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Arvin, Erik; Jensen, Allan Bardow; Spliid, Henrik

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Caries affected by calcium and fluoride in drinking water and family income

Erik Arvin, Allan Bardow and Henrik Spliid

ABSTRACT

Water quality and socioeconomics influence caries in populations. This study broadens previous studies on how caries is associated with fluoride and calcium in drinking water and with family income by quantifying the combined effect of the three independent variables. The effects of calcium and fluoride can be described as independent effects of the two ions or, alternatively, in the form of saturation with respect to fluorite (CaF_2). A general linear model describes this relationship with high significance and the model confirms the important protective effect of calcium and fluoride, independently against caries. From the model, the relative importance of fluoride and calcium to protect against caries is quantified. The relationship between caries and family income is also highly significant. It is illustrated how the linear model can be applied in planning and analyzing drinking water softening in relation to caries.

Key words | Danish municipalities, dental caries, socioeconomics, water quality, water softening and desalination, water supply

Erik Arvin (corresponding author)
DTU Environment,
Technical University of Denmark,
Kgs. Lyngby,
Denmark
E-mail: erar@env.dtu.dk; erik@arvin.dk

Allan Bardow
Dental School of Copenhagen,
University of Copenhagen,
Copenhagen,
Denmark

Henrik Spliid
DTU Compute,
Technical University of Denmark,
Kgs. Lyngby,
Denmark

INTRODUCTION

It is very well documented that fluoride in drinking water has an important protective effect against dental caries (Dean *et al.* 1941; Featherstone 1999, 2000; McDonagh *et al.* 2000; Ekstrand *et al.* 2003; Fejerskov *et al.* 2015; US Dept. of Health and Human Services 2015). The natural concentration of fluoride in drinking water varies a great deal depending on the water source. Often, surface water has a low concentration of fluoride. Groundwater fluoride concentrations depend on the geology of the aquifers. Sandy aquifers have a low fluoride concentration. Water sources with such low fluoride concentrations, for example 0.1 mg F/L, are supplemented with fluoride up to 1 mg F/L in, for example, USA, Australia, and several other countries.

It has also been shown that calcium in drinking water reduces development of dental caries measured as the number of Decayed, Filled, and Missing tooth Surfaces

(DMF-S) (Bruvo *et al.* 2008). The study by Bruvo *et al.* (2008) comprised 52,057 15-year-old school children in 249 Danish municipalities in 2004. It was shown that $\ln(\text{DMF-S})$ is linearly related to the concentrations of calcium and fluoride in drinking water. The two ions act independently of each other. Figure 1 gives a survey of the distribution of caries measured as DMF-S in the municipalities in Denmark in 2004 together with the distributions of the calcium and fluoride in drinking water. This figure clearly shows the high prevalence of caries in areas with low concentrations of fluoride and calcium in the drinking water. These areas have sandy aquifers.

It is also very well documented that socioeconomic factors have important effects on caries prevalence, for example family income, parents' education, gender and resources allocated in the municipalities to dental visits/dental care (Petersen 1992; Christensen *et al.* 2010; Kirkeskov *et al.* 2010; Peres *et al.* 2000; Fejerskov *et al.* 2015). Kirkeskov *et al.* (2010) investigated the effect of fluoride, income and gender on caries among 5-year-old and 12-year-old school children in 2004 in Denmark. In addition to the protective

