An Economic Evaluation of Community Water Fluoridation

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Abstract

Objective: *The purpose of this research was to assess the local cost savings resulting from community water fluoridation, given current exposure levels to other fluoride sources.* ***Methods:*** *Adopting a societal perspective and using a discount rate of 4 percent, we compared the annual per person cost of fluoridation with the cost of averted disease and productivity losses. The latter was the product of annual dental caries increment in nonfluoridated communities, fluoridation effectiveness, and the discounted lifetime cost of treating a carious tooth surface. We obtained or imputed all parameters from published studies and national surveys. We conducted one-way and three-way sensitivity analyses.* ***Results:*** *With base-case assumptions, the annual per person cost savings resulting from fluoridation ranged from $15.95 in very small communities to $18.62 in large communities. Fluoridation was still cost saving for communities of any size if we allowed increment, effectiveness, or the discount rate to take on their worst-case values, individually. For simultaneous variation of variables, fluoridation was cost saving for all but very small communities. There, fluoridation was cost saving if the reduction in carious surfaces attributable to one year of fluoridation was at least 0.046.* ***Conclusion:*** *On the basis of the most current data available on the effectiveness and cost of fluoridation, caries increment, and the cost and longevity of dental restorations, we find that water fluoridation offers significant cost savings.* *[J Public Health Dent 2001;61(2):78-86]*

Key Words: cost, cost savings, cost effectiveness, water fluoridation, and caries increment.

The Centers for Disease Control and Prevention recently identified water fluoridation as one of 10 great public health achievements in the 20th century (1). Before 1980, communities with fluoridated water supplies typically experienced 50 percent less tooth decay than did nonfluoridated communities (2). Because of the relatively high caries before 1980, economic evaluations of community water fluoridation during this time typically found that the cost of averted disease attributable to fluoridation exceeded the cost to implement and maintain fluoridation (3-5). For example, Niessen and Douglass reported a ratio of cost of averted disease to program cost of 8.22 (5), while Davies reported a ratio of 6.6 (3). In the 1980s, national survey data indicated a secular decline in caries prevalence (2,6) largely attributed to the widespread use of fluoride toothpaste, increased fluoridation of community water systems, and the associated diffusion of fluoride to nonfluoridated communities via the export of beverages and foods (2,7).

This led some to question whether community water fluoridation was still a worthwhile public health investment. For example, according to White, "as recently as 1989, major newspapers have reported articles that call for reexamination of water fluoridation programs, citing the decline in dental caries as a reason to reconsider fluoridation and proposing that water fluoridation may no longer be needed" (8). To date, no economic evaluation of community water fluoridation has assessed the associated cost of averted disease in the presence of lower caries incidence. Therefore, the purpose of this research is to determine if reduction in cost of restorative care due to averted disease still exceeds the program costs of water fluoridation, and, if not, to measure its cost effectiveness. Our analysis was conducted from a societal perspective, which may be adapted to decisions at the local level.

Methods

Form of Economic Evaluation. We examined the per person net cost resulting from one year of exposure to water fluoridation, where (9)

$$\text{Net Cost} = \text{Cost}_{\text{Water Fluoridation}} - \text{Cost}_{\text{Disease Averted and Productivity Losses Averted}} \qquad \text{(Equation 1)}$$

If net cost is negative, then water fluoridation is cost saving. We confined our analysis to two alternatives—implementing or not implementing fluoridation—because previous studies have found that it is the least costly way to deliver fluoride (10). We used the following formula to calculate the *Cost of Disease Averted and Productivity Losses Averted:*

$$\text{Costs}_{\text{Disease Averted and Productivity Losses Averted}} = (\text{Caries Increment}_{\text{Nonfluoridated}}) * (\text{Effectiveness}_{\text{Water Fluoridation}}) * (\text{Average Discounted Lifetime Cost of Carious Surface}) \qquad \text{(Equation 2)}$$

where

$\text{Caries Increment}_{\text{Nonfluoridated}}$ = annual increment of decayed, missing, and filled surfaces (DMFS) in persons not exposed to fluoridated water,

$\text{Effectiveness}_{\text{Water Fluoridation}}$ =

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$| (DMFS_{Fluoridated} - DMFS_{Nonfluoridated}) / DMFS_{Nonfluoridated} |$.

The product of the first two terms on the right-hand side of Equation 2 measures the *number of carious surfaces that can be attributed to foregoing one year of water fluoridation exposure.* A more detailed explanation of the origination of equations 1 and 2 is found in the appendix at the end of this article.

