Hair and Toenail Arsenic Concentrations of Residents Living in Areas with High Environmental Arsenic Concentrations

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Surface soil and groundwater in Australia have been found to contain high concentrations of arsenic. The relative importance of long-term human exposure to these sources has not been established. Several studies have investigated long-term exposure to environmental arsenic concentrations using hair and toenails as the measure of exposure. Few have compared the difference in these measures of environmental sources of exposure. In this study we aimed to investigate risk factors for elevated hair and toenail arsenic concentrations in populations exposed to a range of environmental arsenic concentrations in both drinking water and soil as well as in a control population with low arsenic concentrations in both drinking water and soil. In this study, we recruited 153 participants from areas with elevated arsenic concentrations in drinking water and residential soil, as well as a control population with no anticipated arsenic exposures. The median drinking water arsenic concentrations in the exposed population were 43.8 µg/L (range, 16.0–73 µg/L) and median soil arsenic concentrations were 92.0 mg/kg (range, 9.1–9,900 mg/kg). In the control group, the median drinking water arsenic concentration was below the limit of detection, and the median soil arsenic concentration was 3.3 mg/kg. Participants were categorized based on household drinking water and residential soil arsenic concentrations. The geometric mean hair arsenic concentrations were 5.52 mg/kg for the drinking water exposure group and 3.31 mg/kg for the soil exposure group. The geometric mean toenail arsenic concentrations were 21.7 mg/kg for the drinking water exposure group and 32.1 mg/kg for the high-soil exposure group. Toenail arsenic concentrations were more strongly correlated with both drinking water and soil arsenic concentrations; however, there is a strong likelihood of significant external contamination. Measures of residential exposure were better predictors of hair and toenail arsenic concentrations than were local environmental concentrations. *Key words:* **arsenic, exposure, hair, risk factors, toenail.** *Environ Health Perspect* **111:187–193 (2003). [Online 25 October 2002]**
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Arsenic concentrations in soil and water in many rural areas of Australia are high because of both natural geohydrologic conditions and the presence of contamination resulting from gold mining operations, industrial wastes, and runoff from agricultural land [Australian Water Resources Council (AWRC) 1982; Department of Manufacturing and Industry Development (DMID) 1991]. Surface soil and groundwater have been found to contain high concentrations of arsenic in areas where gold mining has been undertaken (DMID 1991). Town water supplies that are based on groundwater extraction have been found to have elevated arsenic concentrations in some rural areas of Victoria (DMID 1991). The relative importance of human exposure to these sources has not been established in Australia.

Because arsenic accumulates in hair and nails and has limited mobility once incorporated into keratin, their analysis for arsenic concentration is used as an index of longer term (several months) exposure to inorganic arsenic (Koons and Peters 1994; Takagi et al. 1988). Analysis of nails is considered to be a good reflection of long-term exposure because nails—after rapid growth—remain isolated from other metabolic activities in the body (Takagi et al. 1988).

Fingernails and toenails have, therefore, been purported to be preferable markers for assessment of long-term exposure and as measures of absorption. Toenails are also considered a preferable biologic medium because of ease of collection, storage convenience, their usefulness in estimating intake of minerals in nutritional studies, ease of handling, reproducibility of later analysis results, and the potential for less external contamination compared with hair or fingernails (Garland et al. 1993; Hunter 1990; Karagas et al. 1996; Takagi et al. 1988). Each clipping represents several weeks of growth, and because nails from various toes vary in the time between formation and clipping, nails from all 10 toes are likely to reflect exposure integrated over a 2–12 month period (Hunter 1990).

Several studies have investigated chronic exposure to arsenic using hair and toenails as measures of exposure to elevated concentrations in the environment. Where long-term exposure has been measured using hair as the biomarker of choice, an increase in hair arsenic concentration has been observed associated with increasing arsenic concentrations in drinking water (Armienta et al. 1997; Chiou et al. 1997; Lin et al. 1998; Olgiun et al. 1983; Valentine et al. 1979). Fewer studies have explored the relationship between exposure to contaminated soil and hair arsenic concentrations. Diaz-Barriga et al. (1993) reported an increase in hair arsenic concentrations associated with an increase in soil, dust, and air arsenic concentrations. They were not able to distinguish among the sources contributing to the hair arsenic concentrations.

