A Simulation Model for Designing Effective Interventions in Early Childhood Caries

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Abstract

Dental caries in primary teeth of children 5 years of age or younger is one of the major health problems in the United States, especially for low-income children. This paper presents a framework for assessing the impact of various programs designed to reduce the prevalence and consequences of Early Childhood Caries. The paper describes a System Dynamics simulation model of the population of children 0-5 years old in Colorado. Results of simulations with a number of individual interventions and combined strategies are presented and program costs and savings in treatment costs are compared.

Introduction

> **Dental caries in primary teeth of children 5 years of age or younger is still one of the major health problems in the United States, especially for low-income children. This largely preventable disease continues to affect many children in lower socioeconomic strata and many ethnic minorities. Poor oral health leads to chronic pain that affects a child's ability to chew food, thrive, and speak, as well as their psychological well being. One of the measurable impacts of severe dental disease in young children is the general medical condition referred to as "failure to thrive." Reports of children with severe dental caries and inappropriately low body weight have been reversed after completing dental care. (taken from C M Jones, et al, 2000)**

This paper presents a framework for assessing the impact of various programs designed to reduce the prevalence and consequences of Early Childhood Caries. The paper describes a System Dynamics simulation model of the population of children 0-5 years old in Colorado. The development and initial implementation of the model was a joint effort of the Children's Dental Health Project (CDHP) and the Oral Health Unit of the Colorado Department of Public Health and Environment (CDPHE). The model is designed to be generic and, with the appropriate data inserted, could represent any state or large city, county, or metropolitan area.

A model such as this one is needed to provide a better idea of the long-term and cumulative effects of different programs on a population of children. Interventions implemented at the same point in time can have very different effects over time depending on the age and income groups they are targeted at, their efficacy in reducing prevalence, and inherent time delays before their impact is realized. Combinations of interventions have even more complex effects that cannot be readily anticipated, but often represent the most effective strategies.

This paper will present the model, describe the various data sources used in its quantification, and present the results of simulations with a number of different interventions and combinations of those interventions. The value of these simulation results is not to provide forecasts, but to help compare interventions for their relative impacts. In addition to calculating reductions in prevalence, dmf scores, and fraction of children with untreated decay, the model also estimates reductions in restorative care costs that may be possible with the application of preventive interventions.

System Dynamics (SD) has a long history of applications to health care delivery and population health. (Homer and Hirsch, 2006) A comprehensive model of dental care and oral health was developed in 1975 for the Division of Dentistry in the Bureau of Health Manpower, USDHEW that projected dental manpower requirements and showed how slightly higher levels of supply could encourage shifts in care-seeking behavior and improve oral health. (Hirsch and Killingsworth, 1975; Pugh-Roberts Associates, 1975) Later work applied the methodology to heart disease. (Luginbuhl et al, 1981) More recent work has applied System Dynamics to developing strategies for dealing with chronic illnesses such as diabetes (Homer et al, 2004; Jones et al, 2006) and cardiovascular disease (Hirsch et al, 2010; Homer et al, 2010). The CDC has also supported the development of a policy game called HealthBound that is based in an SD model and helps people understand the importance of prevention and primary care capacity in the context of health reform. (Milstein et al, 2010).

Structure of the Early Childhood Caries (ECC) Model

The basic structure of the ECC model emerged from a meeting of experts in various aspects of children's oral health in April, 2009 at Columbia University. The overall structure of the model, shown in Figure 1, separates children by age and risk of developing ECC. It was felt that separation by risk is important to characterize differences in ECC prevalence in the population and also to provide options in the model for allocating public health and dental resources to children at greatest risk. Furthermore, socioeconomic status as measured by household income was decided to be the best surrogate for risk, given the significant differences in ECC prevalence among children at different income levels. (Edelstein, 2002) The model distributes Colorado's population of children ages 0 to 5 among these groups.