In this analysis, we made the following assumptions:

- The benefit from water fluoridation is primarily topical and posteruptive (11). We limited our estimates of cost savings to the permanent dentition. Thus, we assumed that benefits begin at age 6 years, the age at which the first permanent teeth typically erupt. Additionally, we assumed that benefits accrue only to age 65 years.
- The benefit of fluoride does not accumulate and is constant over time. That is, for an individual with many years of exposure to fluoridated water, the benefit from exposure in year 1 equals the benefit from exposure in year 2 equals the benefit in year 3, and so on (12).
- All decay is eventually treated. A 1997 American Dental Association/Gallup survey reported that 75.5 percent of adults had visited a dentist within the last year (13).
- The adverse effects resulting from water fluoridation exposure are negligible (14).
- The discounted cost of treating decay in the future is at least as high as treating decay when it first occurs.
- Dental fees are equal to the cost of the resources used to provide the dental service.
- Among the many modes of fluoride delivery (e.g., prescription supplements, application at the dental office) water fluoridation is the least costly (14). Because other modes of fluoride delivery, other than fluoride toothpaste, usually would not be required if community water systems were fluoridated, our analysis was confined to comparing water fluoridation with no water fluoridation. Thus, when measuring water fluoridation's effectiveness, we controlled for exposure to fluoride from other sources, where possible (with the exception of toothpaste).
- A decayed tooth surface will always receive a one-surface restoration, regardless of the number of times the restoration is replaced or which surface is affected.
- The social discount rate is 4 percent. All costs were converted to 1995 dollars. We varied the social discount rate from 0 percent to 8 percent in our sensitivity analysis.

Obtaining Parameter Estimates. *Annual Caries Increment in Nonfluoridated Communities.* We estimated annual caries increments in the permanent dentition for three age groups: ages 6–17 years, ages 18–44 years, and ages 45–65 years. Data were obtained from the following sources: studies published from 1978 to 1988 and cited in Garcia's 1989 review of the literature (10); the National Survey of Oral Health in US Schoolchildren (15) and the National Survey of Oral Health in Employed Adults and Seniors (NSOH) (16); and both the First National Health and Nutrition Examination Survey, 1971–74 (NHANES I) (17) and the Third National Health and Nutrition Examination Survey, 1989–94 (NHANES III) (18).

The published studies reviewed by Garcia reported annual caries increments for controls in clinical and community trials. Among children aged 5–17 years who lived in nonfluoridated communities, annual increments ranged from 0.8 to 2.6 surfaces, with a median of 1.4 surfaces. Caries increments in adults, which were not stratified by water fluoridation exposure, ranged from 0.75 to 1.47 coronal surfaces per year, with a median of 0.78 for adults aged 18–44 years and from 0.91 to 1.31 with a median of 0.93 for adults aged 45–65 years. Median increments of root caries in adults equaled 0.05 surfaces for adults aged 18–44 years and 0.31 for adults aged 45–65 years (Table 1). Evidence tables summarizing the studies may be obtained from the authors.

We also imputed increments from the National Survey of Oral Health in US Schoolchildren, 1986–87 Public Use Data File (15) and data reported in the National Survey of Oral Health in Employed Adults and Seniors, 1985–86 (16). The mean annual caries increment for children of 0.77 was estimated by dividing the difference in mean DMFS for 6-year-olds (DMFS=0.14) and 17-year-olds (DMFS=8.62) living in communities without fluoridation by 11.

Caries increment in adults was calculated with the following formula:

$$\text{Increment} = DFS_{\text{Age Group 2}} - (\text{Teeth}_{\text{Age Group 2}} / \text{Teeth}_{\text{Age Group 1}}) * DFS_{\text{Age Group 1}} \qquad \text{(Equation 3)}$$

where

$DFS_{\text{age group x}}$ = mean number of decayed or filled surfaces in age group x

$\text{Teeth}_{\text{age group x}}$ = mean number of teeth in the mouth in age group x

Equation 3 can be stated as increment equals the total number of decayed and filled surfaces in time period 2 less the expected number of decayed and filled surfaces remaining from time period 1. Because DFS figures for adults were not stratified by community fluoridation status and approximately 50 percent of the population were receiving fluoridated water (19), it was likely that national

TABLE 1
Estimates of Annual Caries Increment (Tooth Surfaces) from Selected Studies, by Age

	Age (Years)			
Source (Reference)	6–17	18–44	45–65	Average
Published studies (best case) (39,54)	1.4	0.83*	1.24*	1.16
National Survey of Oral Health (base case) (15,16)	0.77	1.09†	0.43‡	0.76
NHANES (worst case) (17,18)	0.49	0.49	0.00	0.33

*Includes root surfaces and coronal caries.
†Includes annual root caries incidence of 0.03 surfaces.
‡Includes annual root caries incidence of 0.09 surfaces.

estimates of DFS would underestimate caries increment in unexposed persons. To correct for this bias, we used mean DFS figures from Region VII (Pacific), the region with the lowest percentage of the population receiving fluoridated water (20 percent). Imputed mean annual increments equaled 1.09 surfaces for adults aged 18–44 years and 0.43 for adults aged 45–65 years.