The major concern with using hair or nails is the ability to account for the presence of exogenous arsenic, which may cause an overestimation of body burden (Agahain et al. 1990; Vahter and Lind 1986; Yamauchi et al. 1989). On the contrary, because of the potential presence of exogenous arsenic, hair and toenails have been considered useful markers for environmental contamination, as opposed to personal exposure.

A variety of techniques have been tried to wash off external arsenic, with varying degrees of success. Washing is also complicated by differing hair types and their response to the solution used to wash the hair (de Peyster and Silvers 1995). The large range of values reported may reflect varying sampling preparation and analytical and digestion procedures. Despite these limitations, hair and toenail arsenic concentrations remain the only currently available markers for long-term exposure to inorganic arsenic.

In this study we aimed to investigate long-term exposure of residents living in areas with high environmental arsenic concentrations. We also aimed to identify the sources of exposure that make important contributions to hair and toenail arsenic concentrations of residents in areas with elevated arsenic concentrations.

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Methods

The study was a cross-sectional survey of hair and toenail arsenic concentrations in residents living in rural areas with varying environmental arsenic concentrations as well as a control population. Ethics approval for this study was obtained from the Monash University Standing Committee on Ethics in Research on Humans (approval no. 82/95).

We selected areas based on the presence of arsenic above established investigation and intervention criteria. We defined three exposure groups to account for the different combinations of soil and water arsenic concentrations. The control population was recruited from an area with similar demographic characteristics to the exposed area and where there were no industries or hydrogeologic conditions that would indicate elevated concentrations of arsenic in the environment. The four categories were as follows:

- High water As, where one or more samples of ground, surface, or tap water samples had arsenic concentrations > 10 µg/L, the current World Health Organization (WHO) standard for arsenic in drinking water (WHO 1996), and where median soil arsenic concentrations were below the Australian and New Zealand Environment Council and National Health and Medical Research Council Australia (ANZECC/NH&MRC) background concentration of 30 mg/kg (ANZECC/NH&MRC 1992)
- High soil As, where one or more soil samples had arsenic concentrations greater than the ANZECC/NH&MRC (1992) health investigation guideline of 100 mg/kg and median ground, surface, and tap water arsenic concentrations were < 10 µg/L
- High water/high soil As, where one or more ground, surface, or tap water samples had arsenic concentrations > 10 µg/L and one or more soil samples had arsenic concentrations > 100 mg/kg
- Control, which was a comparison area with no activities or industry to indicate the presence of arsenic.

All houses in the identified areas were systematically visited for recruitment until the sample size was reached or no more residents were available for recruitment. If a resident was not at home when called on, a later visit was made. Home visits occurred during the week and weekends to maximize the chances of residents being home.

A total of 153 participants provided 241 hair and 230 toenail samples. Because of a limited budget, we analyzed a random selection of samples from participants in each of the four exposure categories. This was done by using random number generation and selection using SPSS statistical software (SPSS Advanced Statistics, Version 7.5; SPSS Inc., Chicago, IL, USA). We do not know whether the subset of samples was significantly different from those not analyzed.

Because of insufficient sampling, 28 hair samples and 15 toenail samples were unable to be analyzed, leaving 209 hair samples and 83 toenail samples for analysis; 77% of participants of the whole population provided one hair or toenail sample, and 30% provided two hair or toenail samples.

Residents who agreed to participate were given an information sheet outlining the study and their participation and were asked to provide formal written consent. Parental consent was required for children (younger than 18 years) to take part in the study.

Participants were required to have resided in the house visited for longer than 2 months at the time of recruitment, to avoid underestimating long-term arsenic exposure as measured by hair and toenail arsenic concentrations.

Participants in the high-water and high-soil/high-water areas who reported consumption of a contaminated water supply as their main drinking water source were eligible. Residents were excluded if they reported consumption of tank water or another uncontaminated source in the high-water exposure areas, to reduce misclassification of exposure.

Data collection. **Hair samples.** Participants were asked to provide two hair samples during the year. Both samples represented growth over a 4-month period. Full strands of hair were taken from several locations from the nape of the neck.

To minimize the difficulties in interpreting data arising from people with varying hair length, hair longer than 3 cm from the scalp was excluded; 500 mg of hair was required for analysis (a small handful of hair or a pencil thickness of 3 cm length). Where hair was short, several hair cuts were combined to form one sample over a 4-month period between the different sample collection times. Hair was placed into small plastic bags by participants.

