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A review of the role of solar ultraviolet-B irradiance and vitamin D in reducing risk of dental caries

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Large geographical variations in dental health and tooth loss among US adolescents and young adults have been reported since the mid-1800s. Studies in the 1920s and 1930s noted that vitamin D and ultraviolet-B (UVB) irradiance reduced caries formation, the proposed mechanism being improved calcium absorption and metabolism. This paper reviews the history of studies of dental caries with respect to vitamin D, geographical location and available solar UVB doses. In addition, data on mean dental health rank by state for US servicemen from three periods, 1918, 1934 and 1943, were used in regression analyses with respect to summertime solar UVB doses and an index for mottled enamel, a proxy for natural fluoridation of drinking water, for 1935. There was a significant inverse correlation for dental health rank with respect to solar UVB from doses of 4.0 to 6.5 kJ/m^2 with little change thereafter. Adding data for mottled enamel rates for the states with UVB doses <6.6 kJ/m^2 improved the adjusted R^2 from 0.45 to 0.52. The mechanism whereby UVB reduces risk of dental caries is likely through production of vitamin D, followed by induction of cathelicidin and defensins, which have antimicrobial properties. Serum 25-hydroxyvitamin D concentrations at or above 30–40 ng/ml should significantly reduce the formation of dental caries. It is unfortunate that the UVB and vitamin D findings were not given more consideration in the 1950s as a way to reduce the risk of dental caries when water fluoridation was being proposed.

Introduction

Dental caries is one of the most prevalent diseases in humans. It is the primary source of tooth loss for those younger than 40 years, with periodontal disease being the primary cause after that age.[1] Loss of homeostasis of an oral cavity overgrown with *Streptococcus mutans* are the primary cause of the disease.[2] *S. mutans* adheres strongly and releases acids by the fermentation of carbohydrates, thereby demineralizing the tooth.[3] Eating sweets and not brushing teeth both contribute to the formation of dental caries,[4] but less well known is that solar ultraviolet-B (UVB) irradiance, through additional production of vitamin D and vitamin D supplementation in deficiency appears to reduce the risk of caries.

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This study reviews the literature on UVB, vitamin D and dental caries (as identified using the search terms 'vitamin D, dental caries, ultraviolet' in PubMed and www.scholar.google.com). It also includes an ecological analysis of dental condition by state, for men in the US armed forces during World War I and II and Navy servicemen in between those wars[5] versus July solar UVB doses.

Results

A moderate-sized body of literature exists on the role of geographic location and solar UVB in association with reduced risk of dental caries in the United States and Australia. The first study finding a latitudinal gradient in dental caries was a report of men rejected from the draft for the Civil War for lost teeth, from 8 per 1,000 men in Kentucky to 25 in New England.[6] However, no reason seems to have been given to explain the finding.

There were several studies reported on vitamin D and dental caries in the 1920s and 1930s. May Mellanby and coworkers in Sheffield, England, did studies on the role of vitamin D on teeth in the 1920s. The first experiments were with dogs, where it was found that vitamin D stimulated the calcification of teeth.[7] Subsequently, they studied the effect of vitamin D on dental caries in children, finding a beneficial effect.[7] Additional studies were conducted on children in New York regarding dental caries with respect to season, artificial UVB irradiance and oral intake of vitamin D with the finding that it took 800 IU/d to prevent caries effectively.[8]

Using data for adolescent males aged between 12 and 14 years from a cross-sectional survey in 1933–1934,[9] Mills[10] first linked the geographical variation in prevalence to sunlight exposure. He placed isopleths of arithmetic averages of county indices of dental caries incidence for schoolchildren living in rural areas or towns with populations of less than 5,000 in 19 states on a map of the United States. This mapping showed a general increase with increasing latitude, with an anomaly in the Rocky Mountain States. A factor of greater than three existed between the indices for Oklahoma and Pennsylvania (150 and 531 caries/100 children, respectively); there was also an inverse correlation with respect to

water hardness, regression analysis showing a reduction of 33% for >500 ppm versus <50 ppm total mineral levels, with calcium and magnesium important components. Using the same data set, East[11] found that dental caries were inversely related to mean hours of sunlight/year, with those living in the sunny west (3,000 hours of sunlight/year) having half as many carious lesions as those in the much less sunny northeast (<2,200 hours of sunlight/year); rates in areas with intermediate annual hours of sunlight fell between those for the extremes of sun exposure. East referred to other contemporaneous papers indicating a role of vitamin D[8] and season[12] in affecting the risk of caries. Many other studies reported geographical variations in dental caries, sometimes linking the variations to differences in solar radiation. If a mechanism for the effect of sunlight was proposed, it was production of vitamin D and improved calcium absorption and metabolism.