Caries increments from NHANES (I–III) were imputed with the same basic methodology as the NSOH estimates and calculated with the following formula:

$$\text{Increment} = DFT_{t2} - (TEETH_{t2} / TEETH_{t1}) * DFT_{t1} \quad \text{(Equation 4)}$$

where

DFT_{tx} = number of decayed and filled teeth in time period x

$TEETH_{tx}$ = the number of teeth in the mouth in time period x

With NHANES, however, we used data on the same birth cohort over time while with NSOH we used data from different birth cohorts for the same time period. Additionally, NHANES data in earlier time periods were reported at the tooth level rather than the surface level. To obtain surface level increments for the NHANES data, tooth level increments for each cohort were multiplied by the ratio of DFS to DFT from the NSOH data (16). Finally, NHANES did not report findings by fluoridation status or region of the country.

We used Equation 4 to calculate increments for children aged 8–17 years between 1971 and 1974 and adults aged 25–34 years between 1988 and 1991. This increment, 0.49 surfaces, was generalized both to children and to adults aged 18–45 years. For older adults we compared adults aged 35–44 years between 1971 and 1974 with adults aged 55–65 years between 1988 and 1991. For this group, increment rounded to 0.0 surfaces.

Table 1 contains increment estimates for each age group derived from the three data sources. Because our evaluation criterion is net cost or cost savings, worst-case assumptions are those that decrease cost savings (NHANES) and best-case assumptions are those that increase cost savings (published studies).

Water Fluoridation Effectiveness. Estimates of the effectiveness of water fluoridation were obtained from the published literature and imputed from the National Survey of Oral Health in US Schoolchildren, 1986–87 Public Use Data File (15). A review of published studies that were conducted from 1979 to 1989 among US children reported a mean caries reduction of 26 percent from water fluoridation (2). The few post-1980 studies documenting the effectiveness of water fluoridation in adult populations also produced effectiveness parameters close to 25 percent. For example, Grembowski et al. found that adults aged 30 years living in fluoridated communities in the Pacific Northwest experienced 31 percent less dental decay than did adults in nonfluoridated communities (12). Eklund et al. found that adults who received water with a high fluoride concentration (3.5 ppm) experienced 20 percent fewer carious surfaces than did adults living in communities in which the fluoride content was 0.7 ppm (21).

Effectiveness estimates obtained from cross-sectional surveys vary widely across geographic region (2). For example, analysis of the National Survey of Oral Health in US Schoolchildren, which compared caries prevalence in children with lifetime exposure and with no exposure to fluoridated water, found that water fluoridation's effectiveness ranged from –5.6 percent in the Midwest to 60.6 percent in the Pacific region. The national estimate of effectiveness, after controlling for exposure to other sources of fluoride, was 25 percent (22). The negative effectiveness value in the Midwest may have been due to small sample size because few children living in this region actually received nonfluoridated water (2). Using the NSOH data set we estimated effectiveness from the age-adjusted DMFS for children aged 6–17 years who were not exposed to fluoride drops or tablets and who had lifetime residence in communities either with or without fluoridation. Base-case effectiveness (25%), worst-case effectiveness (12%), and best-case effectiveness (29%) were calculated, respectively, from data for all children living in the United States, children living within the four regions with the lowest effectiveness ($DMFS_{Fluoridated}$=2.73, $DMFS_{Nonfluoridated}$ =3.11), and children living in the three regions with the highest effectiveness ($DMFS_{Fluoridated}$=2.56, $DMFS_{Nonfluoridated}$= 3.60).

Number of Carious Surfaces Attributable to Foregoing One Year of Water Fluoridation Exposure. Estimates of the *number of carious surfaces attributable to foregoing one year of water fluoridation exposure* (annual caries increment in nonfluoridated communities * fluoridation effectiveness), ranged from 0.04, assuming low effectiveness and increment, to 0.34, assuming high effectiveness and increment, and equaled 0.19 under base-case assumptions.