Toenail samples. Participants were asked to provide two toenail clipping samples (500 mg) during the year. The samples were to represent growth over a 4-month period. Toenail clippings from all 10 toes were collected by participants in new biohazard bags.

Questionnaire. Each participant was asked to complete a self-administered questionnaire, which asked for demographic characteristics such as age, sex, and diet and information on potential exposure sources, such as source of drinking water, water consumption patterns, consumption of homegrown produce, smoking patterns, location of residence, and occupation. Participants were required to record whether they ate a given food and, if so, how many portions in an average week, in a food frequency questionnaire. The foods were based on those found to contain arsenic in the NH&MRC market basket survey and included fish, canned fish, and seaweed products (NH&MRC/FDA 1990). The questionnaire did not differentiate between freshwater or seawater fish.

Drinking water samples. In each of the two sampling periods, drinking water samples were collected in acid-washed 500-mL polyethylene bottles from the kitchen tap (or other designated drinking water source, excluding bottled water) after allowing the water to run through the pipes for several seconds. The bottle was filled to the top, the lid replaced, and the label completed and affixed. The water samples were placed in a refrigerated container for transport.

Soil and dust samples. One composite surface soil sample was taken from each household. Eight locations in a grid pattern were sampled and combined for analysis using a 1.5-inch bore auger in a clear heavy-duty plastic bag. Dust was collected by emptying the contents of the vacuum cleaner and placing it in a large clear heavy-duty plastic bag. The 63-µm fraction of dust was collected by settling of the heavier fractions. This method enabled sufficient sample to be collected for analysis and was the most cost-effective option.

Sample treatment and chemical analysis. Hair and toenail samples were washed twice with deionized water (5 mL) and then methanol (5 mL) to reduce any external material without leaching arsenic out of the hair or toenail. The hair was dried and digested by boiling in a mixture of nitric/perchloric/sulfuric acids for 3 hr until the acid evaporated. The remaining volume was reconstituted to 25 mL with HCl and an aliquot was analyzed. Total arsenic was detected by continuous-flow hydride generation atomic absorption spectrometry (AAS) using a GBC Scientific Atomic Absorption Spectrophotometer 906 and a GBC Hydride Generator 906 (GBC Scientific, Melbourne, Australia).

The analytical limit of detection for arsenic in hair and toenails was 0.1 mg/kg. The detection limit for arsenic in drinking water was 1 µg/L.

We mixed, sieved, and freeze-dried composite soil samples and selected 0.5 g for analysis. Dust samples were weighed and digested using nitric and perchloric acid, treated with $NaBH_4$, and analyzed using AAS. The detection limit was 1 mg/kg arsenic in soil and dust.

Quality control. Every assay included quality controls to determine assay performance. The precision, accuracy, and interassay reproducibility of the method for hair and toenail analysis was undertaken using a low (5 µg/L) and high (30 µg/L) quality control target. The coefficient of variation (CV) for the low-quality control group was 14.9%, with an interassay reproducibility of 8.7%. The CV for the high-quality control sample was 7.5%,

with an interassay reproducibility of 4.1%. The Australian Standard recommends a CV of 20% for total arsenic analysis (Australian Standard 1987). External quality control using the Trace Element Quality Assurance Program Biological Matrices was also performed by Quality Control Technologies, Charlestown, New South Wales.

Statistical methods and analysis. The biologic arsenic concentrations were highly skewed to the right and highly censored. Hair and toenail arsenic concentrations were log transformed and subsequently normally distributed. Comparisons between groups were made using nonparametric tests on highly skewed data and *t*-tests where the data were normally distributed, using SPSS Advanced Statistics software. We calculated Spearman correlation coefficients on untransformed data.

For all analyses, biologic and environmental samples with measured arsenic concentrations below the detection limit were assigned a value of one-half the detection limit (Liu et al. 1997).

Each potential risk factor was tested using both nonparametric methods and random-effects linear regression modeling. Random-effects linear regression modeling was performed on log-transformed data using STATA statistical software (Release 5.0; Stata Corporation, College Station, TX, USA). We included an analysis of household arsenic to take into account the potential for similarities among individuals within households.

Results

The environmental arsenic concentrations of the households recruited into the respective exposure categories are shown in Table 1. The high-water and high-soil groups had higher geometric mean (GM) drinking water and soil arsenic concentrations compared with the other groups. The high-water/high-soil group did not have an elevated GM concentration in water compared with the high-water group, and the soil arsenic concentration was lower than the high-soil group. There were few participants recording both high-water and high-soil arsenic concentrations. It was evident that some participants in this group were misclassified.