Several studies were conducted in Oregon in the 1950s. It was noted that dental caries prevalence was lower in the sunnier parts of the state, a finding that persisted after considering other factors that affect dental caries rates.[13-15] The mechanism was attributed to vitamin D through its effects on calcium metabolism.

Table 1 summarizes the results from previous studies.

A study of dental health rank, by state of origin, for United States draftees to World War I, Navy servicemen in 1934, and Army servicemen in 1943 was reported by Dunning.[5] Ranking was based on decayed and missing teeth as well as filled teeth for the Navy veterans. These were averaged ranks for each of the 48 states and ranged from 2 (Arkansas) to 45 (Rhode Island). The highest ranks were near Texas and the lowest in the Northeast. These dental health rank scores were plotted versus July UVB doses and the index of mottled enamel from 1936.[25] **Figure 1** gives the dental health score ranks by state for men entering the armed forces during World War I and II[15] versus July solar UVB dose. Dental health decreased in a nearly linear fashion as UVB dose increased up to UVB levels of 6.5 kJ/m^2, above which there was little additional change. The regression relationship for UVB below 6.5 kJ/m^2 for rank is 87-12x UVB dose ($r = -0.68$, adjusted $r = 0.45$ $p < 0.001$) and above 7 kJ/m^2 is 20-0.69x UVB dose ($r = 0.07$). This finding is similar to previous observations for many types of cancer.[26,27] In a regression analysis restricted to those states with UVB doses <6.6 kJ/m, with inclusion of the mottled enamel index, the association was increased, giving a normalized correlation coefficient, β, of -0.63, $p < 0.001$ for UVB and of -0.30, 0.03 for mottled enamel; the adjusted R^2 being increased to 0.52.

Figure 2 shows a plot of July solar UVB doses (http://toms.gsfc.nasa.gov/ery_uv/dna_exp.gif) and 1935 mottled enamel indices[25] versus dental health rank. States with dental health 30 or greater had a mean UVB dose of 4.5 kJ/m^2. While the linear fit for each data set sloped downwards with increased rank, the correlation coefficient, r, was -0.71, $p \leq 0.001$ for UVB and -0.37, $p = 0.01$ for fluorosis. In a multiple linear regression analysis, the addition of fluorosis to UVB did not change the result.

Discussion

These results indicate that from the mid-1800s through the 1980s, solar UVB was inversely correlated with dental caries and tooth loss among adolescents and young men. Tooth loss and dental caries rates between low- and high-UVB-dose states in the mid-1800s and 1933 differed by factors of three. In both periods, little to no understanding existed of the role of UVB or vitamin D in reducing risk of dental caries.

Although the original mechanism proposed for UVB and vitamin D related to calcium metabolism,[7] the effect is at least as likely to involve vitamin D and its induction of the antimicrobials cathelicidin and defensins as already noted to be important in periodontis.[28] In recent years several papers have discussed how cathelicidin and defensins reduce the risk of dental caries through attacking oral bacteria linked to dental caries.[29-35] However, these papers apparently did not discuss the involvement of vitamin D in the process. These polypeptides reduce the risk of several other types of bacterial infections, such as tuberculosis,[36] pneumonia,[37,38] and severe sepsis.[39-41] In 1928, Mellanby[7] stated "*It is interesting to note that even in sections of teeth in which caries appears to be completely arrested the dentinal tubules may contain micro-organisms. These, however, are apparently inactive.*"

Low serum 25(OH)D status has also been reported as a risk factor for periodontal disease, reviewed in Grant and Boucher.[42] One recent paper found vitamin D insufficiency (serum 25(OH)D <30 ng/mL) is associated with maternal periodontal disease during pregnancy.[43]