Average Discounted Lifetime Cost of a Carious Surface. An amalgam restoration requires maintenance over the life of the tooth. To simplify the calculation of the discounted lifetime cost associated with a carious surface, we divided the population into 10 age groups (6–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, and 60–65). For each age group, we calculated the discounted expected lifetime cost of applying and maintaining a one-surface amalgam restoration for a carious surface developed at the midpoint of the age group. This calculation required estimates of the costs associated with treatment and lost productivity, the expected life of an amalgam, and the probability that a previously restored tooth was present at the midpoint of each age group.

An American Dental Association Survey found that the average cost of a one-surface amalgam restoration in 1995 was $54 (23). To calculate productivity losses, we assumed that the average loss in work time due to a restorative dental visit was one hour. The average hourly total compensation per US worker in 1995 was $18.12 (24). We included this cost for all individuals, regardless of age or work status. For individuals not earning an income outside of the home, this value reflected the opportunity cost of that decision; for children, this value reflected the sacrifice in caregiver time to take the child to the dentist. Hence, the total cost to society resulting from a decayed tooth surface was approximately $72.

We estimated the expected life of an amalgam from five published studies (25-29). The estimated median life for an amalgam ranged from 9 to 14 years and for our calculations, we assumed the expected life of an amalgam to be

12 years. The expected number of replacements for an amalgam restoration in each age group was calculated as follows:

(65 – Midpoint of Age Group) / 12 (rounded down to whole number)

(Equation 5)

For example, an individual in age group 6–19 years would expect to have an amalgam restoration replaced four times in a lifetime [(65 – 12.5) / 12].

The need to replace an amalgam restoration every 12 years will exist only if the tooth is not lost. Hence, for a particular age group the probability that an amalgam will need one replacement can be expressed as:

Pr (having a tooth at midpoint age + 12 years | tooth was present at midpoint age)

(Equation 6a)

and the probability that an amalgam restoration will need a second replacement as:

Pr (having a tooth at midpoint age + 24 years | tooth was present at midpoint age + 12 years)

(Equation 6b)

and so on. Conditional probabilities were imputed from the mean number of teeth present for each age group reported in the National Oral Health Survey of Employed Adults and Seniors, 1985–86 (16).

The discounted lifetime cost of a carious surface equals the sum of the discounted cost of the first amalgam restoration and the discounted costs for each replacement multiplied by the conditional probability the tooth is in place. The costs associated with the first amalgam restoration must also be discounted because the benefits of fluoride begin after one year of exposure. For example, using a 4 percent discount rate, the discounted lifetime cost of a carious surface for decay that developed when an individual was in age group 6–19 years would be:

$$\$72/1.04 + \$72 * 1/1.04^{13} + \$72 * 0.90/1.04^{25} + \$72 * 0.86/1.04^{37} + \$72 * 0.79/1.04^{49} = \$159.61$$

Base-, worst-, and best-case average discounted lifetime costs associated with a carious surface for various age groups were calculated with a 4 percent, 8 percent, and 0 percent discount rates, respectively. Tables with detailed calculations may be obtained from the authors.

Finally, we weighted the average discounted lifetime cost of a carious surface (in 1995 US dollars) for each age group by the proportion of the total US population in 1995 that were represented by persons in that age group (30). These values were summed to obtain the *average discounted lifetime cost of a carious surface*. With a discount rate of 4 percent, this value equaled $100.62 (Table 2) and ranged from $75.57 using a discount rate of 8 percent to $166.68 using a discount rate of 0 percent.

Costs of Disease Averted and Productivity Losses Averted, for various combinations of discount rate, increment, and effectiveness assumptions, ranged from $2.99 in the worst-case scenario to $56.07 in the best-case scenario, with a base-case value of $19.12.

Cost of Water Fluoridation. Cost data for water fluoridation were obtained from a published study that reported the one-time fixed costs and annual operating costs for 44 Florida communities that implemented community water fluoridation in the 1980s (31). All costs were reported in 1988 US dollars. One-time fixed costs included equipment, installation, testing equipment, safety equipment, and consultant engineering fees. All equipment was assumed to have a useful life of 15 years and no salvage value. Annual operating costs included chemicals, labor, and maintenance. Chemical costs (all

TABLE 2
Weighted per Person Discounted Lifetime Cost of Carious Surface Initially Occurring at Various Ages

Age Decay Detected (Years)	Discounted Expected Lifetime Cost of Decayed Surface (US$)	1996 US Population (%)	Weighted Cost ($)
0–5		8.4	
6–19	159.61	20.4	32.56
20–24	146.95	6.8	9.99
25–29	144.86	7.2	10.43
30–34	128.24	8.3	10.64
35–39	127.76	8.5	10.86
40–44	105.12	7.7	8.09
45–49	105.55	6.6	6.97
50–54	106.42	5.2	5.53
55–59	69.23	4.2	2.91
60–64	69.23	3.8	2.63
65+		12.8	
Total		100*	100.62*

*Rounded.