Because of the wide range of soil and drinking water arsenic concentrations found in residential samples, and the subsequent misclassification of participants in terms of residential exposure, participants were recategorized into a high-water category (household drinking water with > 10 μg/L), a high-soil category (residential soil > 30 mg/kg arsenic), a low-personal/high-environmental exposure group (where participants were originally recruited into a high-exposure group but recorded low household drinking water and low residential soil concentrations), and the low-exposure group (recruited from the control population and having < 10 μg/L arsenic in drinking water and < 30 mg/kg arsenic in soil). This category allowed us to consider whether residential exposure was more significant than local environmental exposure. Where drinking water arsenic concentrations were elevated, these concentrations did not vary significantly during the study period. The demographic characteristics of the recategorized groups are shown in Table 2.

The GM, 95% confidence interval (CI), geometric standard deviation (GSD), and range of hair arsenic concentrations for each exposure group are shown in Table 3. The hair arsenic GM concentration was significantly higher in the high-water group compared with the other three exposure groups. The high-soil group GM was also higher than the low-personal/high-environmental exposure and control group GMs. The control group recorded the lowest hair arsenic GM concentrations.

Sixty-two participants provided two hair samples for analysis. Figure 1 shows the plot of the difference in hair arsenic concentrations (sample 1 – sample 2) against the mean [(sample 1 + sample 2) ÷ 2] for each individual. Agreement between the two samples was good, with 95% of samples within 2 SDs. With an increasing mean hair arsenic concentration, the difference increases, suggesting an increase in individual variability. The Spearman correlation between the samples was significant at 0.80, and the hair arsenic concentrations were not significantly different by paired *t*-test.

Table 4 shows the GM, 95% CI, GSD, and range of toenail arsenic concentrations for each environmental arsenic exposure group. These data show that the highest toenail arsenic concentrations were recorded for participants in the high-soil group, followed by participants in the high-water group. The control group had the lowest toenail arsenic concentration.

The low-personal/high-environmental exposure category had significantly higher GMs and medians for toenail and hair arsenic concentrations than did the low personal exposure category. The data may reflect external contamination, given the high environmental arsenic concentrations recorded for the area before recruitment.

Only 12 pairs of toenail samples were available for use in evaluating individual variation because of the limited selection of samples for analysis. The correlation coefficient for the repeat toenail arsenic concentrations was 0.82 and statistically significant, and a paired *t*-test showed no significant differences in toenail arsenic concentrations.

The influence of environmental concentrations and other factors on hair and toenail arsenic concentrations. The relationship between drinking water arsenic concentrations and hair arsenic concentrations was positive and significant, with a Spearman correlation coefficient of 0.49. The Spearman correlation between toenail arsenic concentrations and drinking water was 0.55 (Table 5).

The relationship between residential soil arsenic concentrations and average hair arsenic concentrations was slightly positive, with a Spearman correlation coefficient of 0.16 (Table 5). The relationship between residential soil arsenic and average toenail arsenic concentrations was strong, with a Spearman correlation coefficient of 0.50.

The relationship between hair arsenic and dust arsenic concentration was significant, with a correlation coefficient of 0.82 ($n = 37$). The correlation for toenail arsenic and dust arsenic concentrations was 0.54 ($n = 32$).

We investigated age, sex, water consumption, and time spent outdoors for their influence on hair and toenail arsenic concentrations; when an association was observed, as shown in Table 5, the factor was included in a random-effects linear regression model. We also investigated cigarette smoking and diet; because we did not find them to have any influence on hair or toenail arsenic concentrations, we did not include smoking and diet in subsequent models.

Table 1. Geometric mean (GM) and median environmental concentrations for each exposure group.

	High water	High soil	High water/high soil	Control
Soil arsenic (mg/kg)				
n	20	26	28	26
GM	12.3	123.1	26.4	4.3
Median	9.6	92.0	27.0	3.3
Range	3.4–71	9.1–9,900	4.7–340	1.7–80
Water arsenic (μg/L)				
n	20	26	28	26
GM	35.7	0.7	1.2	0.6
Median	43.8	0.8	< DL	< DL
Range	3.5–73.0	< DL–1.3	< DL–52.5	< DL–8.0
Dust arsenic (mg/kg)				
n	16	11	13	11
GM	10.2	60.8	9.7	3.9
Median	8.3	53.0	8.5	3.9
Range	< DL–230	12–1,300	1.5–50	2.2–21

DL, detection limit.

