Hair Analysis Does Not Support Hypothesized Arsenic and Chromium Exposure from Drinking Water in Woburn, Massachusetts

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We hypothesized that residents of Woburn, Massachusetts, had been exposed to as much as 70 μg/l of arsenic (As) and 240 μg/l of chromium (Cr) in drinking water from municipal supply wells G and H. To test this hypothesis, we measured the concentrations of As and Cr in 82 hair samples donated by 56 Woburn residents. Thirty-six samples were cut between 1964 and 1979, the period during which wells G and H were in operation. The remainder were cut either before 1964 (1938–1963; n = 26) or after 1979 (1982–1994; n = 20). Washed hair samples were analyzed by instrumental neutron activation. Exposure to the well water—measured as access—was estimated using well pumping records and a model of the Woburn water distribution system. Our results show that access to wells G and H water was not significantly correlated (95% confidence interval) with As and Cr concentrations measured in the hair of Woburn residents, but As concentrations have declined significantly over the last half century. Linear regression of As concentrations (micrograms per gram) upon year of haircut and access to Wells G and H water yielded a standard coefficient for year of -0.0074 ± 0.0017 (standard error; p = 2.5 × 10^-4) and -0.12 ± 0.10 (p = 0.22) for access. The r² value for the model was 0.19. The geometric mean concentrations (geometric standard deviation) of As and Cr in the hair of residents who had access (i.e., relative access estimate >0) to wells G and H water (n = 27) were 0.14 (2.6) and 2.29 (1.8) μg/g, respectively; the geometric mean concentrations of As and Cr in all of the hair samples from residents who did not have access (1938–1994; n = 55) were 0.13 (3.0) and 2.19 (2.0) μg/g, respectively. Key words: arsenic, chromium, groundwater, human hair, Woburn, Massachusetts.

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Chemical manufacturing and leather tanning activities on the Aberjona River watershed in eastern Massachusetts (Fig. 1) have left a legacy of environmental contamination. The earliest records of contamination date to the 1870s when it was reported that tanneries in Woburn were discharging their wastes into tributaries of Horn Pond, which then served as a drinking water supply for Woburn (1–3). Since that time, reports of additional contamination resulting from leather tanning, chemical manufacturing, and other industrial activities on the watershed have been made with alarming regularity (4,5). As a result, there are over 100 sites in the watershed—including two EPA Superfund sites (Industri-Plex and Wells G and H)—that are now being investigated for the presence of hazardous man-made chemicals (6).

Although many of the chemicals identified at these disposal sites (e.g., gasoline, organic solvents, pesticides, plasticizers) are from contemporary sources, large quantities of toxic elements released by historical tanning and chemical manufacturing operations have been discovered. For example, at four sites in Woburn and one in Winchester, tanning wastes containing elevated concentrations of chromium, arsenic, lead, and other elements have been detected (5). In addition, at the Industri-Plex site, it is estimated that several tons of arsenic, chromium, and lead were released during the manufacture of arsenic-based pesticides, sulfuric acid, and glues (5,7).

The concern that arsenic and chromium residues may be moving off these sites by leaching into groundwater and surface waters has led to several recent investigations. Davis et al. (8) reported that the sediments of Halls Brook Pond, which is immediately downstream of the Industri-Plex site, contain as much as 3,000 mg/kg As and 1,400 mg/kg Cr [average crustal abundances are on the order of 1–10 mg/kg for As and 10–100 mg/kg for Cr (9,10)]. Knox (11) found that many sediments along the Aberjona river, and in particular a riparian wetland area within the wells G and H site boundary (see Fig. 1), contained elevated concentrations of these elements. Splethoff and Hemond (12) reported that the sediments of Upper Mystic Lake, into which the Aberjona drains, contained the depositional record of As and Cr dating back to the mid-1800s. Peak concentrations in these sediments were found to be as high as 1,800 mg/kg As and ~6,000 mg/kg Cr.