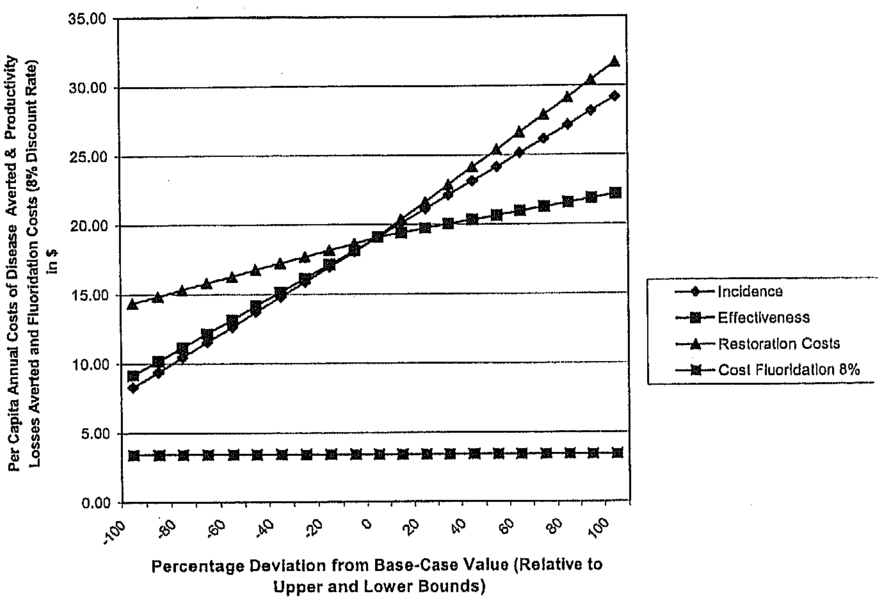
TABLE 3
Range of Estimates for Annual per Person Water Fluoridation Costs for Communities of Various Sizes

Community Population	Per Person Fluoridation Cost at 3 Discount Rates		
	0%	4%	8%
<5,000	$2.94	$3.17	$3.44
5,000–9,999	$1.54	$1.64	$1.75
10,000–20,000	$.98	$1.06	$1.15
>20,000	$.46	$.50	$.54

TABLE 4
Annual per Person Cost Savings (Negative Net Cost) from Water Fluoridation

Community Size	Best Case	Base Case	Worst Case
<5,000	$31.04	$15.95	$0.85
5,000–9,999	$32.57	$17.48	$2.38
10,000–20,000	$33.15	$18.06	$2.96
>20,000	$33.71	$18.62	$3.52

FIGURE 1
One-way Sensitivity Analysis for Varying Incidence, Effectiveness, and Average Discounted Lifetime Cost of Carious Surface



but two of the systems used hydrofluosilicic acid) covered an increase in fluoride from <0.3 ppm to 0.8 ppm. We annuitized the one-time fixed costs over 15 years using discount rates of 4 percent (base case), 0 percent (best case), and 8 percent (worst case) (32). All costs were converted to 1995 US dollars with use of the CPI-U (33) (Table 3).

Sensitivity Analysis. To test the sensitivity of our results to estimated parameter values, we varied the parameters one at a time and calculated their break-even values. Additionally, we conducted three-way sensitivity analyses, allowing the discount rate, effectiveness, and increment to vary throughout their plausible ranges simultaneously.

Results

With a 4 percent discount rate and with the *number of carious surfaces attributable to foregoing one year of water fluoridation exposure* taking on its best-, worst- and base-case values, the net cost of community water fluoridation was negative (cost saving) under all scenarios (Table 4).

In the one-way sensitivity analysis, the per person *Cost of Disease Averted and Productivity Losses Averted* (hereafter termed *Costs Averted*) was calculated as the increment, effectiveness, and *average discounted lifetime cost of a carious surface* (hereafter termed *costs of caries*) were varied individually between their lower- and upper-bound estimates (Figure 1). The slopes of the resulting lines suggest that *Costs Averted* was most sensitive to increases in *cost of caries* above its baseline value and to decreases in increment below its baseline value. Holding all other parameters constant and allowing effectiveness to vary from its worst- to best-case value caused *Costs Averted* to range from $9.18 to $22.18. Allowing only increment or *cost of caries* to vary from their worst- to best-case values produced *Costs Averted* estimates of $8.30 to $29.18 and $14.74 to $31.67, respectively. The horizontal line in Figure 1 shows a per person fluoridation costs of $3.44 (worst-case scenario costs for a community of fewer than 5,000). Thus, when only one parameter (increment, effectiveness, or *cost of caries*) is varied between its upper- and lower-bound values, water fluoridation is cost saving for communities of all sizes.