One factor thought to be of importance with respect to long-term measure of exposure was duration of exposure. Participants estimated the length of time they resided in the area in which the study was undertaken. The number of years residing in the area was correlated with hair and toenail arsenic concentrations. No relationship between either hair or toenail arsenic concentrations and duration of exposure was observed (Table 5).

Participants were stratified into age categories: 1–12 years, 13–29 years, 30–50 years, and ≥ 51 years. Both the hair and toenail arsenic concentrations were higher for the 1–12-year age group compared with the other age groups. The effect of environmental exposure could not be examined because of small numbers in each age category and associated personal exposure category (Table 6).

Females had lower hair and toenail arsenic concentrations compared with men, except in the high-soil group where females had significantly higher toenail arsenic concentrations (Table 6).

Participants also estimated the amount of water they consumed in an average day, including tea, coffee, and cordial and alcoholic drinks, in the questionnaire. No increase in toenail or hair arsenic concentrations was observed with increasing consumption of drinking water (Table 5).

The only other factor that showed some effect on hair and toenail arsenic concentrations, based on questionnaire data, was the amount of time spent outdoors. Participants responded to whether they spent 0–1, 1–5, or > 5 hr per day outdoors. A slight increase in hair arsenic concentrations was observed in the > 5-hr category. The same pattern was also observed for toenail arsenic concentrations; however, numbers were small.

In the preceding univariate analyses, a number of factors were shown to be associated with hair and toenail arsenic concentrations. The most significant factors were water and soil arsenic concentrations. Dust arsenic concentrations also had an influence, but there were too few data points to enable appropriate subanalysis.

To test the significance of these factors and to assess the degree of the effect, we performed a random-effects model using STATA software. This included an analysis of household arsenic account for the potential similarities among individuals within a household. The models were also run without the household analysis, which did not significantly affect the results.

Table 7 shows the output summaries for the random-effects model run for both average hair and toenail arsenic concentrations, including the regression coefficient and 95% CI for each variable, the chi-square test (which represents the goodness of fit of each model), and an overall R^2.

The model that explains most of the variance in hair arsenic concentrations includes drinking water arsenic concentrations, soil arsenic concentrations, age (stratified into four categories), and sex. This model explained 40% of the variance in hair arsenic concentrations. Water and soil arsenic concentrations were the major risk factors for increased hair arsenic concentrations, with water arsenic concentrations being the most significant contributor.

The same factors—water arsenic concentrations, soil arsenic concentrations, age, and sex—provided the best fit for toenail arsenic concentrations (Table 7). The soil arsenic concentration was the most significant risk factor for toenail arsenic concentrations, followed by drinking water arsenic concentration. Age and sex were important but not significant in the models. This model explained 63% of the variance.

Table 2. Demographic characteristics of the recategorized exposure groups.

Characteristic	High water	High soil	Low personal/ high environmental	Low personal
n	31	35	51	38
Age (median)	45.2	37.9	42.8	36.5
Sex (% male)	39.6	45.0	42.3	41.8
Smoking status (%)				
Current smoker	50	57.5	50	64.8
Nonsmoker	50	42.5	50	35.2
Fish intake (%)				
Do not eat fish	12	35.0	14.3	12.7
At least once per week	68	65.0	51.9	45.5
Estimated water intake (median no. of glasses/day)[a]	8.0	7.0	7.5	5.0
Years lived at current address (mean)	16.0	10.5	7.5	11.9
Water arsenic concentration (μg/L)	40.2	1.8	1.3	< DL
Soil arsenic concentration (mg/kg)	14.6	1,434	36.6	13.9
Dust arsenic concentrations (mg/kg)	10.4	219	34.1	4.9

DL, detection limit.
[a]250 mL/glass.

Table 3. Hair arsenic concentrations for each personal exposure category (mg/kg).

