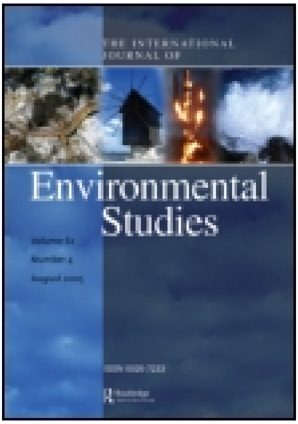

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WATER TREATMENT WITH SILICOFLUORIDES AND LEAD TOXICITY

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Toxic metals like lead, manganese, copper and cadmium damage neurons and deregulate neurotransmitters like serotonin and dopamine (which are essential to normal impulse control and learning). Earlier studies show that–controlling for socio-economic and demographic factors–environmental pollution with lead is a highly significant risk factor in predicting higher rates of crime, attention deficit disorder or hyperactivity, and learning disabilities. Exposure and uptake of lead has been associated with industrial pollution, leaded paint and plumbing systems in old housing, lead residues in soil, dietary habits (such as shortages of calcium and iron), and demographic factors (such as poverty, stress, and minority ethnicity). We report here on an additional "risk co-factor" making lead and other toxic metals in the environment more dangerous to local residents: the use of silicofluorides as agents in water treatment. The two chemicals in question–fluosilicic acid and sodium silicofluoride–are toxins that, despite claims to the contrary, do not dissociate completely and change water chemistry when used under normal water treatment practices. As a result, water treatment with siliconfluorides apparently functions to increase the cellular uptake of lead. Data from lead screening of over 280,000 children in Massachusetts indicates that silicofluoride usage is associated with significant increases in average lead in children's blood as well as percentage of children with blood lead in excess of 10 μg/dL. Consistent with the hypothesized role of silicofluorides as enhancing uptake of lead whatever the source of exposure, children are especially at risk for higher blood lead in those communities with more old housing or lead in excess of 15 ppb in first draw water samples where silicofluorides are also in use. Preliminary findings from county-level data in Georgia confirm that silicofluoride usage is associated with higher levels of lead in children's blood. In both Massachusetts and Georgia, moreover, behaviors associated with lead nurotoxicity are more frequent in communities using silicofluorides than in comparable localities that do not use these chemicals. Because there has been insufficient animal or human testing of silicofluoride treated water, further study of the effect of silicofluorides is needed to clarify the extent

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to which these chemicals are risk co-factors for lead uptake and the hazardous effects it produces.

Keywords: Lead; toxicity; pollution; children's health; public water supplies

INTRODUCTION

Although it has been known since antiquity that lead is harmful to human health, its precise neurotoxic effects have only recently been studied in detail [1, 2]. Lead exposure is now considered a risk factor in fetal and early childhood developmental deficits, premature birth, low cranial circumference, lower IQ, learning deficits, attention deficit disorder (ADD) or hyperactivity (ADHD), and reduced impulse control [3]. Lead neurotoxicity has also been linked with higher rates of aggressive or criminal behavior in both correlational [4] and prospective studies [5]. Although acute exposure to lead also increases susceptibility to hypertension, heart disease, renal disease, or cancer, evidence of disease risk from chronic, low-level exposure is mixed (suggesting the importance of other risk co-factors) [6]. For some behavioral effects of lead neurotoxicity, data based on individual levels of lead absorption have been confirmed by ecological comparisons between communities or counties in the U. S. that vary in the exposure to lead pollution [7, 8].

Apart from occupational hazards, attention was long focused on leaded gasoline and house paint as the principal vectors of public exposure to lead. The prohibition of these products has been associated with a significant drop in children's blood lead levels [9]. Nevertheless, chronic low level lead intoxication remains a major problem of public health and behavioral dysfunction in the United States [10].

