Water turnover in 458 American adults 40–79 yr of age


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Water turnover in 458 American adults 40–79 yr of age. Am J Physiol Renal Physiol 286: F394–F401, 2004. First published November 4, 2003; 10.1152/ajprenal.00295.2003.—Despite recent interest in water intake, few data are available on water metabolism in adults. To determine the average and range of usual water intake, urine output, and total body water, we administered 2H oxide to 458 noninstitutionalized 40- to 79-yr-old adults living in temperate climates. Urine was collected in a subset of individuals (n = 280) to measure 24-h urine production using p-aminobenzoic acid to ensure complete collection. Preformed water intake was calculated from isotopic turnover and corrected for metabolic water and insensible water absorption from humidity. Preformed water intake, which is water from beverages and food moisture, averaged 3.0 l/day in men (range: 1.4–7.7 l/day) and 2.5 l/day in women (range: 1.2–4.6 l/day). Preformed water intake was lower in 70- to 79 (2.8 l/day)- than in 40- to 49-yr-old men and was lower in 70- to 79 (2.3 l/day)- than in 40- to 49- and 50- to 59-yr-old women. Urine production averaged 2.2 l/day in men (range: 0.6–4.9 l/day) and 2.2 l/day in women (0.9–6.0 l/day). There were no age-related differences in results in women, but 60- to 69-yr-old men had significantly higher urine output than 40- to 49- and 50- to 59-yr-old men. Only the 70- to 79-yr-old group included sufficient blacks for a racial analysis. Blacks in this age group showed significantly lower preformed water intake than did whites. Whites had significantly higher water turnover rates than blacks as well. Multivariate regression indicated that age, weight, height, and body mass index explained 8% for preformed water intake (n = 22) and 9% for 24-h urine production (n = 222). These results demonstrate that water turnover is highly variable among individuals and that little of the variance is explained by anthropometric parameters.

water intake; twenty-four-hour urine; preformed water; insensible water

RECOMMENDATIONS FOR CONSUMPTION OF water and nonalcoholic beverages have recently been questioned (20). The interest in this issue is widespread because water is among the most important nutrients for the maintenance of life. The body uses water for transporting nutrients and wastes, lubrication, temperature regulation, and tissue structure maintenance. In addition, plentiful fluid consumption may be protective against diverse medical conditions, including kidney stones (26), constipation (2), colorectal cancer, premalignant adenomatous polyps (35), and bladder cancer (23).

Water deprivation results in life-threatening dehydration within a few days. Loss of body water exceeding 5% of body weight leads to decreased endurance, culminating in heat exhaustion (20, 25). Older vs. younger individuals have been shown to have a higher risk of developing dehydration than younger adults, which may be attributed to decreased total body water (TBW) with age (33), impaired renal fluid conservation (3), and physiological hypodipsia (8).

Despite the physiological importance of water to life, little is known about water intake and excretion patterns in free-living individuals, because fluid intake, particularly from noncaloric, nonalcoholic, and noncaffeinated beverages is poorly documented. The 1977–1978 National Food Consumption Survey (16) is one of the few sources of information on water intake, but these data are limited by unaccounted water found in foods and the use of a single 24-h dietary recall (14, 20). Moreover, nonquantitative intake from water fountains and the likelihood that many people consume fluids with little thought leads to underreporting (19).

An alternative approach that does not depend on self-reported intake is the use of hydrogen-labeled water turnover, a method used by comparative animal physiologists for decades to objectively measure water turnover in wild animals (24). The procedure begins with a bolus administration of isotopically labeled water, such as nonradioactive 2H oxide. Within 2–3 h, this tracer equilibrates with body water and provides a measure of the volume of the TBW pool (32). The labeled water is then excreted from the body through all routes of water loss and is diluted by unlabeled water through all routes of input. The time course of labeled water dilution provides a measure of water turnover (input and output) per unit of time (9, 24).