To date, no work has been done to determine whether residents of this watershed (population ~75,000) have been exposed to elevated levels of As and Cr. Based on our knowledge of As and Cr distribution and transport in the watershed, we considered the possibility that water from municipal supply wells G and H may have been contaminated with these elements (13). Wells G and H were used between 1964 and 1979 to supplement supplies to east Woburn, providing as much as 35% of the city's water (14). Although little information is available on the elemental composition of well G and H water, the hypothesis that the well water contained elevated concentrations of As and Cr—possibly other elements—was supported by two discoveries: as much as 60% of the recharge water for the wells came from the Aberjona river (15), and during the 15 years that the wells were in use, the peak concentrations of As and Cr in the river were estimated, on the basis of lake sediment analysis, to be on the order of 120 and 400 μg/l, respectively (12). This suggested that residents who consumed water from wells G and H could have been exposed to as much as 70 μg/l As and 240 μg/l Cr (the drinking water quality standard for As and Cr are currently 50 μg/l and 100 μg/l, respectively).

If Woburn residents ingested these elevated concentrations of As and Cr, a record of this exposure would be stored in hair that was grown during the period of exposure. Once in the body, As and Cr accumulate in hair, binding strongly to keratin in hair strands (16–18). Retrospective studies performed to determine whether people who had been dead for a long time had experienced acute As exposures [e.g., Napoleon, and the mayor

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of Zurich who died in 1360 (19) suggest that As in hair may be used as a biomarker, even in samples that are several hundred years old. Although similar studies of the Cr content of historic hair samples have not been reported, it has been demonstrated that Cr within hair strands in not easily removed, even upon washing with shampoo and organic solvents (20); thus, it is reasonable to expect that Cr levels in decades-old hair samples will reflect the levels at the time Cr was initially incorporated in the hair. The relationship between As and Cr in hair and drinking water has been demonstrated in studies in which populations exposed to elevated levels of As and Cr in their drinking water were found to have significantly higher concentrations of these elements in their hair than control populations (21–24).

In this study we compared As and Cr concentrations measured in the hair of Woburn residents with estimates of each donor’s access to water from wells G and H. We posited that if As and Cr were present in the well water, then individuals consuming the water would have incorporated As and Cr into their hair in proportion to the amount of well water consumed. We used instrumental neutron activation analysis to determine the As and Cr concentrations of the hair samples, a model of the Woburn water distribution system to estimate access to wells G and H, and linear regression analysis to determine whether As and Cr concentrations in hair samples were dependent upon access to well water in a statistically significant manner.

Methods

Hair collection. The samples used in this study were obtained from Woburn residents who saved locks of hair cut from their children or themselves before, during, and/or after the period when wells G and H were in use. The samples, many of which had been stored in photograph albums and scrapbooks, were placed individually in air-tight polyethylene bags and transported to the laboratory for analysis. For each sample, the donor’s sex, age, and address at the time the hair was cut were recorded, as were the month and year of the haircut. For 14 of the samples collected between 1964 and 1979, the month that the hair was cut was not known so only the year was recorded. A total of 82 samples were collected, representing 56 donors and 34 different residences. Twenty-six of the samples were cut between 1938 and 1963, 36 were cut between 1964 and 1979 (the period during which wells G and H were in operation), and 20 were cut between 1982 and 1994. Seventy-two samples were from children between the ages of 1 month and 19 years; the remaining samples were from adults over 19 years of age.

Elemental analysis. To distinguish elements incorporated in the hair during growth from those that were deposited on the outside of hair strands, the samples initially were washed with both acetone and water according to a hair cleaning procedure described elsewhere (25). After drying in a fume hood at room temperature, the samples were irradiated with a thermal neutron flux of \(8 \times 10^{12} \text{ n/cm}^2/\text{sec} \) for 12 hr. The samples were then cooled for 2–3 days, washed again with acetone, and transferred
to clean polyethylene bags for counting. All of the gamma-ray spectroscopy was performed using four high purity germanium detectors coupled to an 8192-channel Genie system operating on a VAX 3100 workstation. Elemental concentrations were determined using custom-made interactive peak fitting and analysis software (all hardware and software were from Canberra Industries, Inc, Meriden, CT). A fly ash standard reference material (SRM 1633), purchased from the National Institute of Standards and Technology (Gaithersburg, MD), was used to calculate elemental concentrations. Two other reference materials, SRM 1571 (orchard leaves) and SRM 1577a (bovine liver), were used to check the system stability. All samples, standards, and control samples were counted for 12 hr at a constant geometry. Additional details of the analytical procedure have been published elsewhere (26).