Recent research has shifted to other sources of lead, including urban soils with lead residues from gasoline additives [11] and industrial pollution [12]. The possibility that supplied municipal water might be an additional vector was suggested in a recent study of over 2800 counties in the continental United States in which – controlling for such socio-economic and demographic variables as population density, income, and race as well as industrial pollution – the percentage of households on public water supplies was an additional risk factor for high school drop-out, welfare dependence, and violent crime [7].

The relation between municipal potable water and enhanced lead uptake was analyzed for all communities in Massachusetts by combining: (i) data compiled in an extensive survey of children's blood lead levels conducted in 1990–91 by researchers at Dartmouth College and Mary Hitchcock Hospital [13], (ii) reports of "first draw" water lead monitored in 1992–93 under the EPA "Lead/Copper Rule", (iii) data from the 1990 US National Census; and (iv) water fluoridation methods employed by individual communities as tabulated in the "CDC Fluoridation Census, 1992."

The use of silicofluorides–fluosilicic acid (H_2SiF_6) and sodium silicofluoride (Na_2SiF_6)–is suspect for several reasons [14]. First, dissociation of these compounds into free fluoride anion (F^-) and the associated acidic cation (H_3O^+) is almost certainly not complete under the conditions of normal water treatment, leaving residues of toxic silicofluorides in the water stream [15]. Consequently, there is a strong likelihood that additional F^- and H_3O^+ will be liberated into the water after it has left the water treatment facilities, with attendant chemical reactions that increase acidity (lower pH) beyond the expectations established by current practice. Acid water in turn can extract lead from pipes, solder and fixtures made of lead-bearing alloys, and increase the bioavailability of lead from water at the tap [16]. In addition, traces of undissociated fluorinated silica residues may complex dissolved lead and facilitate its transport from the gastrointestinal tract to the blood stream [17].

METHODS

1. Blood Lead Levels

The Dartmouth-Hitchcock Hospital study sampled children ages 0 to 4 for capillary blood levels in μg/dL; a much smaller sample of venous blood lead levels in μg/dL was also recorded. (For detailed methods, see earlier published reports) [12, 13]. Because the total number of children screened for venous blood was so small (median of 8 children per community, with the lowest quartile towns averaging only 2 children between the ages of 0 and 4) and reflected potential selection bias, community average levels of capillary blood were used for statewide multivariate statistical analysis. To confirm that these findings were not due to confounding factors, including possible contamination of capillary blood, venous blood was used to assess the prevalence rate of children between 0 and 4 whose blood lead level was above the CDC recommended maximum of 10 μg/dL. (Selection bias, due to retest of children with high levels of lead in capillary blood, need not confound this measure as it does for community averages of blood lead uptake).

2. Public Water Supplies

Water quality reports from Massachusetts towns for levels of lead and other toxic metals are routinely maintained by Federal law [18]. Our analysis is based on reports provided by the Massachusetts Department of Environment's Drinking Water Program, listing each community's average 90th percentile first draw levels of lead – that is, the highest decile of reported lead (in ppb) when tested household taps are first turned on in the morning. Although so-called "service" levels, after water has been allowed to run, are typically much lower than first draw, our measure is the nationally accepted measurement of safe water quality. Inspection of raw data from local water systems shows, however, that these measures vary considerably over time as well as between one household and another in the same neighborhood. Because statistical analysis using reported water lead levels as a continuous variable may be less reliable than has often been assumed, we have also divided the sample by quartile in order to compute analyses of variance.

Methods of fluoridation are classified and reported by the United States Public Health Service census of water treatment facilities [19]. Three principal agents are utilized in the U.S.: 30% fluosilicic acid (H_2SiF_6), a liquid which is injected into a main water stream *via* a flow rate control device; sodium silicofluoride (Na_2SiF_6), a dry powder which is made up to a saturated solution which is then metered into the main stream, and sodium fluoride (NaF), the agent used in most toothpastes, which is also made up to a saturated solution for metering into the main water stream. The two silicofluorides require addition of neutralizing agent since they both produce significant acidity. Some communities are also considered to be "naturally" fluoridated due to levels of fluoride in the water prior to treatment; such communities are allowed to distribute water with up to 4 ppm of fluoride, whereas when fluoridation agents are used, water is adjusted to between 0.8 and 1.2 ppm fluoride.