	High water	High soil	Low personal	Low personal/ high environmental
Sample 1				
n	28	6	27	30
GM	5.55	1.26	1.12	1.69
95% CI	4.20–7.33	0.71–2.25	0.75–1.68	1.13–2.53
GSD	2.11	2.05	2.93	3.10
Range	1.0–20.4	0.50–2.80	0.10–6.40	0.10–16.9
Sample 2				
n	17	29	24	45
GM	5.23	3.30	1.10	2.27
95% CI	3.61–7.58	2.22–4.89	0.72–2.34	1.72–3.00
GSD	2.18	2.94	2.90	2.60
Range	1.30–18.4	0.40–27.3	0.10–4.80	0.30–21.9
Averaged data				
n	31	29	37	50
GM	5.52	3.31	1.27	2.13
95% CI	4.29–7.11	2.24–4.90	0.99–1.61	1.64–2.78
GSD	2.05	2.94	2.11	2.60
Range	1.15–20.4	0.4–27.3	0.20–4.80	0.25–16.5

Discussion

Analysis of total arsenic in hair and toenail samples of residents exposed to varying concentrations of environmental arsenic has shown that increased hair and toenail arsenic concentrations were associated with high arsenic concentrations in drinking water, high concentrations of arsenic in residential soil, or both. Both hair and toenail arsenic concentrations increased with increasing environmental arsenic concentrations in a dose–response pattern.

Hair arsenic concentrations were higher in residents consuming arsenic-contaminated water compared with residents in other categories of exposure. Toenail arsenic

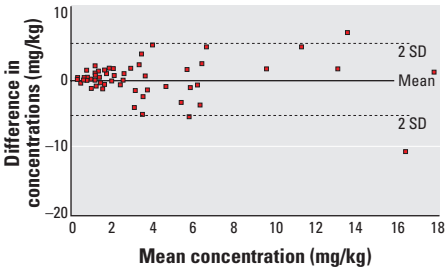

Figure 1. Bland Altman plot of the difference in hair arsenic concentrations (mg/kg) for each participant against the mean [(sample 1 + sample 2) ÷ 2].

concentrations were higher in residents exposed to high concentrations of arsenic in soil, and slightly lower concentrations were observed in residents consuming contaminated water. Participants in these categories of exposure had significantly higher toenail arsenic concentrations compared with the other groups. High concentrations of arsenic in toenail samples were also recorded in the low-personal/high-environmental exposure group, indicating that arsenic in the environment, outside of the household, may be an important source of exposure.

Toenail arsenic concentrations were more strongly correlated with all exposure sources compared with hair.

Table 4. Toenail arsenic concentrations for each personal exposure category (mg/kg).

	High water	High soil	Low personal	Low personal/ high environmental
Sample 1				
n	12	2	4	8
GM	25.0	20.5	2.83	6.90
95% CI	16.7–37.2	—	1.60–5.00	3.17–15.03
GSD	2.03	—	1.79	3.07
Range	8.8–79.4	3.60–117	1.30–5.10	2.00–62.7
Sample 2				
n	12	21	5	21
GM	19.4	36.1	3.55	10.8
95% CI	15.9–23.8	20.0–65.3	2.12–5.93	1.91–17.4
GSD	1.43	3.99	1.79	3.04
Range	12.6–39.9	3.20–477	1.70–7.70	0.30–104
Averaged data				
n	21	22	8	25
GM	21.7	32.1	3.35	10.4
95% CI	17.1–27.5	17.7–58.0	2.29–4.90	7.29–14.9
GSD	1.75	4.13	1.73	2.48
Range	8.80–55.3	3.20–477	1.30–7.70	1.35–104

Table 5. Spearman correlation coefficient matrix for all available data.

	Toenail arsenic concentration	Hair arsenic concentration
Toenail arsenic concentration	—	0.53**
Hair arsenic concentration	0.53**	—
Age	–0.32**	–0.08
Fish intake (estimated on questionnaire)	–0.34**	–0.158*
Water arsenic concentration	0.55**	0.49**
Dust arsenic concentration	0.46**	0.34**
Soil arsenic concentration	0.50**	0.16*
Time outside and in contact with soil (estimated hr)	0.15	0.19**
No. glasses of water (estimated)	0.006	0.13
Years lived at current address	–0.17	–0.023

*Significant at 0.01 (two-tailed) level. **Significant at 0.05 (two-tailed) level.

Both drinking water and residential soil were significant predictors of hair and toenail arsenic concentrations, as shown in the random-effects model. Drinking water and soil arsenic concentrations explain more of the variance in toenail arsenic concentrations compared with hair arsenic concentrations (54.4% vs. 29.8%).