Exposure estimation. An accurate method for relating As and Cr concentrations measured in hair samples to exposure to these elements in water from wells G and H would have been to determine the amount of each element imbibed during the period when each donor’s hair sample was grown. However, because As and Cr were not measured in water from wells G and H when the wells were in use and because the volume of water from wells G and H consumed by each hair donor were also unknown, measurements of actual exposure to As and Cr could not be made. Instead, we investigated the relationship between As and Cr concentrations in hair samples and the donors’ relative access to water from wells G and H. Access is defined here as the ratio of the amount of water from wells G and H to the total amount of municipal water delivered to a hair donor’s house during the period when the hair sample was grown. Access was calculated by combining estimates of the period of time when each hair sample was grown and the fraction of water supplied to a residence by wells G and H. The methods used in determining these estimates are described below.

The hair growth period was estimated by dividing the length of the hair by an assumed growth rate of 1 cm/month (27). The dates corresponding to the oldest and youngest parts of the hair strands (i.e., the dates between which As and Cr exposure would have been recorded in the hair sample) were calculated using the date that the hair was cut and estimates of the length of hair on a donor’s head remaining after cutting. If the length of hair remaining after cutting was unknown (i.e., it was not supplied by the donor or the donor’s parents), lengths were assumed based on the sex and age of the donor. For boys, the length of hair remaining after cutting was assumed to be 4–6 cm; for girls younger and older than 2 years of age, values of 4–6 cm and 8–12 cm, respectively, were used.

For the 14 samples for which only the year of collection was known, the growth period was deliberately overestimated to ensure that the true growth period for the hair was included within the estimated growth period. The beginning of the hair growth period was calculated using the earliest possible month of hair cutting (January) and the longest estimate of hair length; the end of the hair growth period was calculated using the latest possible month (December) and the shortest estimate of hair length. The disadvantage of this technique is that the true growth period for a sample was actually shorter than the estimated growth period; therefore, episodes of low or high access to wells G and H water cannot be resolved. Despite this distortion, this method was chosen over the alternative, which was to arbitrarily choose a shorter growth period that may or may not represent the true growth period.

Estimates of well water access were based on a model of the city’s water distribution system developed by Murphy (14). In the original model, well pumping records and data on the water distribution system in Woburn were used to estimate the relative amounts of water arriving at a particular location from wells G and H and the Horn Pond well fields (Fig. 1). Recently, hydraulic mixing calculations were incorporated into the model, and source apportionment indices for various distribution nodes located throughout the city were calculated for each month that wells G and H were in use (28). In estimating the amount of water from wells G and H to which hair donors had access, we divided the sum of these published monthly exposure values by the number of months that the hair was estimated to have grown. Average monthly access estimates ranged from 0 (none of the water delivered to a residence during the period of hair growth was from wells G and H) to 1 (all of the water delivered to a residence during the period of hair growth was supplied by wells G and H).

Results

Arsenic. Overall, our results indicate that donors who had access to water from wells G and H did not have higher concentrations of As in their hair than donors who did not have access. A plot of As concentrations in hair versus a donor’s relative access to wells G and H is shown in Figure 2A. The figure shows that there is no apparent correlation between access and As concentrations measured in hair. A least squares regression line through the data has a slope that is not significantly different from zero. Interestingly, a plot of the As concentrations in all hair samples versus the year that the hair was cut (Figure 3A) indicates that As levels in the hair of Woburn residents have decreased over the last 50 years. To determine whether there was a relationship between As concentrations in hair and a donor’s relative access once this temporal variation in As concentrations was accounted for, multivariable regression was performed. Since As concentrations are linearly related to year (Figure 3A), the form of the regression was

$$[\text{As}]_{\text{hair}} = B_0 + B_1 \times \text{year} + B_2 \times \text{access} + \text{error}$$

The results in Table 1 show that As concentrations in hair were statistically dependent (at the 95% confidence level) upon year, but not upon access. The $R^2$ value for the model was 0.19.