Data on both fluoridation agent and average first draw lead levels in water were available for 227 towns: 51 using fluosilicic acid, 40 using sodium fluoride, 7 towns using sodium silicofluoride, and 129 not using a fluoridation agent.

3. Demographic and Socio-economic Measures

WTown-level data were compiled from the U.S. census, FBI, and Massachusetts Department of Education. Variables studied include population density, per capita income, ethnic composition, housing age and quality, percentage of households on public welfare, percentage high school dropouts (per capita), and rates of both violent and property crime. Because census data on high school dropouts reflects economic opportunity and social class as well as educational failure, standardized test scores (MEAP) and dollar expenditures per town were also used. (Special education budgets would be unreliable for this purpose, both because towns vary greatly in educational policies such as mainstreaming and because the influence of lead on IQ has been shown to be continuous, with no threshold effects allowing a segregation of the population potentially affected [20].

4. Statistical Analyses

Analysis of variance and multivariate models were used to asess the associations between children's blood levels of lead and the lead levels in their community's water supply, between lead levels in water supplies and fluoridation agents, and between behavioral deficits otherwise associated with lead uptake and children's blood lead levels. Because this is an ecological study and sampling error in each community's average level of blood lead was a matter of concern, different measures of lead toxicity (average levels of lead in capillary blood, and percent screened with venous blood above 10 μg/dL, the current CDC threshold) were used, as were a variety of behavioral factors associated with lead neurotoxicity.

Multivariate analyses provided a control for such socio-economic and demographic factors as population density, income, housing age, and race. Although the original survey included children from the entire state of Massachusetts (350 communities), multivariate data could only be analyzed for the 213 communities for which we could obtain water quality reports and census data as well as blood lead screening. This group, however, includes all but one fluoridated town and virtually all other communities over 3,000 population.

To control for the methodological questions that have been raised concerning multiple regression models in epidemiological research [21], a sample of 30 communities with populations between 17,000 and 48,000 (total population 837,300) using silicofluorides was compared with a matched set of 30 unfluoridated communities (total population 845,100). This sample excludes Boston and other large cities, where higher rates of poverty, crime and educational failure might confound the analysis. Because most of the localities not included in at least one of these data analyses are extremely small and have populations that often use household wells for their water supplies, the resulting findings incorporate all major towns and cities and the vast majority of the Massachusetts population.

RESULTS

Whereas a community's average uptake of lead by children is weakly associated with the so-called "90th percentile first draw" levels of lead in public water supplies (adjusted $r^2 = 0.02$), the fluoridation agents used in water treatment have a major effect on lead levels in children's blood. Average levels of lead in capillary blood were 2.78 μg/dL in communities using fluosilicic acid and 2.66 μg/dL in communities using sodium silicofluoride, while they were significantly lower in communities that used sodium fluoride (2.07 μg/dL) or did not fluoridate (2.02 μg/dL) (one way ANOVA, $p = 0.0006$; DF 3, 209, F 6.073). The prevalence rate of individuals whose capillary blood lead was above the maximum permissible level of 10 μg/dL was also significantly higher in the communities using either of the silicofluoride compounds (fluosilicic acid = 2.9%, sodium silicofluoride = 3.0%; sodium fluoride = 1.6% untreated = 1.9%; $p < 0.0001$; DF 3,212, F

8.408). Despite smaller samples tested, similar findings were obtained using venous blood uptake. These findings are independent of recorded 90th percentile first draw lead levels in the public water supplies [22].