Given the strength of association between hair and soil arsenic concentrations and toenail and soil arsenic concentrations, and the very high toenail arsenic concentrations recorded in the high-soil category, there is a strong likelihood of significant external contamination. The significant correlation between hair and toenail arsenic concentrations and dust arsenic concentrations also support the likelihood of external contamination. The degree of external contamination, however, influencing hair or toenail arsenic concentrations cannot be determined.

For participants exposed to high arsenic concentrations in drinking water, the water arsenic concentrations may contribute significantly to exogenous arsenic in hair and toenails via bathing. Literature on this topic indicates that arsenic is likely to be absorbed into hair from the hair surface, making washing of external contamination ineffective (de Peyster and Silvers 1995).

The degree to which arsenic at the concentrations in water measured in this study may contribute to hair arsenic concentrations is also not known. Whether the concentration involved can result in such high concentrations in hair and toenails needs further investigation.

In this study, males had a slightly higher concentration of arsenic in hair and toenails compared with females, although the differences were not statistically significant. This finding supports another study that has shown

Table 6. GM toenail and hair arsenic concentrations (mg/kg) for different age groups and for males and females.

	High water		High soil		Low personal/ high environmental		Low personal	
Long term measure, risk factor	Concentration (*n*)	Significance	Concentration (*n*)	Significance	Concentration (*n*)	Significance	Concentration (*n*)	Significance
Toenail arsenic								
Age (years)								
≤ 12	43.3 (5)	$\chi^2 = 3.05$	99.5 (5)	$\chi^2 = 9.9$	65.7 (2)	—		—
13–20	— (2)	$p = 0.38$	42.0 (2)	$p = 0.007$*	7.85 (2)	—	3.89 (1)	—
21–50	21.1 (10)		31.4 (10)		10.3 (13)		3.16 (8)	
≥ 51	15.6 (10)		21.3 (10)		6.61 (12)			
Sex								
M	24.1 (12)	$\chi^2 = 0.74$	28.5 (12)	$\chi^2 = 0.36$	15.3 (14)	$\chi^2 = 5.2$	3.88 (5)	$\chi^2 = 0.06$
F	19.6 (12)	$p = 0.39$	41.1 (13)	$p = 0.55$	6.1 (15)	$p = 0.02$*	3.33 (4)	$p = 0.86$
Hair arsenic								
Age (years)								
≤ 12	8.76 (5)	$\chi^2 = 8.02$	10.95 (5)	$\chi^2 = 3.7$	2.74 (7)	$\chi^2 = 3.6$	1.56 (4)	$\chi^2 = 0.82$
13–20	3.19 (4)	$p = 0.04$*	2.29 (4)	$p = 0.27$	3.52 (5)	$p = 0.31$	1.24 (16)	$p = 0.84$
21–50	5.05 (16)		2.35 (16)		2.19 (42)		1.06 (24)	
≥ 51	5.00 (23)		2.05 (23)		1.42 (22)		1.08 (8)	
Sex								
M	9.10 (19)	$\chi^2 = 16.5$	3.11 (16)	$\chi^2 = 0.23$	2.91 (32)	$\chi^2 = 4.7$	1.38 (22)	$\chi^2 = 0.41$
F	3.71 (27)	$p = 0.000$*	2.55 (19)	$p = 0.63$	1.56 (44)	$p = 0.03$*	1.10 (30)	$p = 0.57$

*Significant at $p = 0.05$.

males to have higher hair arsenic concentrations (Wolfsperger et al. 1994). In a study of toenail arsenic concentrations and arsenic in drinking water, Karagas et al. (1996) observed little difference between men and women, although the sample size was small.

In the present study, children had higher arsenic concentrations in both hair and toenails than did the other age groups tested, although numbers were small. This finding is also supported by other studies in which children have been shown to have higher hair arsenic concentrations (Armienta et al. 1997; Paschal et al. 1989; Takagi et al. 1988). Children may simply be exposed to more arsenic because of their play activities and through pica behavior.

Smoking status has been shown to be significant in a study of occupational exposure to arsine (de Peyster and Silvers 1995), but smoking was not significant in the present study. The large concentrations of arsenic recorded and the presence of exogenous arsenic may have obscured any effect or may explain the results for the low-personal/high-environmental exposure group.