We combined data from two studies in healthy, free-living American adults across a broad age range to which 2H-labeled water was administered to measure total energy expenditure (TEE) using the doubly labeled water (DLW) technique (32). In one of these studies, two 24-h urine collections were made from many of these same participants using p-aminobenzoic acid to ensure complete collection. Preformed water intake was calculated from isotopic turnover and corrected for metabolic water and insensible water absorption from humidity. Preformed water intake, which is water from beverages and food moisture, averaged 3.0 l/day in men (range: 1.4–7.7 l/day) and 2.5 l/day in women (range: 1.2–4.6 l/day). Preformed water intake was lower in 70- to 79 (2.8 l/day)- than in 40- to 49-yr-old men and was lower in 70- to 79 (2.3 l/day)- than in 40- to 49- and 50- to 59-yr-old women. Urine production averaged 2.2 l/day in men (range: 0.6–4.9 l/day) and 2.2 l/day in women (0.9–6.0 l/day). There were no age-related differences in results in women, but 60- to 69-yr-old men had significantly higher urine output than 40- to 49- and 50- to 59-yr-old men. Only the 70- to 79-yr-old group included sufficient blacks for a racial analysis. Blacks in this age group showed significantly lower preformed water intake than did whites. Whites had significantly higher water turnover rates than blacks as well. Multivariate regression indicated that age, weight, height, and body mass index explained <12% of the gender-specific variance in water input or urine output, yet repeat measures indicated that within-individual coefficient of variation was 8% for preformed water intake (n = 22) and 9% for 24-h urine production (n = 222). These results demonstrate that water turnover is highly variable among individuals and that little of the variance is explained by anthropometric parameters.

water intake; twenty-four-hour urine; preformed water; insensible water

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acidi (PABA) to confirm completeness. These data are among
the first objective assessment of water turnover in American
adults and provide documentation of both the average and
range of water input and urine production.

METHODS

To evaluate the water requirements of normal adults, we combined
two data sets for which we measured water influx and efflux. The first
was the Health, Aging and Body Composition (Health ABC) study
conducted between July 1998 and August 2000 in Memphis, TN, and
Pittsburgh, PA. The main objective of Health ABC was to establish
relationships between the changes in body composition and the
development of early disabilities and mortality in the elderly. The
second was the Observing Protein and Energy Nutrition (OPEN)
study, which took place in Rockville, MD, between August 1999 and
March 2000. The main objective of the OPEN study was to assess the
structure of dietary measurement error associated with food frequency
questionnaires and 24-h dietary recalls in middle-aged adults. The
experimental protocols for the Health ABC and OPEN studies have
been previously described (6, 34). Data from these two studies were
combined.

Participants

To be eligible for the Health ABC study, elderly persons had to be
free of difficulties with activities of daily living and lower-extremity
functional limitations, defined as difficulty walking one-quarter mile
or climbing 10 steps without resting. Participants were recruited from
a random sample of white Medicare beneficiaries and all age-eligible
black community residents in designated zip codes in and around
Pittsburgh, PA, and Memphis, TN. The Health ABC study involved
3,075 participants aged 70–79 yr stratified by race (black, white) and
gender. Of these, a subgroup of 323 individuals, with the same race
and gender stratification, participated in an energy expenditure study
published elsewhere and thus were eligible for inclusion in the current
analysis of water metabolism (6). Of the 323 participants, data from
40 were excluded, including 9 who did not have usable isotopic data,
and 15 who did not have different physical characteristics, and 15 who
were over 79 yr old. Of the remaining 283 participants, 145 were
white and 138 were black. Because the Health ABC study included far
more blacks than the OPEN study and because the Health ABC study
included only one age group (70–79 yr olds), age-related data analysis
focused on white participants only.

The OPEN study involved 484 healthy participants aged 40–69 yr
(34). Among the 399 white participants in the OPEN study, 27
participants had unusable TEE and were excluded from the analysis.
Of the 372 remaining participants, 59 participants either did not have
24-h urine collected or their urine was deemed unusable due to
incomplete PABA recovery.

Together, there were 458 white participants who had complete data
and were included in the primary analysis, of which 145 participants
were from the Health ABC study and 313 from the OPEN study. In
addition, the 138 elderly black participants (70–79 yr olds) from the
Health ABC study were included in a secondary analysis to examine
race-related differences in preformed water intake in the elderly
population.

The Health ABC and OPEN protocols were reviewed and approved
by the institutions involved in each of the respective studies. All
subjects provided informed, written consent regarding their participa-
tion in the respective study.

Protocol

In both the OPEN and Health ABC studies, TEE was measured
using the DLW method according to protocols described elsewhere
(6, 34). Briefly, participants made two visits approximately 2 wk apart.