To explore more fully the effect of both silicofluorides, a matched sample of 30 communities using these agents and 30 nonfluoridating towns was studied in detail (Tab. I). The matched groups are similar in total population (837,300 *versus* 845,100) and numbers of children between 0 and 5 (57,031 *versus* 56,446). While the non-fluoridated towns are slightly poorer (per capita income $16,600) than the communities using silicofluorides ($19,600) and have a lower percentage of residents with a college degree (23.6% *versus* 30.5%), they also have fewer residents who are either below the poverty line (4.6% *versus* 5.1%) or are nonwhite (6.6% *versus* 11.5%).

None of these factors would predict our finding that the communities using silicofluorides in water treatment have a disproportionate prevalence of children with dangerously high levels of blood lead: in our matched sample of similar communities, where silicofluoride was used, 1.94% of the children screened had over 10 μg/dL, whereas only 0.76% of the non-fluoridating towns had similarly high levels of lead in venous blood lead. This translates to a risk ratio of 2.55 ($p < 0.001$ by chi-square analysis).

DISCUSSION

Out findings suggest that chemical attributes of water treatment and delivery systems can mediate or enhance the deleterious effects of environmental exposure to lead. Such an hypothesis is confirmed by analysis of variance to assess interactions between fluoridation treatment agents and other sources of lead in the environment as factors influencing local variations in children's uptake of lead. When both fluoridating agents and 90th percentile first draw lead levels are used as predictors of lead uptake (Tab. II), the silicofluoride agents are only associated with substantially above average infant blood lead where lead levels in water are higher than 15 ppm. This interaction between the use of silicofluorides and above average lead in water as

TABLE I Percent children screened with blood levels above CDC maximum (10µg/dL): matched sample of 30 nonfluoridated and 30 silicofluoride treated communities

	Total population (x 100,000)	*Children* 0 – 5	*# Children screened*	*# Lead risk (Pb* > 10 *μl/dL)*	*%Screened high risk*	*@ H_2O Pb (pbb)*	*4th Gr MEAP (average)*	*%Poor*	*%Non white*	*%AB*	*Income percap* ($1,000)	*Elem budget* ($1,000)
30 Non-fluoridated Communities	837.3	57031	37310	283	0.76	21	5440	4.6	6.6	23.6	16.6	3584
30 Fluorosilicic Acid or Sodium Fluorosilicate Treated Communities	845.1	56446	39256	762	1.94	30	5455	5.1	11.5	30.5	19.6	4067

TABLE II Correlation of lead in public water and fluoridation agents with children's blood lead

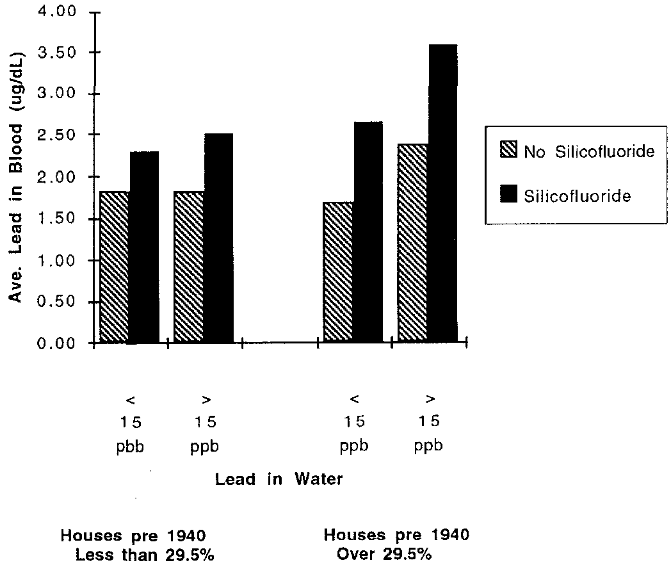
	None	*Sodium fluoride*	*Fluoridation agent* *Sodium Silico-fluoride*	*Fluosilicic acid*	*Average*
Lead in Public Water					
< 15 ppb	1.97	2.11	2.37	2.31	2.08
n =	*86*	*31*	*6*	*26*	*149*
> 15 ppb	2.18	1.9	4.38	3.27	2.61
n =	*29*	*8*	*1*	*25*	*63*
Average	2.02	2.07	2.66	2.78	2.23