The hair and toenail arsenic concentrations recorded in this study were significantly higher than those reported in many other studies. Chatt and Katz (1988) reported a mean arsenic concentration in unwashed hair of unexposed persons to be 0.276 μg/g, whereas the mean in the present study is on the order of 1 μg/g. Chatt and Katz (1988) also reported concentrations submitted by a commercial laboratory, which indicated a background range to be between 2 and 3 mg/kg.

The comparison is more evident in the studies of Taiwanese populations, where hair arsenic concentrations ranged from 0.2 to 0.7 mg/kg, corresponding to a drinking water arsenic concentration of 400 μg/L (Lin et al. 1998). In a study by Armienta et al. (1997), the mean concentration of arsenic in hair of a highly exposed population (consuming drinking water with arsenic concentrations up to 1,090 μg/L) was 8.55 mg/kg; this is higher than the hair arsenic concentrations observed in the present study, in which drinking water arsenic concentrations were no higher than 73 μg/L.

The washing procedure used in this study was probably not completely effective in removing exogenous contamination. Further, the significantly higher concentrations of arsenic in the control or low-exposure categories, compared with the findings of other researchers, may reflect a difference in sample preparation such as no oven drying and a longer, more aggressive digestion procedure.

In studies in which hair was unwashed or undried, higher arsenic concentrations were reported and are of the same magnitude of concentrations reported here (de Peyster and Silver 1995).

Table 7. Random effects linear regression on transformed hair and toenail arsenic concentrations.

Model, variables	Regression coefficient	95% CI	χ^2	Overall R^2
Hair				
Water	0.292	0.20–0.38	76.1	0.400
Soil	0.139	0.06–0.22		
Age (years)				
13–20	–0.389	−0.94–0.16		
21–50	–0.415	−0.84–0.01		
≥ 51	–0.497	−0.98–−0.02		
Sex	–0.508	−0.75–−0.26		
Toenail				
Water	0.285	0.18–0.40	87.97	0.633
Soil	0.332	0.23–0.43		
Age (years)				
13–20	–0.223	−0.96–0.52		
21–50	–0.741	−1.2–−0.28		
≥ 51	–1.00	−1.6–−0.46		
Sex	–0.276	−0.55–−0.004		

A hair arsenic concentration of 1 mg/kg has been associated with levels at which health effects have been observed (Hindmarsh and McCurdy 1986; Pan et al. 1993). Nerve conduction impairment has been observed in persons with 2 mg/kg hair arsenic concentrations (Hindmarsh and McCurdy 1986). A value of 5 mg/kg has been used by the Canadian government to indicate a significant increase of ingested arsenic (Pan et al. 1993). Such levels cannot be applied to the results of this study because the contribution of exogenous arsenic has not been accounted for.

There are a number of additional limitations with this study. In general, compliance with provision of one toenail or hair arsenic was good. However, compliance with a second sample was very poor, making it difficult to evaluate interpersonal variation. Nonparticipation, noncompliance, and the inability to analyze samples of < 500 mg may have introduced bias. The random sample selection of toenail samples may also have introduced bias.

The results may be confounded by a number of factors. Compliance with the provision of a full sample over the 4-month period may not have been high and was not assessed in this study. It is likely the presence of a high concentration of exogenous arsenic may have masked the detection of effects due to such factors as smoking.

Occupation and the use of arsenic-containing substances may also have confounded the results; however, questionnaire data tend to indicate the influence of such factors was negligible.

This study has shown that hair and toenails may be useful biomarkers for exposure to both contaminated water and contaminated soil. In this study we have confirmed that factors such as age and sex are important and should be considered when investigating the potential exposure of human populations to environmental arsenic concentrations. However, before using these measures, it is necessary to demonstrate that washing hair in contaminated water causes minimal external contamination. For assessing absorption from different environmental sources of exposure, hair may not be a suitable method because of the presence of external contamination from sources such as soil and dust.

Toenail arsenic may be a better surrogate than hair arsenic concentrations because of the improved correlations with environmental concentrations compared with hair. Interindividual variability was also lower.

It is not possible to conclude from the results of this study that residents with high hair and high toenail arsenic concentrations, exposed to high environmental arsenic concentrations in drinking water and residential soil, are absorbing arsenic to a greater extent because of the likelihood of external contamination. However, residents are certainly exposed to arsenic from these sources as measured by hair and toenail arsenic concentrations, compared with the control population. Further work is required to characterize chronic exposure in residents known to be exposed to high concentrations of environmental arsenic.

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