The serum 25(OH)D 'level' necessary for dental caries reduction does not appear to have been worked out in detail, but it might be inferred from studies of other diseases. Serum 25(OH)D level-cancer incidence relations for breast and colorectal cancer start to flatten around 30–40 ng/mL.[44] This value is in accord with a recent observational study on incidence of influenza, which found 38 ng/mL to be the lower end of the optimal range.[45] Vitamin D confers many health benefits, including reduced risk of cancer and infectious diseases, as mentioned earlier, as well, it is suggested, of cardiovascular disease and type 2 diabetes mellitus,[46] autoimmune diseases, falls, fragility fractures and many other diseases[47] and may improve physical fitness[48] and age-adjusted brain function.[49] It was estimated that if all Americans could raise their serum 25(OH)D levels to more than 40 ng/mL, all-cause mortality rates could be predicted to decrease by about 15%.[50] Similar effects have been estimated for other countries including Canada[51] and Nordic countries.[52] A recent review both underscored the global importance of vitamin D and proposed changes to vitamin D nutritional policies.[53] Thus, serum levels above 30–40 ng/mL may significantly reduce the risk of dental caries, but more research is required to determine the serum 25(OH)D level-caries risk relationship.

Casual solar UVB irradiance in summer can raise serum 25(OH)D levels by 10–15 ng/mL, on average, in those aged 45 years living in England.[54] Higher increases are likely for young people living in the United States. Vitamin D production from solar UVB depends on many factors, including age, skin pigmentation, body mass index, surface area exposed, time of day and geographic location but the easiest way to raise serum 25(OH)D levels is through vitamin D3 supplementation. For most people, increases of 10–15 ng/mL would require intakes of 1,000–2,000 IU/day.[55] However, there is considerable person-to-person

Table 1. Summary of findings in earlier studies of geographic variation of dental caries

Location	Finding	Reference
Northeastern United States	A significant increase of men rejected from the draft for the Civil War for lost teeth, from 8 per 1,000 men in Kentucky to 25 in New England.	6
England	Children aged 5–9 years were given vitamin D2 and followed for 28 weeks. Those taking higher doses of vitamin D2 developed fewer caries than controls taking lower amounts or none.	7
United States	A general increase in dental caries for school boys aged 12–14 years, with lower rates in the Rocky Mountains; controlled for water hardness.	10
United States	Seasonal incidence of dental caries	12
New York	The role of vitamin D in dental caries	8
United States	The number of dental caries for boys aged 12–14 years varied by a factor of two from east to west with the number of hours of annual sunshine.	11
United States	Summarized pervious data on dental caries among those called to the Armed Forces such as the Navy, showing latitudinal effect, although sunshine was not mentioned. Showed that a similar latitudinal effect for tooth loss was apparent in the northern states in 1963–64.	16
United States	Inverse correlation of dental caries with amount of available sunshine noted.	17
United States	Sunshine and production of vitamin D, thought vitamin D increased calcification during tooth formation.	18
Oregon	Fewer dental caries in school children living in sunny inland county compared to coastal county; controlled for fluoride in water supply, density of dentists, candy bars and carbonated drinks.	13, 14
United States	Dental disease rankings by state of draftees to World War I, 1918 [decayed, missing teeth (DMT)], Navy, 1934 [decayed, missing and filled teeth (DMFT)], and Army, 1943 (DMT). The lowest disease rate was in Texas and Alabama, the worst in Maine. For any longitude band, there was a significant increase in dental disease with increasing latitude. Correlated with hours of sunlight; also with consumption of baked goods (refined carbohydrates); also with relative humidity as well as rainfall, which could leach minerals from the soil	5
South Africa	Declining number of dental caries for children with increasing distance from the east coast; analysis restricted to magisterial districts with less than 0.7 ppm fluoride in the water. Sunshine noted to increase with distance from the east coast.	5
Oregon	Inverse correlation found for native white boys aged 14–16 years with respect to location and altitude, linked to amount of sunshine available. Checked for fluoride in drinking water, finding little use at that time. Also, for water selenium content a modest direct correlation was found.	15
Chile	Mean dental caries for 12–14 year old children in 1945 were 3.8, 7.1 and 8.8 for northern (18°–32°S), central (32°–40°S) and southern (40°–55°S) regions. Some of this effect was attributed to fluoride in the drinking water, but the data do not support this interpretation.	19
Eastern United States	Studied boys aged 12–14 years. Included towns with <0.3 ppm fluoride in drinking water. Inverse correlation with selenium in soil, but that did not explain all of the variance, with highest rates in New England, lowest in southern Atlantic states.	20
Australia	The variation of dental caries in members of the Royal Air Force was compared to latitude and multiple sclerosis (MS) death rate. Correlation coefficient with MS was 0.97 ($p < 0.002$). Risk of MS had been linked to high dietary fat and low vitamin D status.	21
United States	Data from Dunning.[5] Correlation coefficient with MS was 0.55 ($p < 0.001$)	21
World	Data for MS prevalence and dental caries for 45 countries. Correlation coefficient for dental caries with MS was 0.78 ($p < 0.001$).	21
Burma	DMF scores in children were measured for 12 towns. An inverse correlation with daily mean hours of bright sunshine was found ($b = -0.38$, $p < 0.01$)	22
Australia	DMF scores in 12-yr-old children were higher in the southern states, and rates of edentulousness in 35–44-yr-olds in Tasmania (latitude 40°–45°S) were double those for people in more northerly states.	23
U.K.	A study of 11-year-old children from across England and Wales, Scotland, Isle of Man, and Jersey was conducted in 2004/5. Mean D3MFT across England was 0.64 (D3T = 0.32, MT = 0.06, FT = 0.25), across Wales it was 1.09 (D3T = 0.48, MT 0.11, FT = 0.50), and across Scotland values were 1.29 (D3T = 0.52, MT = 0.17, FT = 0.60).	24