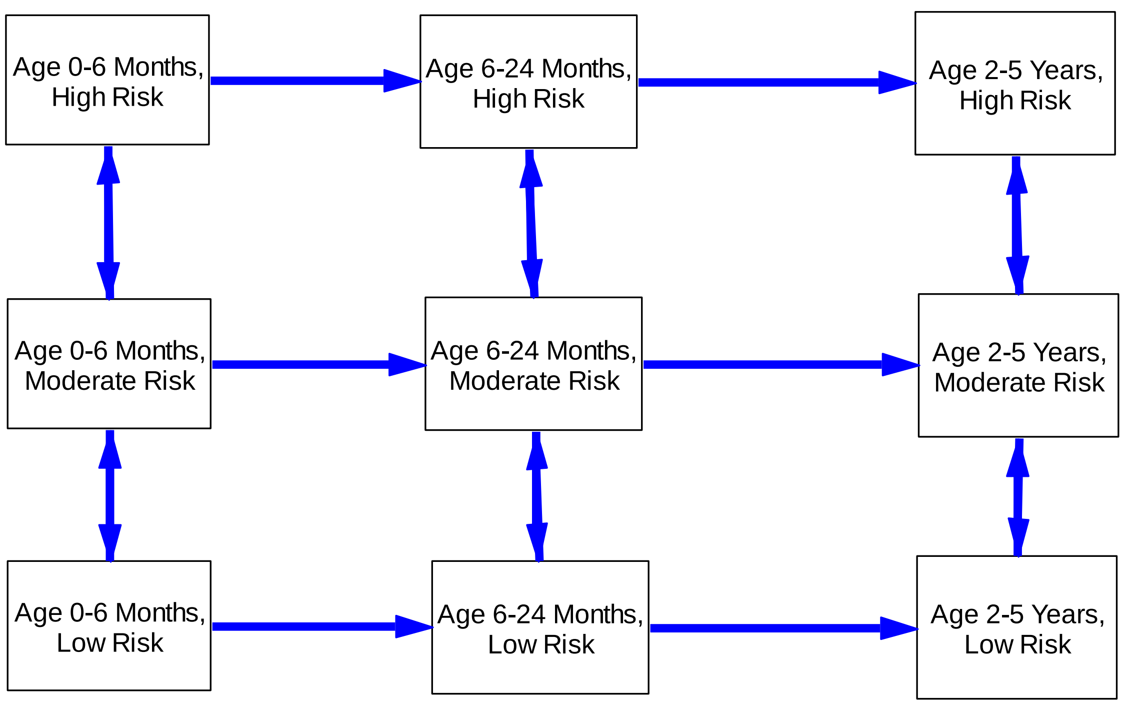

Figure 1: Overview of ECC Model Structure

In simulations with this model, children naturally age over time with births introducing new children and others aging out as they reach their sixth birthday. There is also the possibility of moving between risk categories if, for example, preventive programs result in a different set of circumstances for some children in lower income (higher risk) groups that are less conducive to ECC development and help to promote better oral health.

There are also important things going on within each of the boxes in Figure 1: the progression of ECC. The stages of the disease process, as represented in the model, are shown in Figure 2. Over the course of a simulation, children move from left to right as they develop ECC. Children start initially with No Caries Activity (NCA) and many remain in this category throughout their early childhood. However, some develop caries at rates tied to their age and risk groups and to various other factors that may be affected by preventive interventions. The experts at the April, 2009 meeting urged that the model make an important distinction between caries, that is any presence of the disease, and cavities where the disease creates measurable depressions in teeth. Children who move from the No Caries Activity (NCA) box to the one second from the left labeled Caries are ones who have developed pre-cavity lesions (e.g., white spots), but do not yet have measurable cavities. The purpose of adding this stage to the model is to provide an additional (critical) point at which to test interventions in the ECC process.