Before visit 1, participants fasted for 4 h and, in most instances,
overnight. Body mass was measured either in a clinic setting or in a
hospital, and baseline urine samples were collected. Then, a dose of
DLW was given orally to each participant. The dose provided ~1.9 g
10 atom% 15O water and 0.12 g 99.9 atom% 2H water/kg of estimated
total body water (32). Urine collections were taken either at 2, 3, and
4 h postdose (OPEN study) or 4 and 6 h postdose (Health ABC study)
to assess isotope equilibration in body water. Plasma samples were
collected at 4 h postdose in participants above 60 yr of age in the
OPEN study and in all participants in the Health ABC study. The
participants came back for visit 2 ~14 days later and provided
end-dose urine specimens. Urine samples were stored in cryogenic
stable tubes at −20°C before analysis by isotope ratio mass
spectrometry.

All participants in the OPEN study were asked to collect two 24-h
urine sets between visits 1 and 2. The urine was analyzed for urinary
nitrogen, potassium, and sodium. For 24-h urine collection, the
participants were asked to take three PABA pills orally, one at each
meal. The completeness of the 24-h urine collection was assessed
using the amount of PABA excreted in urine as described by Bingham
et al. (5). When PABA recovery was >85%, the subject’s urine was
considered complete. Recoveries of less than 70% were removed from
the analysis. When recoveries were between 70 and 85%, urine
samples were considered usable after their adjustment to 93% recov-
ery of PABA (n = 51 of 935 24-h urine collections) (18). All samples
in excess of 110% recovery by the colorimetric technique were
analyzed by HPLC to distinguish between PABA and acetaminophen,
a drug commonly taken by participants (n = 123 of the 935 urine
collections in the study).

Isotopic Analysis

The isotopic analyses have been previously described for Health
ABC as well as for OPEN (6, 36). Briefly, 2H analyses were per-
formed by chromium reduction according to Schoeller et al. (30) using
a dual-inlet isotope ratio mass spectrometer (Delta Plus Mass Spec-
rometer, Finnigan MAT, San Jose, CA). 15O enrichments were
measured by CO2 equilibration on a Delta-S isotope ratio mass
spectrometer (Finnigan MAT) through a continuous-flow inlet system
developed in the laboratory (30). To protect against possible interfer-
ence from postvoid residual volume, plasma specimens were collected
from the participants who were in their seventh and eighth decades of
life. Urine analyses were used unless the enrichment differed by
>2%; plasma enrichment was used for calculating TBW. Agreement
was observed in 87% of participants.

Calculations

TBW. The isotopic dilution spaces (N) of 2H and 15O were calcu-
lated according to Cole and Coward (7)

$$N (kg) = \frac{(W A/1,000a \delta_d - \delta_d)(\delta_c - \delta_p)}{\delta_c - \delta_p}$$

where W is water (g) used to make a dilution of the dose water; A is
the dose water (g) administered to the participant, and a is the dose
water (g) used in the dilution; \(\delta_d\) is the isotopic abundance of the
diluted dose water; \(\delta_d\) is the isotopic abundance of tap water used in
dilution; \(\delta_c\) is the isotopic abundance of postdose specimen; and \(\delta_p\)
is the isotopic abundance of the predose specimen. Isotopic abundances
are measured in permil units (\(\delta_{/\text{Perm}} = (R/R_{\text{r}} - 1) \times 1,000\), where R is the
ratio of heavy to light hydrogen isotope in the sample (R) and standard
(Rr)). The ratio of 2H to 15O dilution spaces averaged 1.034 ± 0.018.

TBW was calculated as an average of the 2H dilution space (\(N_2\)) and
the 15O dilution space (\(N_1\)) after a correction for in vivo isotopic
exchange using the equation (28)

$$\text{TBW (kg)} = (N_1/1.007 + N_2/1.042)/2$$

TEE. DLW-derived carbon dioxide production (rCO2) was calcu-
lated according to Schoeller et al. (31)
Table 1. Mean anthropometric and TBW values of 458 white participants: 251 men and 207 women

<table>
<thead>
<tr>
<th>Variables</th>
<th>Age, yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40–49</td>
</tr>
<tr>
<td></td>
<td>Men</td>
</tr>
<tr>
<td>n</td>
<td>66</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>83±13</td>
</tr>
<tr>
<td>Height, cm</td>
<td>178±7</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>26±4</td>
</tr>
<tr>
<td>TBW, kg</td>
<td>42±5*</td>
</tr>
</tbody>
</table>