Analysis of Variance Lead in Public Water:: $p = 0.026$, F 5.06, DF2, 204; Fluoridation agent: $p = 0.004$, F 6.30, DF 3, 204; Interaction term: $p = 0.052$, F 2.62, DF 3, 204.

predictors of children's lead uptake is statistically significant ($p = 0.05$; DF 3,204, F2.62).

To confirm this effect, we assessed the extent to which silicofluoride usuage might increase the risk from lead paint in old housing as well as lead in the water. Towns were dichotomized according to whether they use silicofluoride agents, whether percent of houses built before 1940 was above the state median, and whether 90th percentile first draw water lead was over 15 ppb. In towns with both more old housing and high levels of lead in water, average blood lead is 3.59 µg/dL in 20 towns where silicofluorides are used, and only 2.50 µg/dL (slightly above the average of 2.23 µg/dL) in the 26 towns not using these agents. Controlling for other sources of lead, silicofluoride usage remains significant (Fig. 1).

Preliminary data from a parallel study at the county-level in Georgia confirm these effects. Since all large cities in Georgia use silicofluorides, data analysis that controls for population size must focus on counties under 250,000 population. In counties under 40,000 with untreated water, 14% of children screened had blood lead levels over 10 µg/dL, whereas in counties of this size where over half the population drank silicofluoride treated water, 16.8% had this level of lead in their blood. In intermediate sized counties (40,000 to 150,000), the rate of screened children with blood lead over 10 µg/dL was 7.1% if the county was not treated, and 10.5% where silicofluorides were



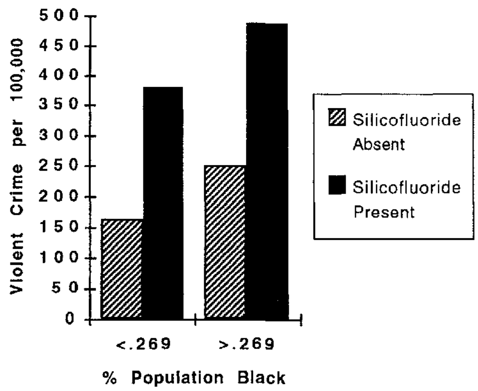
ANOVA Significance:
Main EFFECTS
% Houses pre 1940: p = .00901, F 21.17
90th percentile 1st Draw Lead > 15ppb: p = .0101, F 6.75
Silicofluoride use: p = .0177, F 5.63

Interaction effect
silicofluoride use * 1st Draw Lead in Water: p = .0422, F 4.18

FIGURE 1 Factors associated with children's blood levels – Massachusetts.

used for over half the population. Because communities where silicofluorides are in use were significantly under-sampled, moreover, it would be more accurate to compute estimated prevalence rates. On this basis, the risk-ratio of blood lead levels over 10 μg/dL is apparently increased by 1.46% in counties under 40,000, and 1.23 in counties from 40,000 to 250,000.

These findings suggest that the deleterious effect of the silicofluoride agents is not primarily due to a direct enhancement of lead in water, but rather through chemical effects that maintain lead in supension or biochemical effects that enhance lead uptake (or both). Although many other factors are involved in lead uptake, including dietary deficits in calcium and iron, income, race, and individual lifestyle [24], chemical agents used to treat public water supply appear to be an additional "risk factor" for lead toxicity [25]. It is noteworthy in this regard that rates of violent crime, elsewhere associated with lead neurotoxicity (Fig. 2), are significantly higher in communities that utilize silicofluorides in their water treatment systems not only in Massachusetts, but in Georgia, other states under consideration as this article goes to press, and a sample of cities with lead levels above 15 pbb [7, 26].