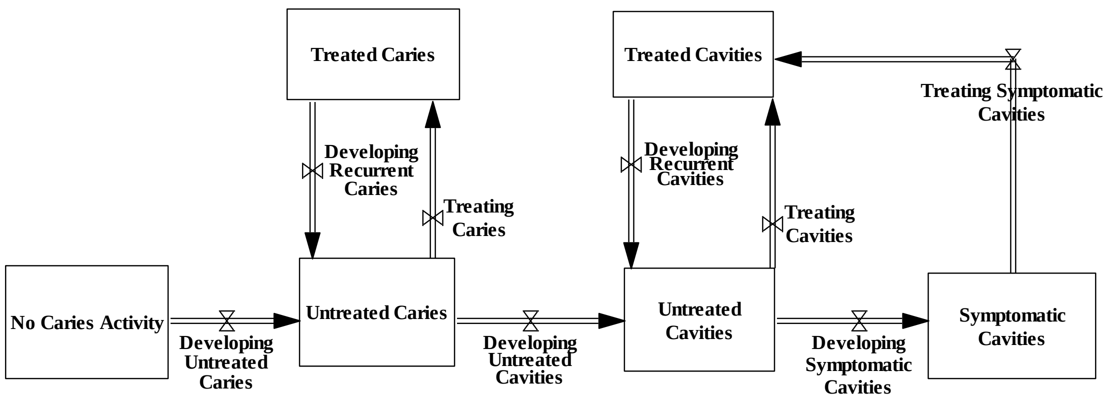

Figure 2: ECC Disease Stages Reflected in the Model

Without treatment or preventive activities, children with Caries develop Cavities that are initially Untreated. Some fraction of these are discovered and Treated during the course of regular dental visits. Others become Symptomatic and require Treatment on a more urgent basis. Some fraction of those children who have had Cavities Treated develop recurrent cavities that are initially Untreated. At each point in a simulation, children are moving in at least two directions as they age and also move through the sequence of stages in ECC and potentially in a third direction if preventive interventions also enable them to move among risk groups.

The model is initially set up in equilibrium and will continue to reflect the initial distribution of children among age and risk groups and distribution among these groups by disease stage in the absence of any new programs. Interventions change rates of flow from one box to another and, over time during a simulation, yield very different patterns of ECC prevalence. The model calculates a number of summary variables (e.g., overall fraction of children with cavities, cumulative cost of restorative care) that enable users to evaluate the potential impacts of different interventions and combinations of programs. The next section describes how the computer model was quantified.

Quantifying the Early Childhood Caries (ECC) Model

Quantifying the ECC model for Colorado required data on prevalence of ECC relative to different demographic and behavioral characteristics such as household income. These data can be obtained for the entire US through the National Health and Nutrition Examination Survey (NHANES), but are not typically available at the state level. Fortunately, it was possible to access data from the Colorado Child Health Survey done as an adjunct to the Behavioral Risk Factor Surveillance System (BRFSS). The Child Health Survey has several oral health questions as well as others about access to medical care and insurance and behaviors such as consumption of sugary drinks. (See http://www.cdphe.state.co.us/hs/yrbs/child_health_questionnaire_2004_1.pdf for a complete questionnaire for this survey.)

The first step in quantifying the ECC model was to choose the income ranges for the High, Moderate, and Low Risk groups. Because there were no data on the fractions of children with cavities in Colorado to explore this question, fractions from the Child Health Survey with a positive answer to the question: **Pain\ Cavities\ Broken or Missing Fillings\Teeth Pulled Because of Cavities?** were used as a surrogate. These data revealed a pattern with a consistently high prevalence of these decay-related problems in income levels going up to 200% of FPL (averaging 18.6%) with some decline from 200% to 300% (15%), and a much lower level for income levels greater than 300% of FPL (8.4%).

The next step was to distribute the population of children in each age and risk group into the stages in the ECC disease process shown in Figure 2, beginning with the fractions of children in each group with cavities. As indicated above, the percentages of children with a positive answer to the question **Pain\ Cavities\ Broken or Missing Fillings\Teeth Pulled Because of Cavities?** in the Child Health Survey to establish the pattern of relative prevalence of cavities among the age and risk groups. However, these patterns reflected self-report by parents rather than the more rigorous identification of cavities by examination that is done as part of the NHANES survey. The fractions in the Child Health Survey data do not, for example, include children whose cavities are asymptomatic and have not come to the attention of parents. Therefore, to get comparable fractions of children with cavities, the fractions with positive answers to this question in the Child Health Survey (about 12.75% overall) were inflated to reflect cavity prevalence of 23% reported for 1999-2002 in the NHANES survey for 2-5 year olds, when adjusted for Colorado's income distribution. (See Beltran-Aguilar et al, 2005). The NHANES data also provided fractions of children 2-5 with untreated cavities, by income level. The fraction of children with symptomatic cavities came from data on 2-5 year olds in "urgent need of treatment" in a GAO report derived from NHANES. (GAO, 2008).

There are no readily available data on the prevalence of what we are calling Caries in our model, pre-cavity conditions such as white spots. Fractions with caries (but not cavities) therefore had to be derived using percentage changes in cavity prevalence between the age groups (6-24 months→2-5 years from the Child Health Survey; 2-5 years→6-11 years from the NHANES data), assuming that children developing cavities in a particular age group who didn't have them before would be likely to have a "pre-cavity" condition. Table 1 shows the fractions of children in the different age/risk groups at different stages in the disease process. Transition rates (flows between the boxes in Figure 2 expressed in terms of children per month) were estimated initially based on increases in prevalence in the various ECC stages between one age group and the next (6-24 months→2-5 years and 2-5 years→6-11 years). The model was then used to more finely calibrate these rates (children per month moving from one stage to the next). As indicated earlier, the purpose of this calibration was to create a model in equilibrium that would make it possible to see the incremental effect of any interventions.