We performed break-even analyses both for communities with populations fewer than 5,000 and those with populations greater than 20,000. Holding the discount rate constant at 4 percent and increment constant at its baseline (0.76), water fluoridation was cost saving for all effectiveness levels greater than 0.04 in the smallest communities or 0.01 in the largest communities. Holding discount rate constant at 4 percent and effectiveness constant at its baseline (0.25), water fluoridation was cost saving for all increment levels greater than 0.13 in the smallest communities or 0.02 in the largest communities. Holding effectiveness and increment constant at their baselines (0.25 and 0.76, respectively), water fluoridation was cost saving if the discount rate was less than 49 percent for the smallest and 202 percent for the largest communities.

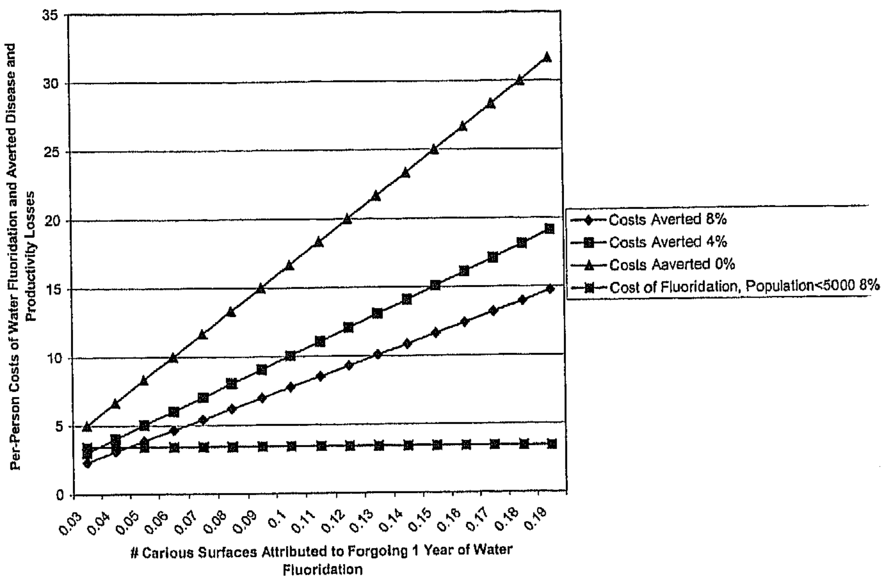
The per person annual cost of water fluoridation was compared with *Costs Averted* when the *number of carious surfaces attributed to foregoing one year of water fluoridation* and the discount rate vary (Figure 2). Only when we allowed effectiveness, increment, and the discount rate to take on their worst-case values (the number of carious surfaces attributed to foregoing one year of water fluoridation equaled 0.04 and the discount rate equaled 8 percent) was water fluoridation not cost saving, and then only for communities with fewer than 5,000 people. Water fluoridation was cost saving for very small communities when the *number of carious surfaces attributed to foregoing one year of water fluoridation* exceeded 0.046 surfaces.

Discussion

With use of the most current data available on the effectiveness and costs of water fluoridation, caries in-

FIGURE 2

Comparing per Person Annual Costs of Fluoridation to Cost of Disease Averted and Productivity Losses Averted for Various Discount Rates Under Base- and Worst-case Scenarios



crement, and the costs and longevity of dental restorations, we found that the reduction in costs of restorative care due to averted disease exceeded the cost of water fluoridation in communities of any size. Our findings were extremely robust to variations in parameters. In this analysis, we allowed the community size, the caries increment in nonfluoridated communities, the effectiveness of fluoridation, and the discount rate to vary. Even with worst-case assumptions, water fluoridation was still cost saving for all communities with the exception of those with populations fewer than 5,000. Cost-saving public health interventions are rare (34). For example, a recent review of the cost effectiveness of life-saving interventions found that only 14 percent of 310 medical interventions were cost saving (35). Implementation of cost-saving interventions actually increases the amount of scarce resources available for other productive uses.

It is important to note that even if water fluoridation has a positive net cost, it may still be desirable. For example, using worst-case assumptions, we found that in communities with populations fewer than 5,000 water fluoridation cost $.42 to save 0.04 tooth surfaces, or $10.50 per tooth surface per year. This may still be an attractive investment for a local decision maker considering several potential public health interventions, dependent upon a community's value of oral health, level of aversion to restorative dental care, and the value of competing public health alternatives.