The arithmetic and geometric mean concentrations of As in hair samples are shown in Table 2. The samples are grouped according to the year that the hair was cut and the donor’s access to wells G and H water. As is evident from Figure 4A, the As concentrations in the hair of donors with access (i.e., relative access estimate >0) and donors without access to the well water are log-normally distributed; thus, the geometric mean concentrations are the more appropriate measure to compare the different groups. The arithmetic mean concentrations were calculated so that we could compare our results with other studies that have reported their findings in terms of arithmetic mean concentrations. The geometric mean concentration (GSD) of As in the hair of residents who had access to water from wells G and H (1964–1979, with access) was 0.14 (2.6) µg/g (n = 27), while for the concurrent control group (1964–1979, no access) the mean concentration was 0.18 (1.6) µg/g (n = 9) (Table 2). The mean concentration of As in the hair of all of the controls (1938–1994, no access) was 0.13 (3.0) µg/g (n = 55).

Chromium. The plots of Cr concentrations in hair samples versus relative access to water from wells G and H and versus the year that the hair was cut are shown in Figures 2B and 3B, respectively. Although there appears to be an increase in the concentrations of Cr in hair just after well G was turned on, well water access estimates and concentrations of Cr in hair are not significantly correlated. A least squares regression line through the data has a slope that is not significantly different from zero. Thus, as was the case for As, there is no indication that increased access to water
from wells G and H resulted in higher concentrations of Cr in hair.

The mean concentrations of Cr in the hair samples are shown in Table 2. Figure 4B shows that the Cr data is not fitted well by either a standard or a log-normal distribution; thus, the arithmetic and geometric mean concentrations are presented in Table 2. The geometric mean concentration (GSD) of Cr in the hair of residents who had access to wells G and H water (1964–1979, with access) was 2.29 (1.8) µg/g (n = 27), while for the concurrent control group (1964–1979, no access) the mean concentration was 3.11 (2.4) µg/g (n = 9). The mean concentration of Cr in the hair of all of the controls (1938–1994, no access) was 2.19 (2.0) µg/g (n = 55). The arithmetic mean concentrations for these three groups were 2.80 ± 2.08 µg/g (n = 27), 4.78 ± 5.14 µg/g (n = 9), and 2.82 ± 2.59 µg/g (n = 55), respectively.

### Discussion

The concentrations of As and Cr in hair have been reported in many different studies. As shown in Table 3, As and Cr in hair have both been reported at concentrations ranging from <0.1 µg/g to >30 µg/g (29). A review of studies in which the hair of only healthy individuals was analyzed suggests that the normal ranges for As and Cr are roughly the same: 0.10–3.7 µg/g (17–19,29–34). In comparing our results with those in Table 3, we find that the concentrations of As and Cr in the hair of Woburn residents are consistent with what others have reported. The arithmetic mean concentrations of As and Cr in the hair of Woburn residents who did not

| Parameter | Parameter Estimate | Standard error | p-value |
|-----------|--------------------|----------------|---------|
| Year of haircut | -0.0074 | 0.0017 | 2.5 × 10^{-5} |
| Access to wells G and H | -0.12 | 0.10 | 0.22 |

### Table 2. Concentrations of As and Cr in hair samples from residents of Woburn, Massachusetts, with and without access to water from wells G and H