One check on the calibration resulted in an additional adjustment. Treatment rates for cavities generated by the model (numbers of children moving from the Untreated Cavities to Treated Cavities boxes) were compared to numbers of children who could be expected to have a restorative procedure during a year based on data from the Medical Expenditure Panel Survey (MEPS) (Manski and Brown, 2007). This comparison revealed that the numbers being generated by the model were too low and they were increased accordingly.

			Age 6-24 Months				
	No Caries Activity	Untreated Caries	Untreated Cavities	Treated Cavities	Symptomatic Cavities	Fraction with Cavities	Fraction with Untreated Cavities
Low Risk	0.85	0.08	0.03	0.03	0.01	0.07	0.63
Moderate Risk	0.73	0.14	0.08	0.03	0.02	0.13	0.74
High Risk	0.67	0.17	0.10	0.04	0.03	0.16	0.76
			Age 2-5 Years				
Low Risk	0.76	0.09	0.07	0.06	0.03	0.15	0.64
Moderate Risk	0.57	0.16	0.16	0.07	0.04	0.27	0.74
High Risk	0.46	0.20	0.20	0.08	0.06	0.34	0.76

Table 1: Fractions of Children at Various Stages of ECC Development by Age and Risk

The model produces restorative visit rates that fall within the range suggested by the MEPS data. (Manski and Brown, 2007) The cost of restorative care for the 0-6 population is also calculated by the model. Cumulative costs for restorative care are a useful metric for comparing simulations and estimating potential savings on restorative care that might offset programmatic costs for implementing various interventions. There are two components to this cost calculation: 1) conventional care in the dental office and 2) care under anesthesia in hospital ORs or ambulatory surgical centers for very young children and others who require it.

The model also includes fractions of children in the different age/risk groups with detectable levels of s. mutans bacteria, a prime causal agent in the ECC disease process. The presence of s. mutans colonization as a discrete element in the model will enable us to test the effects of various interventions such as reducing the transmission of s. mutans from caregiver to child, education to reduce the consumption of sugary drinks and use of baby bottles to put children to sleep, and direct administration to children of substances such as xylitol that reduce s. Mutans colonization.

Simulations with Different Interventions

The model supports a number of possible interventions. Simulations with the model over a ten year period can project changes in fractions of children ages 0-6 with cavities and with untreated cavities and symptomatic cavities, dft scores, and costs of restorative care. These results can be weighed against estimated program costs to get a rough idea of cost-benefit ratios for different interventions. Interventions can be applied to the entire populations or to particular age and/or risk groups. Possible interventions include:

- Educational programs that reduce the consumption of sugary drinks, use of baby bottles at night, and other harmful practices that contribute to the growth of s. mutans and the ECC disease process.

- Programs aimed at reducing the transmission of s. mutans from parents and other caregivers to children using xylitol gum, chlorhexidine, or other substances.

- Use of xylitol products directly with older children.

- Aggressive screening for and treatment of caries (pre-cavities) to reduce progression to cavities.

- Expanded use of fluoride varnish.

- Focused preventive care and education for children who already have cavities to reduce recurrence rates.

- Rigorous tooth brushing programs with fluoride toothpaste.

- Expansion of Community Water Fluoridation (CWF) to the entire population.

- Motivational interviewing with a strong educational component.

The following section describes a number of simulations done with the model and presents their results. Results of each simulation are shown at the end of ten years, once any new interventions have had their full effect, and compared to the results of a "baseline" simulation in which no new interventions are assumed and the model remains in equilibrium.

Community Water Fluoridation and Application of Topical Fluorides

Assumptions:

- In the first simulation (only), Community Water Fluoridation (CWF) is extended to the 24.6% of the population in Colorado not currently covered.