Obtaining good estimates of caries increments in nonfluoridated communities was difficult. Since this was an important variable in the analysis (*Costs Averted* was most sensitive to changes in caries increment at values below baseline), we used three different sources of data. Inferring current caries increment from each of these sources involved estimation bias. We used cross-sectional data to impute caries increment from the NSOH; but given the secular decline in caries, this would tend to overestimate current increment due to the cohort effect (2,7). Although Garcia cited figures obtained from controlled clinical trials that followed the same population longitudinally, the samples used in those studies were probably not representative of the general population. Those studies may have overestimated increment because their estimates often exceeded those from national cross-sectional surveys. However, it is also possible that examinations conducted in clinical settings, which often include radiographs, were more rigorous than those conducted in epidemiologic surveys and hence identified decayed surfaces earlier. Estimates based on the NHANES data probably underestimated the increment in communities without fluoridation. Because the NHANES data do not differentiate observations by fluoridation status, the study estimates are composite figures, which include observations from lower-increment (fluoridated) areas. In addition, this downward bias may be exacerbated because we followed NHANES birth cohorts from 1971 to 1991, a period in which the percentage of the US population receiving fluoridated water increased from 43 percent to 56 percent (19,20). Because the fluoridation status of some of the birth cohort members changed over time, increment captures not only new decay, but also the benefit resulting from increased access to water fluoridation over the same time period. In addition, it is likely that for older adults failure to accurately adjust for tooth loss resulted in an underestimation of the actual change in decay. For example, although the hypothetical lower bound for incidence should be 0 in adults aged 45–65 years, the imputed increment was negative.

Because costs are difficult to identify and measure empirically, the potential exists for bias in our cost figures. Costs that were not considered but would result in an overstatement of the cost savings of water fluoridation included political costs associated with the passage of a water fluoridation referendum and overhead costs such as electricity, insurance, and shared space. Additionally, cost savings may be overestimated by an upward bias in our estimates of *cost of caries*; we assumed that the $54 fee for a one-surface amalgam represented the true cost of resources. Dental fees would equal resource costs (resource costs include the opportunity cost of the dentist's time) if dental markets are competitive. If dental markets were not competitive, fees would overestimate the true resource costs. However, when we decreased the cost of a one-surface amalgam by 50 percent to $27 (*cost of a caries*=$47.23), *Costs Averted* was $8.97 under base-case assumptions. This amount is well above the per person cost to fluoridate a community of any size for one year. If the protective benefits from water fluoridation begin to accrue after more than one year of exposure, then the cost savings are overstated. For example, in small communities if the expected life of a water fluoridation project was 15 years and the benefits did not begin until after five years of exposure, the per person discounted cost savings over the life of the project would be $25.55 (under base-case assumptions). This value would be $66.16 if benefits accrued after only one year of exposure. Finally, we assumed that the costs of dental fluorosis attributable to water fluoridation are negligible (14).

It is important to note that we assumed no change in dentists' behavior in response to income reductions spurred by decreased need for restorative care. Since dental markets are characterized by asymmetric information (patients don't have full information and thus make their dental consumption decisions based on their dentists' recommendations), providers may be able to induce demand for other dental services. Also, dentists' clinical decisions may vary due to differences in knowledge and beliefs about diagnostic criteria, disease processes, risk factors, and alternative treatment options (37). Thus, dentists may be predisposed to diagnose marginal lesions as carious in fluoridated areas with small patient supplies (36). To the extent that this is possible, dentists may provide more diagnostic, preventive, or even restorative services to maintain a steady stream of income, or may reduce the recall interval between dental visits. Such behavior was reported by Grembowski, who found that insured children with continuous fluoridation exposure received more diagnostic, preventive, and simple restorative services than children with low fluoride exposure (36). Thus, the potential cost savings from reduced restorative care may be partially offset by increased consumption of diagnostic and preventive care.

Alternatively, other assumptions made in this analysis may have biased cost savings downward. For example, we did not include the *Costs of Disease Averted and Productivity Losses Averted* for decay in the primary dentition or for adults over age 65 years. Furthermore, we did not include productivity losses due to dental discomfort in our estimates of averted productivity losses. Finally, we assumed that simple amalgam restorations would always be used to treat initial decay and in subsequent replacements. These assumptions ignore potentially costlier treatment, including for example, composite restorations, root canal treatment, crowns, and bridges.

