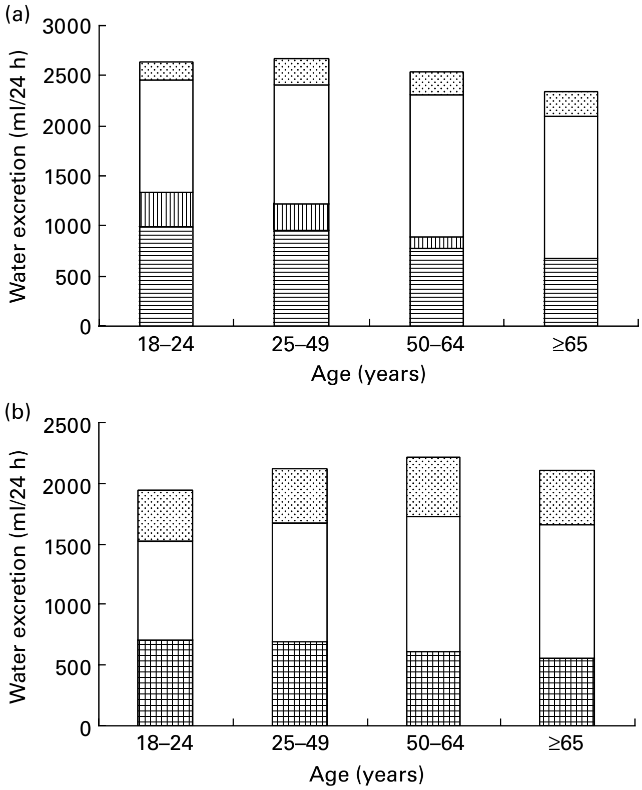

Fig. 1. Comparison of parameters of water excretion between (a) men and (b) women (*n* 1528), categorised according to age. Water excretion in urine: ▨, free-water-reserve; □, obligatory volume. Non-renal water loss: ▥, male specific; ▤, energy related; ▦, total.

from all over the world were surprisingly widely scattered, indicating the large intercultural differences of urine osmolality and hinting at remarkable differences in the hydration status of different societies. Mean urine osmolality ranged from 909 mOsm/kg (China, 50-year-old adults[29]), across 536 mOsm/kg (UK, adults with a mean age of 44 years[30]) to 392 mOsm/kg (Poland, children aged 5–18 years[10]). It is not possible to define a physiological or natural narrow urine osmolality range as it is always influenced by the cultural context and habitual food intake. Only after additionally considering 24 h urine volume, urine solute excretion and maximum urine osmolality, quantification of individual 24 h hydration status is possible.

One unexpected finding was the almost parallel age-related decrease in the mean urine osmolality seen in our study (men −3·0 mOsm/kg per year; women −2·4 mOsm/kg per year) and observed in standardised renal concentration tests (−3·4 mOsm/kg per year)[10] as well as in the USA (−3·9 mOsm/kg per year)[28]. These consistent findings in different cultures hint at a hypothetical physiological homeostatic mechanism that might regulate *ad libitum* drinking behaviour[31] to counterbalance the age-related decrease in renal concentration capacity. In consequence, the free-water-reserve remains constant.

The important feature of the presented concept of free-water-reserve and calculation of AI is that it is not only based on median total water intake and maximum concentration capacity of the kidneys, but considers individual 24 h hydration status and adds a safety margin to ensure adequate water intakes in nearly all (97 %) healthy persons of a population. This safety margin was defined by the 3rd percentile of free-water-reserve. No negative effects have to be expected by the resulting water surplus in individuals with a more favourable hydration status as water balance is regulated with precision in a wide range of water needs and intakes[32]. The fact that to date only a few countries included water in their dietary recommendations, and most of them not even considered renal concentration capacity but only based their recommendations on observed intakes[8], shows the need for research in more depth in this topic. The concept of free-water-reserve can serve as a suitable measure to derive specific water intake recommendations also outside Germany (considering the population-specific maximum renal concentration capacity).