variability in serum 25(OH)D with respect to oral intake,[56] so testing 25(OH)D levels is recommended for those wishing to achieve specific levels.

It is interesting that studies have found little difference in dental caries rates between African American and white American children.[57] Those of African descent have more calcium in their

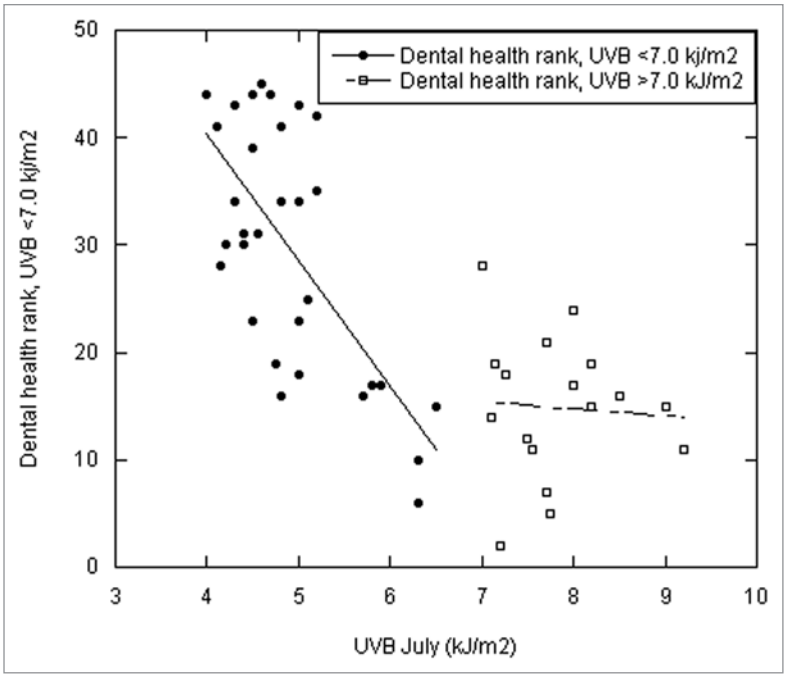

Figure 1. Dental health ranking, by state, for men entering the armed forces during World War I and II15 versus July solar UVB dose.