Values are means ± SD, n. No. of subjects; BMI, body mass index; TBW, total body water. Data with the same superscript symbols are significantly different within gender (P < 0.05).

\[ rC_{O2} \text{(mol/day)} = 0.455 \times TBW \times (1.007k_c - 1.041k_d) \]

where TBW is total body water (moles), and \( k_c \) and \( k_d \) are the oxygen and \(^2\text{H} \) elimination rates per day, respectively. TEE was derived from Wier’s equation, assuming a respiratory quotient (RQ) of 0.86.

**Water turnover.** Water turnover (kg/day) in the body was calculated from the \(^2\text{H} \) dilution space and elimination rate (9)

\[ rH_{2O} = N_d \times k_d \]

and

\[ k_d = \frac{(\ln (c_i - c_f))/t_i}{t_f - t_i} \]

\( N_d \) is the dilution space measured using \(^2\text{H} \), and \( k_d \) is the fractional turnover rate of \(^2\text{H} \) in the body water after equilibration, where \( c_i \) is the final enrichment of \(^2\text{H} \) in the urine, \( c_f \) is the initial enrichment of \(^2\text{H} \) in the urine, \( t_i \) is the final time point, and \( t_f \) is the initial time point. In the calculation of water turnover, equality between the water influx and efflux was assumed.

**Estimation of water influx.** Water influx is accounted for by metabolic water, inspiratory water (moisture content of inhaled air), transcutaneous water intake (water absorbed by the skin), and preformed water intake. Analysis of variance and post hoc Fischer’s protected least significance test were performed to determine the effect of age on preformed water intake. Intra-individual variability was determined from the coefficient of variation between

\[ \text{Transcutaneous water influx} = (0.18 \times \text{absolute humidity}/21.7) \times \text{BSA} \times 1.44 \]

where 0.18 is the rate of transcutaneous absorption in grams per square meter of body surface area in an atmosphere saturated with water vapor (21.7 mg/l). BSA is the body surface area (m²) estimated from the Dubois formula (9). A clothing factor of 50% was assumed, as clothing would decrease the rate of evaporation through the skin.

**Preformed water intake.** Preformed water was calculated by the difference between water turnover (\( rH_{2O} \)) and the sum of all the above-calculated values (metabolic water intake, inspiratory water intake, and transcutaneous water intake).

**Statistical Analysis.** Regression analyses were used to determine the effect of anthropometric variables [height, weight, age, and body mass index (BMI)] on the preformed water intake. Analysis of variance and post hoc Fischer’s protected least significance test were performed to determine the effect of age on preformed water intake. Intra-individual variability was determined from the coefficient of variation between
Table 2. Mean water turnover and influx values in men and women by decade of age

<table>
<thead>
<tr>
<th>Age, yr</th>
<th>n</th>
<th>Mean Water Turnover, l/day</th>
<th>Metabolic Water, l/day</th>
<th>Inspired Water, l/day</th>
<th>Transcutaneous Water, l/day</th>
<th>Preformed Water, l/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40–49</td>
<td>66</td>
<td>3.81±1.24</td>
<td>0.39±0.07</td>
<td>0.11±0.02</td>
<td>0.09±0.04</td>
<td>3.22±1.19</td>
</tr>
<tr>
<td>50–59</td>
<td>58</td>
<td>3.63±0.89</td>
<td>0.38±0.06</td>
<td>0.11±0.02</td>
<td>0.10±0.01</td>
<td>3.03±0.85</td>
</tr>
<tr>
<td>60–69</td>
<td>56</td>
<td>3.55±0.92</td>
<td>0.35±0.06</td>
<td>0.10±0.02</td>
<td>0.10±0.01</td>
<td>3.00±0.87</td>
</tr>
<tr>
<td>70–79</td>
<td>71</td>
<td>3.35±0.78</td>
<td>0.33±0.05</td>
<td>0.13±0.05</td>
<td>0.13±0.04</td>
<td>2.75±0.77</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40–49</td>
<td>49</td>
<td>3.26±0.78</td>
<td>0.33±0.06</td>
<td>0.10±0.02</td>
<td>0.08±0.01</td>
<td>2.75±0.75</td>
</tr>
<tr>
<td>50–59</td>
<td>48</td>
<td>3.03±0.77</td>
<td>0.28±0.05</td>
<td>0.08±0.01</td>
<td>0.08±0.01</td>
<td>2.58±0.73</td>
</tr>
<tr>
<td>60–69</td>
<td>36</td>
<td>2.87±0.66</td>
<td>0.28±0.04</td>
<td>0.08±0.01</td>
<td>0.08±0.01</td>
<td>2.42±0.65</td>
</tr>
<tr>
<td>70–79</td>
<td>74</td>
<td>2.79±0.66</td>
<td>0.25±0.04</td>
<td>0.10±0.04</td>
<td>0.11±0.04</td>
<td>2.33±0.64</td>
</tr>
</tbody>
</table>