| Group | Number | A-mean ± SD* | G-mean (GSD) | Median | Range | A-mean ± SD* | G-mean (GSD) | Median | Range |
|-------|--------|--------------|--------------|--------|-------|--------------|--------------|--------|-------|
| 1938–1994, no access | 55 | 0.22 ± 0.30 | 0.13 (3.0) | 0.13 | 0.009–1.9 | 2.82 ± 2.59 | 2.19 (2.0) | 2.1 | 0.34–15 |
| Male | 19 | 0.34 ± 0.26 | 0.22 (2.6) | 0.22 | 0.009–1.9 | 3.80 ± 3.81 | 2.56 (2.5) | 2.3 | 0.34–15 |
| Female | 36 | 0.16 ± 0.16 | 0.10 (1.7) | 0.10 | 0.018–0.62 | 2.35 ± 1.40 | 2.02 (3.0) | 1.9 | 0.73–6.4 |
| 1964–1979, with access | 27 | 0.21 ± 0.16 | 0.14 (2.6) | 0.22 | 0.017–0.63 | 2.80 ± 2.08 | 2.23 (1.8) | 2.0 | 0.93–15 |
| Male | 7 | 0.28 ± 0.17 | 0.24 (1.7) | 0.23 | 0.11–0.63 | 3.00 ± 2.06 | 2.53 (1.7) | 2.3 | 1.3–7.5 |
| Female | 20 | 0.19 ± 0.15 | 0.12 (2.8) | 0.14 | 0.017–0.45 | 2.73 ± 2.14 | 2.19 (1.9) | 1.8 | 0.93–9.5 |
| 1964–1979, no access | 9 | 0.20 ± 0.09 | 0.18 (1.6) | 0.16 | 0.091–0.34 | 4.76 ± 5.14 | 3.11 (2.4) | 1.9 | 1.7–15 |
| Male | 6 | 0.21 ± 0.07 | 0.20 (1.4) | 0.21 | 0.14–0.31 | 6.57 ± 5.76 | 4.37 (2.4) | 3.8 | 1.7–15 |
| Female | 3 | 0.18 ± 0.14 | 0.14 (1.8) | 0.10 | 0.091–0.34 | 1.60 ± 0.36 | 1.58 (1.2) | 1.7 | 1.2–19 |
| 1964–1979, all samples | 36 | 0.21 ± 0.14 | 0.15 (2.4) | 0.20 | 0.017–0.63 | 3.19 ± 3.16 | 2.47 (2.0) | 2.0 | 0.93–15 |
| Male | 13 | 0.25 ± 0.13 | 0.22 (1.5) | 0.23 | 0.11–0.63 | 4.55 ± 4.36 | 3.30 (2.1) | 2.4 | 1.3–15 |
| Female | 23 | 0.18 ± 0.15 | 0.12 (2.6) | 0.11 | 0.017–0.45 | 2.58 ± 2.03 | 2.10 (1.8) | 1.8 | 0.93–9.5 |
| 1938–1963, no access | 26 | 0.35 ± 0.40 | 0.21 (3.0) | 0.20 | 0.019–1.9 | 2.51 ± 1.70 | 2.04 (1.9) | 1.8 | 0.73–6.4 |
| Male | 7 | 0.68 ± 0.61 | 0.41 (3.0) | 0.48 | 0.046–1.9 | 2.92 ± 2.04 | 2.26 (2.1) | 2.3 | 0.73–6.4 |
| Female | 19 | 0.24 ± 0.18 | 0.16 (2.6) | 0.13 | 0.019–0.62 | 2.39 ± 1.50 | 1.95 (1.8) | 1.8 | 0.73–6.4 |
| 1982–1994, no access | 20 | 0.10 ± 0.10 | 0.06 (2.6) | 0.07 | 0.009–0.41 | 2.43 ± 1.34 | 2.06 (1.9) | 2.2 | 0.34–5.0 |
| Male | 6 | 0.12 ± 0.07 | 0.10 (1.7) | 0.12 | 0.009–0.22 | 2.27 ± 1.57 | 1.74 (2.3) | 2.2 | 0.34–5.0 |
| Female | 14 | 0.09 ± 0.11 | 0.05 (2.8) | 0.05 | 0.018–0.18 | 2.49 ± 1.30 | 2.19 (1.7) | 2.2 | 0.95–4.8 |
| 1938–1994, all samples | 62 | 0.22 ± 0.28 | 0.13 (2.9) | 0.14 | 0.009–1.9 | 2.81 ± 2.42 | 2.22 (1.9) | 2.0 | 0.38–15 |
| Male | 26 | 0.52 ± 0.38 | 0.23 (2.3) | 0.22 | 0.009–1.9 | 3.59 ± 3.41 | 2.57 (2.3) | 2.3 | 0.38–15 |
| Female | 56 | 0.17 ± 0.16 | 0.10 (2.9) | 0.11 | 0.017–0.62 | 2.48 ± 1.69 | 2.08 (1.8) | 1.9 | 0.73–9.5 |