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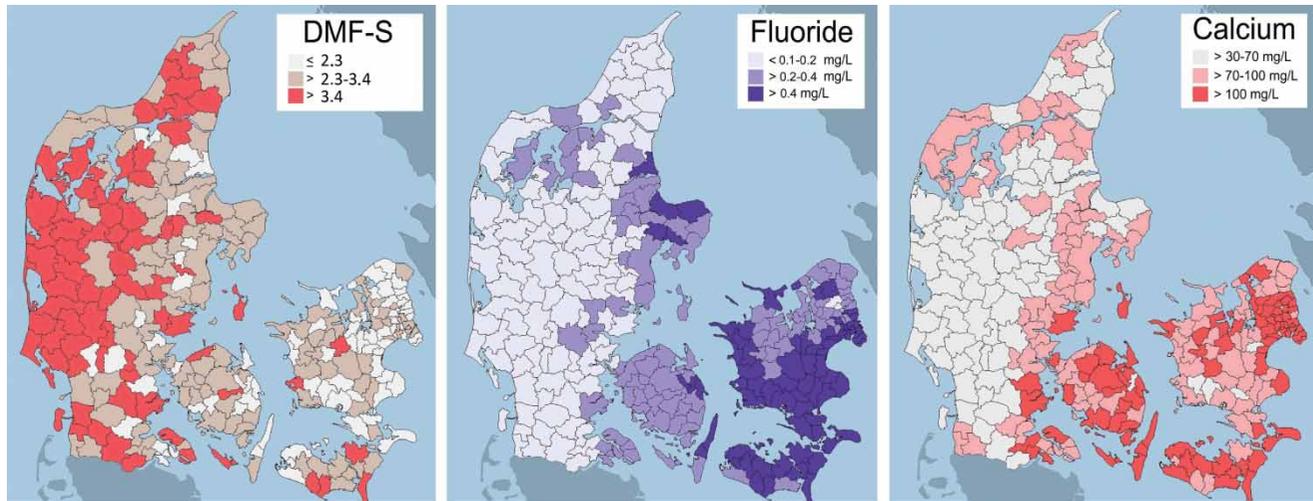


Figure 1 | Distribution of *DMF-S*, fluoride and calcium in Denmark (2004) among 15-year-old children.

effect of fluoride, the study showed a significant increase in *DMF-S* at reduced incomes.

This study aimed at quantifying the combined effect of calcium, fluoride and family income on dental caries in Denmark by 2004 by using linear models. To the knowledge of the authors, this has not been done before.

METHODS

The data material on *DMF-S*, calcium and fluoride was the same as described by Bruvo *et al.* (2008). The average *DMF-S* for all Danish municipalities in 2004 for 15-year-old children was 2.9 surfaces.

Danish water supply relies 100% on groundwater. Chemical data were retrieved from 3,364 water works for the period 1995–2004. The calcium concentrations varied from 31–171 mg/L with an average of 83.5 mg/L and the fluoride concentrations varied from 0.06–1.6 mg/L with an average concentration of 0.33 mg/L. The low calcium and fluoride concentrations are associated with sandy groundwater aquifers in Western Denmark and the high calcium concentrations are related to chalk aquifers. In the chalk aquifers, both high and low fluoride concentrations were observed, probably related to the presence or absence of the mineral fluorite, CaF_2 , in the chalk deposits.

The average family income per year from 249 municipalities in 2002 was obtained from Statistics Denmark (2017). The

family income is the sum of salaries, not including social income (support for housing, children, etc.). It varied by a factor of 3.1 from TDKK 127–397 per year (thousands of Danish crowns, which in TEURO is 18.5–53 per year, or TUS\$ 18.6–58.4 per year). It appears that the inequality in income in Denmark is relatively low. The average family income per year was TDKK 232 (TEURO 31.1, TUS\$ 34.1).

As explained in the work by Bruvo *et al.* (2008), a general linear model with the logarithm of *DMF-S* as the dependent variable was used, applying the R software (R Development Core Team 2011).

RESULTS AND DISCUSSION

Effect of drinking water calcium and fluoride concentrations on dental caries

Very high significances ($p < 4.5 \times 10^{-4}$ – 2.7×10^{-15}) were obtained for all three independent variables: calcium concentration (C_{Ca} , mg/L), fluoride concentration (C_F , mg/L) and average family income per year in the municipality (IC , TDKK) using the following linear model ($R^2 = 0.42$):

$$\ln DMF-S = -0.00435 C_{Ca} - 0.682 C_F - 1.62 \cdot 10^{-5} IC + 1.96 \quad (1)$$

From Equation (1), one can derive a ‘substitution ratio’ between calcium and fluoride: for a fixed *DMF-S* and a fixed family income *IC*, what increase in fluoride concentration would balance a certain decrease in calcium concentration and vice versa. The result is:

$$-0.0064 \Delta C_{Ca} = \Delta C_F \quad (2)$$

Equation (2) shows that in order to maintain a constant *DMF-S* after decreasing the calcium concentration by for example 100 mg/L, then 0.64 mg/L of fluoride should be added to the water and vice versa. Consequently, Equation (2) shows the relative ‘strength’ of calcium and fluoride in drinking water to control caries.

Fluoride has by far the largest caries protection effect per unit weight, but since the fluoride concentrations may be low and the calcium concentrations may be high (groundwater from limestone), calcium can play an important role for caries protection.