The magnitude of the cost savings resulting from water fluoridation will depend on the parameter values of the population under consideration. To measure the cost savings that have accrued from the introduction of water fluoridation in the United States, high-end estimates of effectiveness and increment would be most appropriate, because initial increment and effectiveness rates are likely to be high when no water is being fluoridated. A local community that is evaluating a proposed water fluoridation project may require lower increment and effectiveness assumptions if it receives diffused benefits of water fluoridation from nearby communities (2,7,38). For example, in midwestern US communities, low-end increment and effectiveness parameters would be more applicable, whereas in the Pacific US region, high-end values of incidence and effectiveness would be more pertinent.

Relatively few economic evaluations of community water fluoridation programs have been conducted within the last decade. Brown et al. determined that a negative structural shift in US dental expenditures had occurred around 1979 (55). The authors attributed the shift in part to improved oral health resulting from increased access to community water fluoridation. Expenditures decreased by 10 percent which in turn led to savings of 39.1 billion dollars (1990 dollars) from 1979 to 1989. In 1989 the *Journal of Public Health Dentistry* dedicated a special issue to the proceedings from a University of Michigan workshop on the cost effectiveness of caries prevention in dental public health (56). Many of the articles in that issue provided estimates of parameters used in our analysis. The issue did not, however, feature a complete economic evaluation that explicitly stated all assumptions and findings, nor was a sensitivity analysis performed. Our analysis is unique in that it includes both the productivity losses and the costs of subsequent replacements in measuring the costs associated with a dental restoration. In addition, to our knowledge, no other study has used sensitivity analysis to determine the robustness of water fluoridation cost savings given the secular decline in caries incidence and the increased diffusion of water fluoridation's benefits to communities without fluoridation.

Using knowledge of local increment and effectiveness estimates, local officials may estimate potential cost savings from the information presented here. Tables providing net cost estimates for 756 combinations of effectiveness, increment, and cost of caries may be obtained from the authors. One benefit of the per-year savings approach is that it allows decision makers to customize their calculations for projects in which the *Costs of Averted Disease* differ in each year or for projects of varying duration. This would allow consideration of various scenarios, such as decreasing incidence over time due to fluoridation in nearby areas.

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Appendix

Equation 1 in text is the standard net cost equation, as found in Haddix, p. 109 (9):

$$\text{Net Cost} = \text{Cost}_{\text{Intervention}} - \text{Cost}_{\text{Disease Averted}} - \text{Cost}_{\text{Productivity Losses Averted}}$$

In our Equation 1 we combined $\text{Cost}_{\text{Disease Averted}}$ and $\text{Cost}_{\text{Productivity Losses Averted}}$ into a single term, which we called $\text{Costs}_{\text{DiseaseAvertedandProductivity Losses Averted}}$.

As per convention, $\text{Costs}_{\text{Disease Averted and Productivity Losses Averted}}$ = Cost of Disease and Productivity $\text{Losses}_{\text{nonfluoridated}}$ – Cost of Disease and Productivity $\text{Losses}_{\text{fluoridated}}$. This is analogous to Haddix et al., p. 123 (9).

Assuming that disease treatment costs and productivity losses are constant, the Costs of Disease and Productivity $\text{Losses}_{\text{nonfluoridated}}$ = Caries $\text{Increment}_{\text{nonfluoridated}}$ * Average Discounted Lifetime Cost of Carious Surface.

Likewise, Costs of Disease and Productivity $Losses_{fluoridated}$ = Caries $Increment_{fluoridated}$ * Average Discounted Lifetime Cost of Carious Surface.

Thus, $Costs_{Disease Averted and Productivity Losses Averted}$ reduces to:

(Caries $Increment_{nonfluoridated}$ – Caries $Increment_{fluoridated}$) * Average Discounted Lifetime Cost of a Carious Surface.

This equation is multiplied by (Caries $Increment_{nonfluoridated}$ / Caries $Increment_{nonfluoridated}$), a factor of 1, to yield:

(Caries $Increment_{nonfluoridated}$ – Caries $Increment_{fluoridated}$) * (Caries $Increment_{nonfluoridated}$ / Caries $Increment_{nonfluoridated}$) * (Average Discounted Lifetime Cost of a Carious Surface).

Regrouping terms, this equation may be rewritten:

Caries $Increment_{nonfluoridated}$ * [(Caries $Increment_{nonfluoridated}$ – Caries $Increment_{fluoridated}$) / (Caries $Increment_{nonfluoridated}$] * (Average Discounted Lifetime Cost of a Carious Surface).

The term in brackets is the absolute value of the measure of effectiveness in the studies from which we took our data (2,3). Thus, the equation becomes

$Costs_{Disease Averted and Productivity Losses Averted}$ = (Caries Increment $_{Nonfluoridated}$) * ($Effectiveness_{Water Fluoridation}$) * (Average Discounted Lifetime Cost of Carious Surface),

which is Equation 2 in text.