Rates of violent crime:

25 counties with no Silicofluoride water treatment and less than 26.9% black population = 161/100,000.

24 counties with no Silicofluoride water treatment and more than 26.9% black population = 249/100,000

52 counties with silicofluoride water treatment and less than 26.9% black population = 377/100,000

57 counties with silicofluoride water treatment and more than 26.9% black population = 486/100,000.

Georgia county ave. = 363/100,000. U.S. county ave. = 284/100,000):

Statistical Significance - Two way ANOVA:

effect of silicofluoride treatment: p = .0001, F 19.522, DF 1, 154

% blacks in population: p = .0561, F 3.704, DF 1, 154

Interaction = n.s.

FIGURE 2 Silicofluorides and Race as risk factors for violent crime–Georgia counties.

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[17] These concerns are distinct from the continued controversy over water fluoridation from all methods: see G. L. Waldcott, A. W. Burgstahler and H. L. McKinney, *Fluoridation: the Great Dilemma* (Coronado Press, Lawerence, Kansas, 1997).

[18] "*EPA/625/R-93/001*" Control of Lead and Copper in Drinking Water, (Environmental Protection Agency, Washington, DC, May 1993).

[19] *Fluoridation Census 1992* (USPHS Centers for Disease Control, Atlanta, Georgia, 1993).

[20] D. Dryce-Smith, "Lead Induced Disorder of Mentation in Children", *Nutr. and Health.* **1**, 179–194 (1983).

[21] K. C. Land, P. L. McCall and L. E. Cohen, "Structural Covariates of Homicide Rates: Are There Any Invariances across Time and Social Space?", *Am. J. Soc.* **95**, 922–963 (1990).

[22] Towns using sodium fluorosilicate reported lower first draw water lead values (11.7 ppb) than unfluoridated towns (21.2 ppb) or towns using sodium flouride (17.5 ppb); communities using fluosilicic acid had significantly higher levels of lead than in others (39.3 ppb). Although the difference between usage of fluosilicic acid and all other treatment conditions is highly significant ($p < 0.0001$, DF 3, 223, F 9.32), differences in lead in first draw water cannot account for the fact that levels of children's blood lead are comparable in towns using sodium silicofluoride and fluosilicic acid. In any event, there is one order of magnitude difference between lead levels reported in water supplies (in parts per *billion* or 10^{-9}) and measures of lead uptake in blood (micrograms per deciliter are equivalent to parts per *one hundred million* or 10^{-8}).

[23] This result is all the more impressive because multiple regression reveals that percentage of housing built before 1940 is a significant predictor of which towns use silicofluorides (controlling for population density, % vacant housing, *per capita* income, racial composition, and other demographic variables).

[24] D. R. Juberg, *Lead and Human Health* (American Council on Science and Health, New York, 1997), p. 9; H. Abadin and F. Llados *Draft Toxicological Profile on Lead* (Agency for Toxic Substances and Disease Registry, Department of Health and Humand Services, Atlanta, Georgia, August 1997), pp. 202–3.

[25] This hypothesis may help unravel another paradox recently noted by an official of the EPA, who concluded a discussion of the impact of high levels of local soil lead on infant blood lead by remarking: "There is a mystery in all this. It's clear that soil-borne lead contributes to lead poisoning... What's not clear is why some soil-lead contamination contributes more to blood-lead levels than others ... Theories abound, based on such variables as the size of the lead particles or chemical form of the lead...", M. S. Stapleton, *Lead is a Silent Hazard* (Walker and Co., New York, 1994), p. 81. Our findings suggest that water treated with fluosilicic acid or sodium silicofluoride should be added to the list of suspects.

[26] R. D. Masters and M. Coplan "Lead, Water Fluoridation, and Neurotoxicity", *Global Legal Policy* (S. Nagel, Ed.) (St Martin's Press, New York, in press); R. D. Masters and M. J. Coplan (in preparation).