*aArithmetic mean ± standard deviation.*

*Geometric mean (geometric standard deviation).*

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**Figure 2.** Concentrations of (A) As (y = -0.15x + 0.25, r = 0.36) and Cr (y = -1.20x + 3.59, r = 0.12) in hair samples from Woburn residents versus access to water from wells G and H (see Methods for explanation). The results shown are for hair samples that were cut between 1964 and 1979, the period during which wells G and H were in operation. A least squares regression line is drawn in each plot to show the trend in the data.

**Figure 3.** Concentrations of (A) As and (B) Cr in hair samples from Woburn residents versus the year of the haircut. Hair donors that had and did not have access to water from municipal supply wells G and H are represented by the closed and open symbols, respectively. Well G was in operation between 1964 and 1976; well H was in operation between 1967 and 1979. Line in (A) is least squares regression (y = -0.008x + 16.52, r = 0.45).
have access to water from wells G and H were 0.22 and 2.82 μg/g, respectively; the mean concentrations in residents who did have access was 0.21 μg/g for As and 2.80 μg/g for Cr. While there are differences in the populations reported on in the literature (summarized in Table 3), as well as analytical techniques used, it is generally reported that the background, or normal, level in human hair (i.e., the level in healthy individuals who have no known exposures) for As is <1.5 μg/g [the threshold for abnormal ingestion is thought to be 3 μg/g (19)]. This suggests that the levels of As measured in the hair of Woburn residents were within the normal background range, except for one sample which measured 1.9 μg/g. Background, or normal, levels for Cr in human hair have not been reported.

Previous studies have investigated the relationship between access to water from wells G and H and effects on human health. In response to indications that cases of childhood leukemia in Woburn were significantly elevated from 1964 to 1983, Lagakos et al. (35) carried out an epidemiological study and found that about half of the excess leukemia cases were positively associated with access to water from wells G and H. However, access to water from wells G and H could not explain all of the excess leukemia cases because several cases were in the western part of Woburn, which received its drinking water from a different source. In a second epidemiological study, the Massachusetts Department of Public Health (28) reported positive statistical associations between childhood leukemia and access to water from wells G and H if either the developing fetus had access to the well water or the mother had access for 2 years prior to conception. No association was found between childhood leukemia and water from wells G and H for access that occurred between birth and the diagnosis of the disease.

In both of these studies, access to water from wells G and H was estimated by using records of well pumping rates and models of the Woburn water distribution system. Lagakos et al. (35) used a model developed by Waldorf and Cleary (36); the Massachusetts Department of Public Health (28) used a later model developed by Murphy (14). Although the two models indicate that roughly the same area of Woburn received water from wells G and H, the Murphy model (14) indicates a greater temporal variation in the amounts of water received within individual subunits of this area. The Murphy model was developed using updated information on the city's water distribution system, and it was calibrated with pressure and chemical tracer measurements; therefore, it is likely

**Figure 4.** Histograms of (A) As and (B) Cr concentrations in hair samples from Woburn residents.
to be the more accurate of the two models. In our study, we also used the Murphy model (14) to estimate access to water from wells G and H. While we did not find an association between access to water from wells G and H and the concentrations of As and Cr in hair, our results do not contradict or otherwise bear upon the findings of Lagakos et al. (35) and the Massachusetts Department of Public Health (28). Our results merely indicate that Woburn residents who had access to water from wells G and H were no more likely to accumulate As and Cr in their hair than those who did not.