The importance of calcium and fluoride to achieve caries levels in the range 1–4.5 is illustrated in Figure 2 for a fixed average yearly income level of TDKK 232 (TEURO 31).

In the western areas of Denmark with sandy aquifers with low fluoride and low calcium concentrations in the drinking water, high *DMF-S* values of 5 or more are observed. In areas with chalk aquifers where the drinking water contains high calcium concentrations, but variable fluoride concentrations, the *DMF-S* may vary between 2 and

3. It is obvious that in areas with low fluoride concentrations, for example 0.1–0.3 mg F/L, a high calcium concentration in the drinking water is an important protection factor against caries.

Alternative *DMF-S* model

We also tried to apply a new independent combined variable for calcium and fluoride, the degree of saturation with respect to fluorite (CaF_2), the saturation index, $DS_{\text{CaF}_2} = SI_{\text{CaF}_2} = \log(\{Ca^{++}\}\{F^{-}\}^2/K_s)$, where $\{Ca^{++}\}$ and $\{F^{-}\}$ are the activities of calcium and fluoride and K_s is the solubility product for CaF_2 . The saturation index was calculated using the PHREEQC software (Parkhurst & Appelo 1999) estimating the calcium activity from the total calcium concentration, and the ionic water composition, taking into account all major complexes formed with calcium in drinking water giving the pH, the concentration of bicarbonate and all other ionic species. For fluoride, complexation is not important. The fluorite saturation index values were negative, showing that the water was undersaturated with respect to fluorite.

The degree of saturation together with the average family income per year (*IC*, TDKK) was also highly significant ($p < 1.8 \times 10^{-4} - 2 \times 10^{-16}$) using a linear model ($R^2 = 0.46$):

$$\ln DMF - S = -1.198 DSCaF - 1.67 \cdot 10^{-3} IC + 0.529 \quad (3)$$

Like Equation (1), Equation (3) emphasizes that it is the combined effect of calcium and fluoride that matters.

The significance of the fluorite saturation index may point to a possible mechanism. During tooth-brushing, fluoride probably precipitates in the biofilm layer on tooth surfaces. This precipitate acts as a reservoir of calcium and fluoride that supplies these ions to the tooth surface and thus protects against caries. If the fluorite saturation index is low, the fluorite reservoir is more rapidly dissolved in drinking water and human saliva and the caries protective effect of the fluorite reservoir disappears faster. This hypothesis is supported by the work of Whitford et al. (2002) who showed that plaque fluoride concentrations are dependent on plaque calcium concentrations.

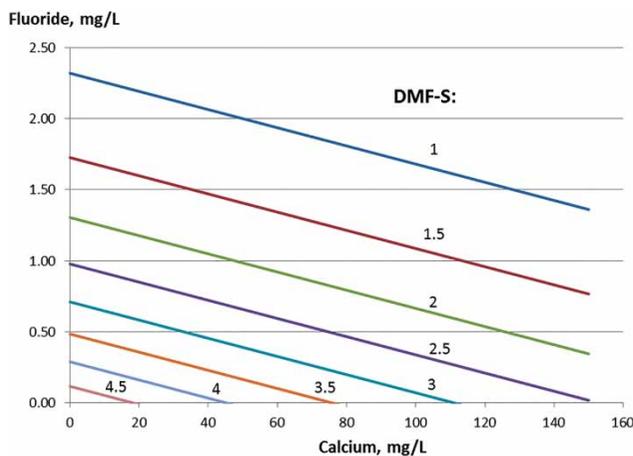


Figure 2 | Effect of calcium and fluoride on caries measured as *DMF-S*. Calculated values for a fixed average yearly income, *IC*, of TDKK 232 (TEURO 31).

Effect of family income

The effect of family income as a single factor can be derived from Equation (1). Let us assume a decrease in average family income per year of 100 TDKK (TEURO 13.4, TUS\$ 14.7). This will lead to an increase in caries of 18%.