Values are means ± SD. n, No. of subjects. Preformed water was calculated by the difference between water turnover and the sum of the other influx variables.

The two 24-h urine collections. Statistical analyses were performed using STATVIEW software, version 5.0.1. Results are expressed as means ± SD. A P value of ≤0.05 was considered significant.

RESULTS

The anthropometric characteristics of 458 participants from the Health ABC and the OPEN study are presented in Table 1.

Water Influx

Percentile distributions of preformed water intake from 251 male and 207 female participants are shown in Fig. 1. Individuals varied widely in their preformed water intake, ranging from 1.4 to 7.7 l/day (mean 3.0 ± 0.9) for men and from 1.2 to 4.6 l/day (mean 2.5 ± 0.7) for women. Average estimated values for water influx components, i.e., metabolic water intake, inspired water intake, transcutaneous water intake, and preformed water, calculated by difference, are shown in Table 2 by age group and gender. Water influx values range from 1.9 to 8.6 l/day (mean 3.6 ± 0.9) in men and from 1.6 to 5.2 l/day (mean 3.0 ± 0.7) in women.

Fig. 2. Percentile distribution of preformed water intake for each age group within genders. The 90th, 75th, 25th, and 10th percentiles are indicated by the top error bar, the top of the box, the bottom of the box, and the bottom error bar, respectively. The median is indicated by the horizontal line dividing the box. Yr old. Age groups with the same letter differ significantly within genders (P < 0.05).

Physical characteristics of the 70- to 79-yr-old black and white participants are presented in Table 4. Among all the 70–79 yr olds, preformed water intake was significantly lower in blacks than whites in both men and women (P < 0.05). Whites had significantly higher water turnover rates than blacks as well (P = 0.01). Gender differences among blacks in this limited group were similar to those of whites with respect to their weight, height, BMI, and TBW.

Body composition data were available for only the 70- to 79-yr-old participants. To ascertain whether these elderly black and white participants were subjected to chronic, hyperosmotic...
dehydration secondary to low water intake, we divided the elderly cohort into quintiles of preformed water intake and compared it with the hydration of fat free mass [FFM; measured using dual X-ray absorptiometry (DXA)] among 70–79 yr olds. The hydration of FFM (TBW/MM) did not differ between quintiles of preformed water intake. Although the difference was not significant, the hydration of the lowest quintile of water intake averaged 0.3% greater than the highest quintile, with a group SD of 0.4%. As water intake was quintile, with a group SD of 0.4%. As water intake was

quintile of water intake averaged 0.3% greater than the highest difference was not signifi
cant, the hydration of the lowest water intake

Water Ef

Average calculated values for water efflux and its components are shown in Table 5 by age and gender. Fecal losses were artifactually equal in all the participants (0.07 l/day) because we used the same assumptions of fecal weight and moisture content (1, 29). Insensible water losses (transcutaneous, expiratory, and sweat losses), calculated by difference, were highly variable among age groups. The 60- to 69-yr-old men showed significantly lower insensible water losses compared with the 40- to 49- and 50- to 59-yr-old men (P < 0.0001 and 0.006, respectively), and the 60- to 69-yr-old women showed significantly lower insensible water losses than the 40-
to 49-yr-old women (P = 0.004).

Distributions of urine volume in 134 women and 180 men from the OPEN data are shown in Fig. 3. The urine output in men was 0.62–4.94 l/day (mean 2.18 ± 0.94) and in women was 0.91–4.87 l/day (mean 2.19 ± 0.75).