According to the concept of free-water-reserve, 40 % of men and 19 % of women with a free-water-reserve below zero were at risk of hypohydration. These sex differences in hydration status are also common in other industrialised countries, where males usually show a higher urine osmolality than females[28,33]. Many biological and social differences such as higher physical activity and preference for food with a low water and high energy density (e.g. meat products, fast food) in men compared to women may be responsible for this phenomenon[34]. In the present study, the in-detail analysis of parameters of water metabolism revealed that the strikingly higher prevalence of negative free-water-reserve in

Table 4. Differences between mean male and mean female parameters of water metabolism after adjusting the values of women to the energy intake of men

Age (years)	18–24	25–49	50–64	≥65	All
Beverages (ml/d)	−68	−100	−51	−135	−92
Food water (ml/d)	−32	−147	−212	−141	−150
Metabolic water (ml/d)	1	3	4	2	3
Total water intake (ml/d)	−98	−245	−260	−273	−238
Male-specific non-renal water loss (ml/d)	345	269	114	−10	199
Obligatory urine volume (ml/d)	−28	−162	0	37	−78
Free-water-reserve (ml/d)	−414	−351	−374	−301	−359*
Total water losses (ml/d)	−99	−245	−260	−273	−238

* The lower free-water-reserve of men of 359 ml/d (100 %) originated from a reduced total water intake of 238 ml/d (66 %) and a male-specific higher non-renal water loss of 199 ml/d (55 %) partly compensated by a lower obligatory urine volume of 78 ml/d (22 %).

men was due to higher NRWL and lower total water intakes that were only partly compensated by a lower obligatory urine volume (Table 4).

In the investigated population, adequate total water intake would have been ensured if all men (women) drank two (one) additional cups of beverages per d. A corresponding decrease in the obligatory urine volume by a lower urinary excretion of solutes is no realistic option. In men (women), protein intake would have had to be reduced by 56 (28) g/d or NaCl intake by 9·3 (4·6) g/d. If AI of total water is to be attained by an exclusive increase in beverage consumption, median beverage intake in this German men (women) should have been 1826 (1354) ml/d. This value is, at least in men, clearly higher than the current German recommendation[6] of about 1400 ml – depending on age – for beverage intake. Current recommended total water intakes for older adults (51 to <65 and ≥ 65 years: 2250 ml/d, not sex-stratified) are nearly equivalent to the observed median total water intakes in the present study (2282 and 2126 ml/d for 50 to <65 and ≥ 65 years, respectively). However, these intake levels were accompanied by a prevalence of 29 and 27 % of the respective age group that was at risk of hypohydration (i.e. had a free-water-reserve <0 ml/d), indicating the need for a revision of the current German intake recommendations. Compared to the US recommendation of the Institute of Medicine of 3700 (2700) ml for men (women), our calculated AI are substantially lower, probably mainly due to the traditionally higher water intakes in the USA compared to Germany[35,36]. As US AI were only set on the observed median intake at which an adequate hydration was assumed (estimated by plasma osmolality), it cannot be excluded that also for the US population lower AI values would be sufficient.

The main limitation of our study is the fact that the data presented in this study were collected a considerable number of years ago, and therefore we cannot draw reasonable conclusions on the actual hydration status of the German population. However, the estimated values for an adequate total water intake should be independent of the time of data collection, as the corresponding results have been yielded with a physiologically based 'free-water-reserve and water balance' assessment tool. Furthermore, we could only estimate whole non-renal water losses and were not able to differentiate between stool water, insensible water loss by respiration and through the skin (i.e. perspiration or transepidermal diffusion) and sweat loss.

In this formerly representative German sample, younger and older adults showed a similar hydration status. Correspondingly, total water requirements did not increase with age, clearly indicating that there is no need for age-specific water intake recommendations for the elderly (in contrast to sex stratification which appears necessary). Nevertheless, the elderly run a higher risk of dehydration, partly because their perception of thirst seems to be impaired[37] and a larger water volume is necessary to excrete a given renal solute load[10]. It can be assumed that the physiological mechanisms which were responsible for the age-independent and widely constant total water requirements observed in this German sample (i.e. compensation of decreased renal concentration capacity by decreased NRWL, especially in men) may represent a universal finding with transferability also to other populations.

Acknowledgements

The present examination was supported by the Ministry of Science and Research, North Rhine-Westphalia, Germany. F. M. designed the study and together with S. A. J. wrote the report; A. W. was involved with analysis and interpretation of the study; H. B. provided administrative and statistical support; T. R. was responsible for the urine analysis and contributed to data interpretation. All authors contributed to the final version of the report. None of the authors has any conflict of interest in regard to this study. The authors thank Professor W. Kübler and Dr K.-J. Moch, Giessen, for their basic contributions to the NVS and VERA studies and the permission to use the respective public use files.

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British Journal of Nutrition