The effect of average family income relative to calcium and fluoride in drinking water can be calculated from Equation (1). Again assuming an income decrease of TDKK 100 per year, then – providing constant *DMF-S* – the concentrations of calcium or fluoride should be increased by:

$$\Delta C_{Ca} = 37 \text{ mg/L}$$

$$\Delta C_F = 0.24 \text{ mg/L}$$

These are the concentrations of calcium or fluoride that should be added to the water if one goes from the municipality with average income to the municipality with the lowest income and one wants to maintain caries neutrality ('zero solution'). The addition of fluoride required is a little lower than the average fluoride concentration in Danish water supplies (0.33 mg/L) and the addition of calcium is a little less than half the average calcium concentration in Danish water supplies (83.5 mg/L). The effect on caries of a DKK 100,000 yearly income reduction is therefore almost the same as the effect of removing most of the protective fluoride from average Danish drinking water. These numbers illustrate that family income has an important influence on caries prevalence. This is most likely due to high income families having greater resources for childcare and caries protective measures.

The *DMF-S* data used in this study are from 2004 where the average *DMF-S* for 15-year-old children was 2.9. In 2010, the average caries prevalence in Denmark for this group had decreased by 28% to 2.1 (SCOR 2010, Central Dentistry Register, The Danish Health Authority). One may speculate whether this decrease in caries can be explained by our linear model due to an increase in family income. In order to investigate this hypothesis, we obtained from Statistics Denmark the average family income from 2010 and the inflation rate from 2004 to 2010. From this information, we obtained an increase in family income in fixed prices of 13%, and by inserting the inflation-corrected average yearly family income for 2010 in Equation (1) together with the average calcium and fluoride

concentrations, the expected 2010 caries level is 2.6 versus the real caries level of 2.1. Consequently, our model can only predict a *DMF-S* decrease of 10% where the real reduction is 28%. However, it seems that when dental caries is in acceleration, as in the 1960s and 1970s the momentum in the disease seems to be stronger than the 'movement itself'. The same goes for caries in deceleration as in the 1990s and past the millennium. Here a continuing decrease in caries seems to persist even though no major changes have been made in the dental care system in Denmark. For these mechanisms of this disease we, and others, have no real solid explanation (Fejerskov et al. 2015).

Model uncertainties

Although the effects of calcium, fluoride and family income on caries are highly significant in Equation (1) and Equation (3), there are many model uncertainties as reflected in the R^2 values of 0.41 and 0.46 and in the differences between observed and model calculated *DMF-S*, Figure 3.

Below, four types of model uncertainties are listed.

First, one has to realize that the dependent variable (*DMF-S*) and the independent variables (calcium, fluoride and income) are average values for each municipality and there may be considerable variability within the municipalities.

Secondly, caries determined by *DMF-S* has an inherent variability because it is a subjective determination by the dentist and there may be a trend in clinical practice versus time. Thus, younger generations of dentists may evaluate a

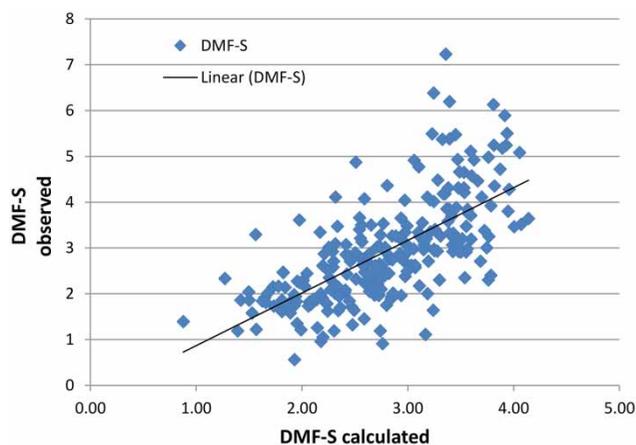


Figure 3 | Observed *DMF-S* versus model calculated *DMF-S* in the Danish municipalities (2004) for 15-year-old children.

decayed surface differently than older generations. Given that older generations have seen the disease some 40 years ago when nearly 90% of all children in Denmark were affected by dental caries, their threshold for giving a diagnosis may naturally be lower than that for younger generations.

Thirdly, all the 15-year-old school children have not lived in the same place all their lives so the exposition to calcium and fluoride may have changed through their childhood. However, Denmark is a country with less geographical mobility than for instance the USA. Most Danes remain in the same municipality for decades, especially after having had children.

Fourth, not surprisingly, it is a very rough approximation to use family income to reflect socioeconomic factors such as educational level, dental care, etc. In Denmark, dental care in schools among municipalities has been very equal for many years due to state regulations. Therefore, household income does not affect dental care in schools. Instead, variations in household income may reflect variations in educational level and thereby the understanding of caries caused by a combination of reduced oral hygiene and exposition for sugar.