- We started with the assumption that initiation of CWF in a population could reduce measured caries by 50.7% based on post exposure measurements of concurrent comparison groups (range: 22.3% to 68.8%) (CDC Task Force on Community Preventive Services, 2002). However, based on expert input, the assumed impact of CWF was reduced by half since many of those children not currently covered by fluoridated water systems might already be getting fluorides from toothpastes, foods and vitamins. (Maas, 2010a) A cost of 50 cents per person is added for the entire additional population covered (including adults) since CWF is applied to everyone. (US Centers for Disease Control and Prevention, 2009)

- In the second simulation, fluoride varnish is applied to <u>all</u> children in age groups 2 and 3 and, in the third simulation, <u>only to children in the high risk groups</u>. A fourth simulation applies fluoride varnish to children in all risk groups, but only those in age group 3.

- Application of fluoride varnish reduces dmfs in deciduous dentition by 33% based on a pooled estimate from Cochrane database review. (Marinho et al, 2002) A range of 27% to 44% was reported in another article. (Kanellis, 2000)

- A cost of $16 per child is assumed for fluoride varnish application. Two applications per year are provided for all children (in the second simulation) and three per year when the high risk group is the focus in the third simulation. (Maas, 2010b)

Results are shown in Table 5 on the next page.

Extending CWF to all children has only a limited impact on the prevalence of ECC because such a large fraction of the population is already covered by community-level fluoridation. However, it is a good investment since $6 million in program costs can potentially buy a $14 million reduction in restorative care costs over the 10 year period. And that does not include reduced treatment costs for older children who also benefit from the fluoridated water.

	Overall Percentage with Cavities	Overall Percentage with Untreated Cavities	Overall_dft	Cumulative Cost of Restorative Care ($ Mil)	Difference in Cumulative Cost of Restorative Care Relative to Base ($ Mil)	Cumulative Program Cost ($ Mil)
Base	18.2%	71.39%	265,923	208	0	0
Extending CWF to Everyone	17.0%	70.80%	249,042	194	14	6
Fluoride Varnish, All Kids, Age Groups 2 and 3	12.4%	67.33%	182,196	143	65	118
Fluoride Varnish, High Risk Only, Age Groups 2 and 3	15.7%	68.68%	214,281	174	33	56
Fluoride Varnish, All Kids, Age Group 3 Only	16.0%	67.79%	233,723	181	27	85

Table 5: Results of Simulations Extending CWF and Applying Fluoride Varnish

Providing topical fluoride varnish for all children in age groups 2 and 3 yields a more significant impact on ECC prevalence. Starting with younger children helps produce this larger impact because it allows this intervention to reach kids early before cavities develop. ECC prevalence is considerably lower and savings on restorative care costs have “paid back” more than half the program costs incurred. Reductions in restorative care cost understate the benefit from this and other interventions because it doesn’t include many other benefits of improved oral health.

The advantage of starting early is evident from comparing the results of the second simulation with that of the last one in which fluoride varnish is only applied to children in age group 3, missing the opportunity for an early preventive effect. Though the program cost is lower in that final simulation, the benefit in terms of reduced restorative care costs is proportionately smaller per dollar spent.

Providing this intervention for the highest risk (lowest income group) also has a smaller overall impact, as might be expected, but slightly a higher ratio of benefit (in terms of reduced restorative care cost) to program cost. This suggests that, with limited funding, priority be given to children at highest risk.

Treatment of Mothers with Xylitol to Prevent Transmission of S. Mutans

Assumptions

- 88% reduction in age group 2 and 64% reduction in age group 3 in S. Mutans colonization for children whose mothers were treated with Xylitol based on one study that produced a 0.2 RR at age 2 and 0.42 RR at age 3, increased to produce better match with colonization prevalence data in older age group. (Soderling et al, 2001). Similar reductions in colonization were found by in children whose mothers went through another preventive program. That program used a combination of education and chlorhexidine, but illustrated what could be accomplished with s. mutans reduction in children when mothers have been treated. (Kohler et al, 1983)

- 73% reduction in development of caries in children without S. Mutans colonization based on the Xylitol study cited above that produced a 0.27 RR in 3-5 year olds who did not have S. Mutans colonization as two-year olds. (Isokangas et al, 2000). The earlier study cited above (education+chlorhexidine) found that children who were not colonized by age 2 were much less likely to have had caries by age 4 (25% vs. 89% for those who were colonized at age 2). (Kohler and Andreen, 1994)

- Applied to mothers of children in age groups 1 and 2 only; delayed effect on children in age group 3 as children who did not benefit from treatment age out and those whose mothers were treated age into that group; 12 month delay assumed between time mother's S. Mutans level is lowered and time transmission would have occurred