Intraindividual variability of 24-h urine output was calculated using two 24-h urine collections from a subset of 90 women and 133 men from the OPEN study. The mean difference between the two 24-h urine collections was 34.9 ml in women and 133 ml in men (P < 0.001). Urine output did not vary significantly with age among women (P > 0.05), but the 60- to 69-yr-old men had significantly higher urine output than the 40- to 49- and 50- to 59-yr-old men, as seen in Fig. 4 (P = 0.04 and 0.02, respectively).

DISCUSSION

This is an unusually large set of objective data on water intake and urine production for American adults. Data on water turnover have proven to be elusive in the past because objective and accurate measures of water intake and urine production were lacking. Virtually no large population data are

Table 3. Univariate regression analysis of preformed water intake

<table>
<thead>
<tr>
<th>Predictive Variable</th>
<th>r²</th>
<th>Intercept</th>
<th>Coefficient</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight, kg</td>
<td>0.052</td>
<td>0.673</td>
<td>0.615</td>
<td>&lt;0.0003</td>
</tr>
<tr>
<td>Age, yr</td>
<td>0.03</td>
<td>3.877</td>
<td>−0.015</td>
<td>0.0043</td>
</tr>
<tr>
<td>Height, cm</td>
<td>0.008</td>
<td>0.486</td>
<td>0.014</td>
<td>NS</td>
</tr>
<tr>
<td>BMI</td>
<td>0.032</td>
<td>1.868</td>
<td>0.041</td>
<td>0.0034</td>
</tr>
<tr>
<td>Urine output (n = 164)</td>
<td>0.512</td>
<td>0.032</td>
<td>0.693</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight, kg</td>
<td>0.012</td>
<td>2.084</td>
<td>0.006</td>
<td>NS</td>
</tr>
<tr>
<td>Age, yr</td>
<td>0.071</td>
<td>3.481</td>
<td>−0.016</td>
<td>0.0001</td>
</tr>
<tr>
<td>Height, cm</td>
<td>0.014</td>
<td>−0.116</td>
<td>0.016</td>
<td>NS</td>
</tr>
<tr>
<td>BMI</td>
<td>0.004</td>
<td>2.173</td>
<td>0.012</td>
<td>NS</td>
</tr>
<tr>
<td>Urine output (n = 116)</td>
<td>0.465</td>
<td>0.349</td>
<td>0.709</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

n, No. of subjects; NS, not significant.

*Significant difference between black men and women. †Significant difference between black women and white men. §Significant difference between black men and white men. $Significant difference between black men and white men. Data with the same superscript symbols significantly differ between gender and racial categories (P < 0.05).

Table 4. Mean anthropometric and TBW values by race and gender among 70- to 79-yr-old participants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Black Men</th>
<th>Black Women</th>
<th>White Men</th>
<th>White Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>72</td>
<td>66</td>
<td>71</td>
<td>74</td>
</tr>
<tr>
<td>Average weight, kg</td>
<td>81.9 ±14.3*</td>
<td>73.8 ±16.6*‡</td>
<td>82.7 ±12.5†</td>
<td>68.2 ±13.9</td>
</tr>
<tr>
<td>Height, cm</td>
<td>174 ±6.9*</td>
<td>160 ±6.5*‡</td>
<td>174 ±7.8†</td>
<td>161 ±5.9</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>27.3 ±4.5</td>
<td>28.7 ±5.8</td>
<td>27.4 ±4.3</td>
<td>26.5 ±5.3</td>
</tr>
<tr>
<td>TBW, kg</td>
<td>40.8 ±5.5*‡</td>
<td>30.5 ±4.6*‡</td>
<td>39.4 ±4.8‡</td>
<td>28.1 ±3.9§</td>
</tr>
<tr>
<td>rH₂O, l/day</td>
<td>3.07 ±0.7*</td>
<td>2.56 ±0.6*‡</td>
<td>3.35 ±0.8‡</td>
<td>2.79 ±0.7</td>
</tr>
<tr>
<td>Preformed water, l/day</td>
<td>2.5 ±0.6*</td>
<td>2.1 ±0.6*‡</td>
<td>2.8 ±0.8‡</td>
<td>2.3 ±0.6</td>
</tr>
</tbody>
</table>

Values are means ± SD, n. No. of subjects.