There is clear evidence that wells G and H were recharging the Aberjona river and that the river water contained elevated concentrations of As and Cr (as much as 70 and 240 µg/l, respectively (13)); therefore, we were surprised not to have found evidence of exposure to As and Cr in the hair of Woburn residents. One possible explanation for our findings is that the concentrations of As and Cr estimated to have been present in the well water were in fact lower. We have recently found that the peatland (which separates the Aberjona river from the aquifer that supplied water to wells G and H) contains significantly elevated concentrations of As and Cr (37), indicating that these peat deposits trapped As and Cr in the infiltrating river water. If sorption to the peat were a major sink for As and Cr in the infiltrating river water, then our estimates of As and Cr levels in wells G and H water would have been too high. In the case of well H, it was also shown that sand lenses that permeate the peat act as preferential flow paths and probably would not have appreciably removed As and Cr from the infiltrating river water. Nonetheless, these sand lenses are insufficiently conductive to explain the large influx of river water into the aquifer during pumping; therefore, other flow paths, which may or may not be sorptive for As and Cr, must exist.

The possibility that the concentrations of As in the well water were lower than our hypothesized values also seems to be supported by the literature (Table 4). Valentine et al. (21), Zhang et al. (22), and Hough (23) report that significantly elevated concentrations (5- to 10-fold higher than the controls) of As were observed in the hair of people consuming drinking water containing in excess of 100–200 µg/l As. In light of these studies, the maximum amount of As (70 µg/l) hypothesized to have been in water from wells G and H should have been high enough to cause discernible increases in the amounts of As incorporated in the hair of Woburn residents who drank this water. Only one study relating levels of Cr in hair to concentrations in drinking water was found. Rosas et al. (24) found that residents of Lechera (central Mexico) exposed to 900 µg/l of Cr in their drinking water had Cr levels in their hair of 5.1 ± 4.3 µg/g (arithmetic mean ± SD), while the control population in Mexico City, which drank water with an average of 20 µg/l Cr, had Cr levels in their hair of 0.68 ± 0.50 µg/g (arithmetic mean ± SD).

### Table 3. As and Cr concentrations reported in human hair

| Samples                      | Arsenic Concentration (µg/g) | Chromium Concentration (µg/g) |
|------------------------------|-------------------------------|------------------------------|
|                              | Number | Mean | SD | Range | Number | Mean | SD | Range | Reference |
| Review of a variety of studies | -      | -    | -  | -     | -      | -    | -  | -     |            |
| Review of selected studies   | -      | -    | -  | -     | -      | -    | -  | -     |            |
| Diverse population           | -      | -    | -  | -     | -      | -    | -  | -     |            |
| Diverse population           | 228    | 0.10±0.09 | 0.08±0.07 | 121 | 0.82±1.66 | 0.56±0.56 | (29) |
| Rural and nonindustrial      | 0      | 0.01±0.01 | 0.00±0.00 | 90  | 0.21±1.13 | 0.15±0.15 | (30) |
| Urban/suburban               | 234    | 0.08±0.01 | 0.02±0.02 | 34  | 0.56±0.20 | 0.00±0.00 | (31) |
| Urban, no known industrial exposure | 1250 | 0.65±0.70 | 0.02±0.17 | -   | -      | -    | (32) |
| Tannery workers              | -      | -    | -  | -     | -      | -    | -  | -     |            |
| Control subjects             | -      | -    | -  | -     | -      | -    | -  | -     |            |
| No access to well water      | 55     | 0.20±0.30 | 0.00±0.01 | 55  | 2.82±3.59 | 1.39±2.59 | (33) |
| Access to well water         | 27     | 0.21±0.16 | 0.017±0.63 | 27  | 2.80±2.08 | 1.46±2.32 | (34) |

*Range of mean values reported in 28 different studies; studies include acutely exposed populations.*