- $100 average one-time cost per mother

	Overall Percentage with Cavities	Overall Percentage with Untreated Cavities	Overall_dft	Cumulative Cost of Restorative Care ($ Mil)	Difference in Cumulative Cost of Restorative Care Relative to Base ($ Mil)	Cumulative Program Cost ($ Mil)
Base	18.2%	71.39%	265,923	208	0	0
Xylitol Moms, All Kids	10.8%	68.22%	160,609	152	56	79
Xylitol Moms, High Risk Only	15.0%	69.27%	201,765	180	28	25

Table 6: Results of Treating Mothers with Xylitol to Reduce Transmission of S. Mutans

A significant (40%) reduction in fraction of children with cavities is projected to occur when mothers are treated with Xylitol gum to reduce transmission of S. Mutans bacteria. Again, concentrating on the highest risk children will yield a smaller over all effect, but larger reduction in restorative care cost per program dollar spent. Treating mothers with Xylitol has its most direct effects on the youngest children and more delayed effects on those in the oldest age group. As with fluoride varnish, the reduction in restorative costs pays back a substantial portion of the program costs. The leverage provided by this intervention, when applied to the highest risk (lowest income) group may pay back all or most of the program's costs.

Figure 5 on the next page contrasts the benefit over time from this intervention with the one in the previous set using fluoride varnish with all children in age groups 2 and 3. The graph shows the effect on the number of children in age group 3 with cavities and how treating mothers with Xylitol is slower to have an impact, but eventually can have a greater effect than the fluoride varnish.

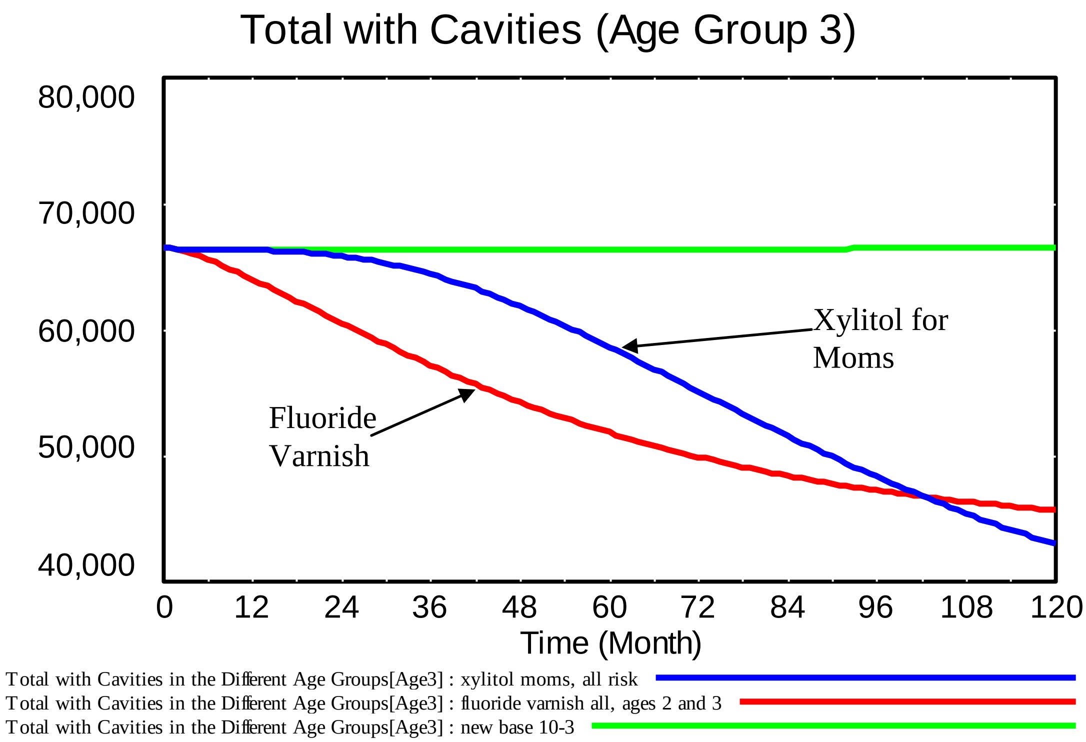

Figure 4: Results over Time Comparing Fluoride Varnish with Xylitol Treatment of Mothers

Motivational Interviewing

Assumptions

- Motivational interviewing, with appropriate follow-up, can reduce cavity prevalence by 63% (Weinstein, 2004). Simulations were done applying this intervention for all children and for those in the highest risk group only.