It has to be emphasized that our data on caries prevalence are valid only for 15-year-old children in 2004. The caries prevalence varies with age, however, we hypothesize that the effects of calcium, fluoride and family income shown in this study still apply in principle, although not with the same coefficients in the linear Equations (1) and (3). This is a subject for further research.

PERSPECTIVES FOR WATER SOFTENING

Equation (1) can be applied in planning water softening in relation to caries. The purpose of water softening is to reduce water hardness and thereby the potential for precipitation of calcium carbonate on surfaces in water installations, bathrooms and on kitchenware. So calcium removal is the primary objective. Some softening processes, for example membrane processes, also lead to fluoride removal. Consequently, softening will lead to increased caries prevalence, if all other factors are kept constant, and it is the combined effect of calcium and fluoride changes that should be taken into account. Therefore a new water quality variable is introduced based on Equation (2), the

caries-related equivalent fluoride concentration, EFC :

$$EFC = 0.0064 C_{Ca} + C_F \quad (4)$$

By applying the variable EFC , Equation (1) can be reformulated and simplified in terms of EFC as follows:

$$\ln DMF - S = -0.68 EFC - 1.62 \cdot 10^{-3} IC + 1.96 \quad (5)$$

This relationship is shown in Figure 4 for the average Danish family income in 2002 and the lowest and the highest income that year.

Equation (5) as well as Equation (3) underline the importance of the combined effect of the calcium and fluoride concentrations on caries.

It is common practice in many countries, for example USA, Australia and the Middle East, to fluoridate water in order to protect against caries. A typical fluoride level is 0.7–0.9 mg/L and the recommended fluoride level from the US Dept. of Health & Human Services (2015) is 0.7 mg/L. This may be taken as a minimum goal for EFC

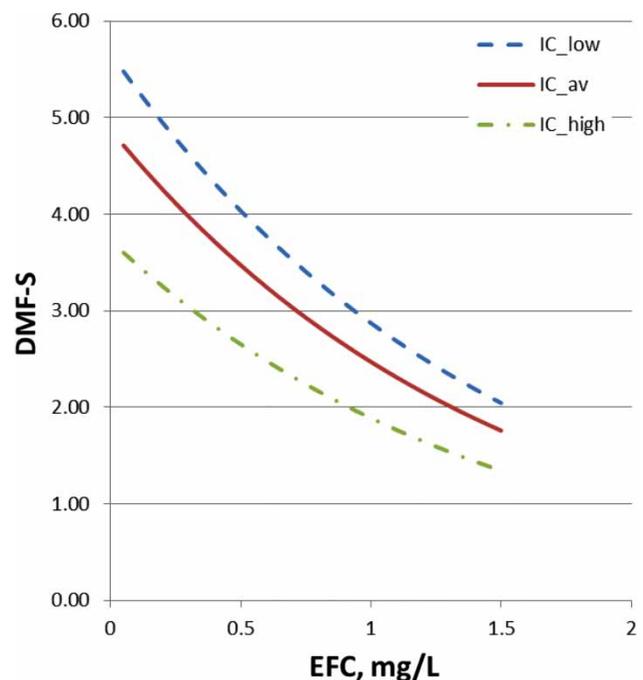


Figure 4 | Caries among 15-year-old children measured as $DMF-S$ versus the equivalent fluoride concentration. Shown for average, lowest and highest Danish average family income per year (2002) (IC , TDKK: 232, 139, 398).

when planning water softening. Any calcium present in the drinking water will add to the *EFC*.

The Greater Copenhagen water company HOFOR plans to soften all their water by the pellet method to a final hardness of 10°dH (German hardness degree) which equals a hardness of 178 mg CaCO₃/L.

In the first water works within HOFOR to adopt softening, Broendby, the magnesium hardness is 5.4, therefore, the final calcium hardness will be 4.6 corresponding to a calcium concentration of 33 mg Ca/L. Since the fluoride concentration is 0.51 mg/L, the equivalent fluoride concentration in the drinking water after softening will be $EFC = 0.7$ mg/L. This corresponds to the above-mentioned minimum *EFC*.

The Broendby raw water (groundwater) currently and naturally has a water hardness of 22°dH and the calcium concentration is 120 mg/L. With a fluoride concentration of 0.51 mg/L, the raw water $EFC = 1.3$ mg/L.