### Table 4. Arithmetic mean concentrations of As and Cr reported in human hair in relation to levels in drinking water

| Location         | Arsenic Concentration in hair (µg/g) | Chromium Concentration in drinking water (µg/l) |
|------------------|-------------------------------------|-----------------------------------------------|
|                  | Number | Mean ± SD | Reference | Number | Mean ± SD | Reference |
| Arsenic          |        |           |           |        |           |           |
| Edison           | 35     | 1.16±0.80 | 0.36–4.31 | 16     | 393±31    | 328–462   | (21) |
| Fallon           | 45     | 0.57±0.45 | 0.08–2.42 | 23     | 98±22     | 95–105    |      |
| Hidden Valley, NV| 21     | 0.50±0.37 | 0.01–1.39 | 10     | 123±16    | 107–163   |      |
| Virginia Foothills, NV | 25   | 0.48±0.44 | 0.07–0.44 | 17     | 51±13     | 33–76     |      |
| Fairfax, NV      | 10     | 0.15±0.11 | 0.04–0.39 | 17     | <0.6      |          |      |
| Xinjiang, China  | 90     | 5.17     | -         | -      | 580       | -         | (22) |
| Hungary          | 22     | 3.81     | -         | -      | -         | >250      | (23) |
|                  | 47     | 1.78     | -         | -      | -         | 50–250    |      |
|                  | 110    | 1.63     | -         | -      | -         | 10–50     |      |
|                  | 80     | 0.59     | -         | -      | -         | <10       |      |
| Chromium         |        |           |           |        |           |           |
| Lechera          | 93     | 5.1±4.3  | 1.10–21   | 900    | 21–1100   | (24) |
| Mexico City      | 89     | 0.68±0.50 | 0.15–2.76 | -      | 20        | 1–30      |      |

SD, standard deviation.

* Samples from control population.

SD, standard deviation.

* A community in Bakersfield, CA.

* Samples were taken from people who had endemic arsenicism.

* Samples were taken from people who did not have endemic arsenicism.

* Samples were collected in a region of central Hungary between the Danube and Tisa rivers.

* City in central Mexico.
mean ± SD) (Table 4). The amount of Cr hypothesized to have been in water from wells G and H, 240 µg/L, and the mean concentration of Cr in the hair of Woburn residents who had access to this water, ~2.8 µg/g, are consistent with the relationship between Cr in drinking water and Cr in hair reported by Rosas et al. (24). However, as we have already noted, the concentration of Cr in the hair of Woburn residents who did not have access to the well water (and thus, presumably, were exposed to substantially less Cr via drinking water) was also on average ~2.8 µg/g. Furthermore, the concentrations of Cr in hair did not change as a function of access. Therefore, it appears that access to water from wells G and H cannot explain Cr levels measured in the hair of Woburn residents.

Another possible explanation for our negative findings is that our analysis lacked adequate temporal resolution. If the As and Cr concentrations to which a hair sample donor were exposed were temporally variable, a more powerful analysis could be achieved by measuring the axial distribution of As and Cr along individual hair strands. This approach has in fact been used by forensic scientists to distinguish chronic and acute As and Cr exposures (38–40). By contrast, our analysis of whole, unsegmented hair strands does not detect concentration spikes along the strand.

There are several other sources of uncertainty associated with our methods that could also bear upon our results. The period of hair growth was overestimated for 14 of the samples grown between 1964 and 1979 because the month that the sample was cut was not known. The water distribution model used to estimate access is not entirely free of error. In addition, As and Cr concentrations in the hair samples could have changed during storage. While it is important to acknowledge that these (and possibly other) sources of uncertainty were inherent in our methods, we do not expect that greater knowledge of any of these uncertainties would significantly alter our findings.

Although we did not find evidence of increased As and Cr accumulation in the hair of Woburn residents who had access to water from wells G and H, we did observe that As concentrations in the hair samples have changed over time. The plot of As concentrations in hair samples versus the year that the samples were cut (Fig. 3A) shows that concentrations of As in hair have decreased over the last half century. The concentrations of As in hair averaged over the period 1938–1963, 1964–1979, and 1982–1994 [expressed as geometric means (GSD)] were 0.21 (3.0) µg/g (n = 26), 0.15 (2.4) µg/g (n = 36), and 0.06 (2.6) µg/g (n = 20), respectively (Table 2). The reasons for this trend are not known; however, replacement of As-based pesticides by synthetic organic chemicals has undoubtedly reduced the amount of As to which people are exposed through diet and use of pharmaceutical products, and improvements in air pollution control technology have reduced the amount of As emitted into the atmosphere. Also, once the major producers of As-laden wastes ceased operating in Woburn (around 1930), natural attenuation processes, such as stabilization of As-containing particles by vegetation and deposition and burial in pond and lake sediments, may have acted to substantially reduce the amounts of available As to which residents of Woburn are exposed.

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