- The estimated cost is $100 per child.

	Overall Percentage with Cavities	Overall Percentage with Untreated Cavities	Overall_dft	Cumulative Cost of Restorative Care ($ Mil)	Difference in Cumulative Cost of Restorative Care Relative to Base ($ Mil)	Cumulative Program Cost ($ Mil)
Base	18.2%	71.39%	265,923	208	0	0
Motivational Interviewing, All	6.5%	59.54%	95,434	86	122	111
Motivational Interviewing, High Risk Only	12.9%	65.99%	159,020	144	64	35

Table 9: Results with Motivational Interviewing

Motivational interviewing can have a significant impact on reducing the fraction of children with cavities and the costs of restorative care. As indicated earlier, these cost savings are only a fraction of the benefit that would be derived from such a large reduction in cavities. Using this technique with only the high-risk group will, as with the other interventions, produce a smaller overall impact, but a larger benefit per dollar spent on the program. Concentrating on the highest risk group also helps to improve equity among the different risk groups.

Combined Interventions

The following interventions were combined in each of the simulations whose results are shown in the table below:

1. Fluoride varnish for all children in age groups 2 and 3 together with screening and treatment for caries (pre-cavity lesions) using lower impact assumption.

2. Interventions in #1 together with secondary prevention aimed at children who have had restorative care for cavities with the assumption that recurrence rates are cut by 50%.

3. Interventions in #2 together with motivational interviewing benefiting all children. The overall effect of this combination is to reduce cavities by 75% as a result of the fluoride varnish (33%) and the motivational interviewing (an additional 63%) and a further amount due to the effect of screening and treating for caries. Program costs are $16 per child per application for the fluoride varnish, $100 for the motivational interviewing, and $242 for the caries (pre-cavity) treatment.

	Overall Percentage with Cavities	Overall Percentage with Untreated Cavities	Overall_dft	Cumulative Cost of Restorative Care ($ Mil)	Difference in Cumulative Cost of Restorative Care Relative to Base ($ Mil)	Cumulative Program Cost ($ Mil)
Base	18.2%	71.39%	265,923	208	0	0
Combined 1	9.1%	66.39%	136,005	121	87	147
Combined 2	9.1%	57.38%	136,005	108	100	147
Combined 3	3.8%	42.44%	56,158	59	149	245

Table 10: Results with Combined Interventions

The results in this table show that combining the various interventions can have cumulative and complementary effects. Combining several interventions can produce a smaller fraction of children with cavities than any of the interventions can individually. Adding secondary prevention for children who already have cavities can reduce the fraction with untreated cavities and the cost of restorative care.

Conclusions

This paper has described a model of Early Childhood Caries in a population of children aged 0-5 and presented results of simulations with a variety of interventions designed to reduce the prevalence and consequences of ECC. The following general conclusions can be drawn from the simulation results presented in Tables 5 through 10:

- Interventions aimed at the youngest children will take longer to affect the entire population, but will ultimately have a more profound effect in reducing prevalence as the impact percolates into the older groups as children age.

- Interventions limited to the highest risk (lowest income) groups of children will have the greatest impact per dollar spent because of the greater relative risk of ECC in that population. Limited budgets are best spent on these groups.

- Combined interventions that target ECC at several stages of development in the disease process are likely to have the greatest impact. Primary prevention provides the greatest leverage, but it is also productive to limit disease progression by, for example, screening for and treating caries before cavities form.

These conclusions are likely to hold for any population of children, but the impacts of particular interventions will differ somewhat depending on the composition of the population and prevalence of ECC. With data similar to that used to quantify the model for Colorado's children, the model can represent any other state, large city or county, or Metropolitan area population and provide simulation results more closely tailored to that area's population of young children and their oral health needs.

While the model is specific to Early Childhood Caries, it also demonstrates how this approach can be applied to many other oral health problems as well as the linkages between oral health and other chronic illnesses. For example, there is an effort currently underway to develop an oral health workforce model for the State of Colorado. This model will project the oral health status and needs of the state's population, both for adults and children, and potential impact of different levels and mixes of personnel as well as other policies. Another model being contemplated is one that represents the relationships between oral health chronic illnesses such as cardiovascular disease and diabetes. That model would help to examine how improved oral health care can serve as a leverage point in reducing the consequences of those common chronic problems.

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