The water softening in Broendby will – according to Equation (5) – lead to an increase in *DMF-S* of 46%. In 2004, the *DMF-S* in Broendby was 2.47. The 46% increase corresponds to an increase in *DMF-S* of 1.1 tooth surfaces in 15-year-old children.

The calculated increase in caries of 46% is a significant increase. If a ‘zero solution’ is wanted where the caries level is unchanged after softening, 0.6 mg/L fluoride has to be added to a level of 1.1 mg F/L. This fluoride level would not be unusual for the local geological conditions around Broendby and south of Copenhagen. However, due to the general decrease in caries experience in Denmark in recent years, a lower addition of fluoride than 0.6 mg/L would probably suffice.

Another action to counteract increases in caries could be to carry out educational and information campaigns where the population is told to maintain high oral hygiene and to prevent too much sugar in the diet, not least for children in kindergartens and schools. Dental caries requires biofilms on tooth surfaces in combination with an intake of sucrose. Dental caries will not develop if one of these variables becomes totally removed.

In Broendby, this is a particular challenge because of the high number of ethnic groups where many languages are represented. According to the model in Equations (1) or (5), the predicted average *DMF-S* in Broendby in 2004 is 2.06. In reality, the *DMF-S* was 2.47. The underestimation of *DMF-S* might be due to the lack of an ‘ethnic factor’ in

the equation. The incorporation of an ethnic factor could be a task for future model development!

Finally, it should be emphasized that the modeling of caries in this paper relates to 15-year-old school children. Later on in life, new caries experiences will inevitably develop and contribute to degradation of teeth, which eventually may lead to expensive teeth restorations. Therefore, a change in water chemistry through softening has a lifelong negative effect on caries.

PERSPECTIVES FOR WATER DESALINATION

Desalination of sea water and brackish water is a technology that is being developed strongly due to water scarcity in many places around the globe, for example in the Middle East, North America, Asia and Australia. The global desalination capacity in 2015 served about 300 million people from 18,426 plants with a total capacity of 86.8×10^6 m³/day (Wikipedia 2017).

Desalination removes most of the ions from the water, in particular divalent cations and anions. Water without calcium and fluoride strongly promotes caries. Therefore, it is common practice to add fluoride to a level of 0.7–0.9 mg/L. Calcium may be added in order to prevent corrosion in steel components of the water supply system. For a case study in Perth, Australia, the recommended calcium concentration was 40 mg/L (Rygaard *et al.* 2011). This together with the usual fluoride concentrations would give an equivalent fluoride concentration, *EFC*, of about 1 mg/L.

The removal of ions from water, partly or almost totally, may have other health effects than increased caries prevalence. Removal of water hardness (calcium and magnesium) may increase diseases for example cardiovascular mortality, but much more information is needed (Cotruvo & Bartram 2003). In one respect, however, low water hardness is beneficial because it reduces atopic dermatitis in infants (Engebretsen *et al.* 2017).

CONCLUSIONS

This work presents linear models for caries experiences (*DMF-S*) among 15-year-old Danish school children that include water chemistry, the concentrations of calcium

and fluoride, and family income. The family income is used as a proxy for socioeconomic factors. The variables calcium, fluoride and income are highly significant and they are also quantitatively important determinants for caries.

It is well known that fluoride in drinking water in concentrations as low as 0.5–1 mg/L effectively reduces caries prevalence. However, our work shows that 100 mg/L of calcium has the same protection effect as 0.64 mg/L fluoride (fluoride equivalence). The combined effect of fluoride and calcium is underlined in this study by introducing a new water quality variable, the equivalent fluoride concentration, *EFC*, which contains the equivalent protection effect of calcium expressed in mg/L fluoride.

The combined effect of calcium and fluoride is alternatively expressed in the form of the saturation with respect to calcium fluorite (CaF_2). This may indicate that fluorite precipitation and dissolution in biofilm fluids on the tooth surfaces is involved in caries processes.

For Danish conditions, we can predict that if the average family income per year decreases by 100 TDKK (13.4 TEURO or 14.7 TUS\$) then 0.24 mg F/L or 37 mg Ca/L should be added to the water to maintain unchanged caries experience.

The effect of calcium to protect against caries may have important implications for water softening where the calcium concentration is strongly reduced. From a case study it is calculated that the reduction in calcium from 120 mg Ca/L to 33 mg Ca/L by softening, may increase the average caries experience by 46%.

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