Fig. 3. Distribution of urinary volume in 133 women and 180 men 40–69 yr of age. The urine output (mean ± SD) of the men varied between 0.62 and 4.94 l/day (2.18 ± 0.94) and that of women varied between 0.91 and 4.87 l/day (2.19 ± 0.75).

AJP-Renal Physiol • VOL 286 • FEBRUARY 2004 • www.ajprenal.org
available regarding individual consumption of drinking water in the United States since the 1977–1978 National Food Consumption Survey data (6), and these data are based on self-reports as against the objective data presented here. Our analysis showed that preformed water intake varied from as low as 1.2 l/day to as high as 7.7 l/day among 458 individuals 40–79 yr old. There was a 15 ± 5 ml decrease in preformed water intake with every decade increase in age among both men and women. The decrease, however, was small and thus only discernable because of the large sample size. Interestingly, the preformed water intake in these individuals did not show a major change when the values were adjusted for their FFM, indicating that in this large sample older subjects are not prone to any greater risk of chronic low water intake than younger subjects. Similarly, the 24-h urinary output values did not show any age-related differences in women. The 24-h urinary output of 40- to 49- and 50- to 59-yr-old men, however, was significantly lower than in the 60- to 69-yr-old men.

Even though there were statistically significant age effects on water turnover and preformed water intake, the differences between the age groups were small, and thus the age-independent mean values for water intake in adults between the ages of 40 and 79 yr can be compared with the National Research Council daily recommendations for water intake (10). For this comparison, water input was expressed in milliliters per kilocalorie of energy expended. The water input per kilocalorie of energy expended in the current study was 1.1 ml/kcal–1·day–1 in men (TEE = 2,746 ± 488 kcal/day) and 1.2 ml/kcal–1·day–1 in women (TEE = 2,138 ± 392 kcal/day), which is slightly higher than the National Research Council’s recommendation of 1 ml/kcal of energy expended (11). Many (38%) of our participants, however, had water intakes that were lower than recommended. Despite this, hyperosmotic dehydration was not observed. Unfortunately, our primary study design was not directed toward the determination of water requirements, and hence we do not have data on health indicators such as urine osmolality, stone formation, or urinary tract infection rates, all of which are good predictors of hyperosmotic conditions and dehydration (12). These observations therefore do not directly refute the NRC recommendation.

It has often been recommended that individuals consume at least eight 8-oz glasses of water each day (≈1.9 l/day) (37); however, it is not clear what data formed the basis for this recommendation. Our data indicate that it is not based on an averaged actual intake. If an intake of 64 oz of water were combined with the typical water content of food (≈1 l/day) (10) and individuals drank no other beverages, intake would be about ≈3 l/day or 1.2 ml/kcal–1·day–1 (as for our participants). If they drank other beverages in addition to the 64 oz of water, intake would be even greater. Preformed water intake at or above this level was observed in only 36% of our participants. Therefore, it is clear from these data that the recommendation that individuals consume eight 8-oz glasses of water daily is not consistent with observed water intake in these healthy adults living in the U.S.

Our findings indicate that preformed water intake and urinary output were highly variable among individuals. Regression analysis of preformed water with urinary output and anthropometric variables (age, weight, BMI, and height) showed that only 4–8% of the variability was explained by anthropometric variables. Thus it is likely that individual behavior and not the physiological differences we investigated account for most of these large interindividual variations. In addition, we found that urinary output accounted for 66% of the total water efflux, rather than the 50% assumed in the past (10). This percentage, however, is likely to be dependent on preformed water intake and ambient conditions.

It is unlikely that the large variability results from measurement error. The methods used herein to measure preformed water intake and urinary output are more accurate than methods used in previous research. The urine collection employed PABA recovery to confirm complete collections and thus reduced errors associated with incomplete collections. The intake data are derived not from self-report but from the 2H2O technique, and this has been validated for accuracy in animal models and humans (7, 23, 31).

An important caveat is that the 2H2O method does not directly measure water intake. Preformed water intake constitutes only 16% of water intake, and transcutaneous water, which are estimated to constitute 16–18% of water influx volume. The assumptions made in these calculations are not perfectly accurate, but even if our assumption were in error by 25% for these minor routes of water metabolism, the relative error in preformed water intake.

Fig. 4. Percentile distribution of 24-h urine output for each age group within genders. The 90th, 75th, 25th, and 10th percentiles are indicated by the top error bar, the top of the box, the bottom of the box, and the bottom error bar, respectively. The median is indicated by the horizontal line dividing the box. Age groups with the same letter differ significantly within genders (P < 0.05).
would be <5%. As such, the accuracy of our estimates of preformed water intake is probably very high.

Our urinary output data should also be considered accurate. Normally, 24-h urine collections are prone to error due to incomplete collection; however, we reduced this error by employing PABA as a tracer for complete collection (4, 5, 17, 18). The average PABA recovery was 103 ± 14% for the data reported herein, indicating little mean collection error.

Perhaps the greatest limitation in our methods was the use of DXA to assess %hydration of FFM. DXA is a widely used method for measurement of body composition in humans (15). However, there is a limit in the use of DXA in estimating the hydration of FFM. Changes in fluid balance in the body cause a small systematic and predictable error in DXA soft tissue composition analysis and can result in a misassessment of dehydration in the body. In a validation study by Lukaski et al. (21), Sprague-Dawley rats were exposed to a variety of dietary stressors, and changes in body composition were measured using DXA, decrease in body mass, and hydration status. DXA underestimated the body mass and FFM by 3% and significantly overestimated the fat mass, the greatest errors occurring in treatment groups in which body mass was diminished and body hydration was decreased (21). In addition, %hydration of FFM is, by its very nature, an insensitive measure of dehydration. A decrease in the TBW by 2% of body weight in a person with 20% body fat will result in a 2.5% decrease in FFM and a 3.4% decrease in TBW. The combined effect is a decrease in FFM hydration of only 1%. Whether this amount of decrease in hydration is detectable by DXA and TBW in humans is questionable. Also, DXA is known to be sensitive to changes in electrolytes. If a hyperosmotic condition exists, as in thermal dehydration where there is an increased loss of fluid relative to electrolytes, the changes in X-ray absorptions can lead to an overestimation of FFM by DXA (27), thereby masking the hydration status differences among age groups. The potential impact of this confounder cannot be ascertained in our data set.

Other limitations of this study include the fact that the participants were selected from only three geographical areas (suburban Washington, DC, Pittsburgh, PA, and Memphis, TN) and that most were studied in fall or winter. Thus our data are limited both geographically and seasonally. Individuals living in hot climates would be expected to have increased sweat loss, decreased urine loss, and/or increased preformed water intake. Thus the data presented here hold only for adults doing low to moderate exercise with little exposure to extremes of temperature and humidity. Racial differences were reported only in the elderly subjects (70–79 yr olds) due to nonavailability of data in the younger age groups. Differences could not be explained by body size, but we did not investigate other causes. These differences could be due to cultural differences with regard to fluid intake or differences in socioeconomic status. However, the above are purely speculations, and further studies need to be done to identify the racial effect on fluid intake.

One of our aims of this analysis was to test whether the elderly had low intakes of water that might predispose them to chronic dehydration. We found that, on average, the oldest group of individuals had a preformed water intake that was 98% that of the younger group of individuals when expressed per kilocalorie of energy expended. Although our methods had limited sensitivity, we did not find any evidence of dehydration in the 70- to 79-yr-old group, despite the majority of the individuals having intakes less than the commonly used suggested eight 8-oz glasses of water each day. Furthermore, recommendations to increase fluid intake to eight 8-oz glasses of water in the elderly may not be prudent because the elderly have an elevated risk of overhydration due to an attenuated osmoregulatory mechanism (22). Instead, it may be better to concentrate on recommendations for increasing fluid intake during periods of acute thermal stress (8).

This is a large set of objective data on water intake and urine production in adults using methods to assess preformed water input and urine production that are more accurate than those used to assess these parameters in the past. We found no evidence of chronic hyperosmotic dehydration among the elderly with lower than average preformed water intake, although the sensitivity of DXA to small changes in hydration is limited. Furthermore, these data do not address the observation that elderly individuals are more prone to dehydration under acute stresses of reduced fluid intake and excessive fluid losses (8). Although our findings are not applicable to all climates and regions, these data provide the largest sample to date for preformed water intake from beverages and foods and urinary output for adults between 40 and 79 yr of age.

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