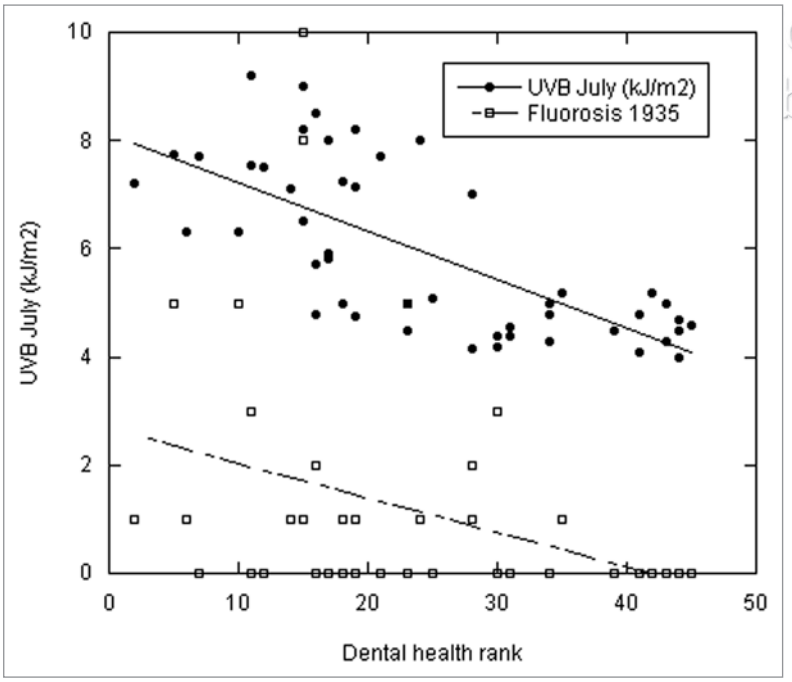

Figure 2. Plot of July solar UVB doses and mottled enamel index for 1935 vs. dental health rank by state for U.S. servicemen from 1918-1943.

bones than white people.[58] They are also likely to have more calcium in their teeth. These data may reflect genetic factors or, in immigrants, higher sun exposure in early life.

The finding of maximal dental health with UVB doses of about 6.5 kJ/m^2, is interesting though it is also possible, though unlikely, that fluoride levels in drinking water are lower in the sunnier states, primarily in the southwest (See **Fig. 2**.).

Since the studies reviewed and the analyses presented are ecological studies and their are due to the usual limitations of such studies. One limitation here is lack of information on dietary factors such as sugar consumption rates, which are important risk factors for dental caries. This analysis assumed that dietary factors were the same for all regions. This assumption is more likely to be satisfied in a single-country study than in a multi-country study, but it still leads to some uncertainty. Another limitation is that the dental index developed by Dunning[5] was not expressed as a quantitative measure of dental caries. Thus, the relation shown in **Figure 1** does not translate directly into a dose-response relation. Another limitation is that summertime solar UVB doses were used as the index of vitamin D production whilst vitamin D production and serum 25(OH)D levels are important during the entire year. Wintertime deficiency of vitamin D lasts several months in the higher-latitude States[59] but is much shorter in States at lower latitudes whilst skin pigmentation also plays a role in vitamin D production but could not be adjusted for.

Fluoridation of municipal drinking water is currently widespread in the United States. It was introduced in Grand Rapids, Michigan in 1945.[60,61] Comparisons of dental caries in 1945 and 1949 in Grand Rapids, Muskegon (with low water fluoride content) and in Aurora, Illinois, with natural fluoridation (at 1.2 ppm) showed that by age 15 years, those in Aurora had one-third the number of dental caries as those in the two Michigan cities whilst for under 7 years old, the dental caries rates were nearly the same for Grand Rapids as for Aurora. Based on this experiment, fluoridation was widely adopted and spread to most states by the 1980s. However, that study was conducted in the Northeast, where solar UVB doses are much lower than in the Southwest. By the end of 1992, 10,567 public water systems serving 135 million persons in 8,573 US communities had instituted water fluoridation.[62] While widely accepted as a primary reason for decreases in dental caries,[63] there is reason to doubt this claim. For example, dental caries have continued to decline in two European regions after water fluoridation was discontinued.[64,65] Dental caries are considered primarily due to consumption of refined sugar and a low frequency of tooth brushing in Europe.[4] In addition, adverse effects of excessive water fluoridation can be severe, including 'moderate dental fluorosis, stage I skeletal fluorosis (arthritis with joint pain and stiffness), decreased thyroid function and detrimental effects on the brain, especially in conjunction with aluminum.'[66,67] Many papers on the adverse health effects are published in the journal Fluoride (www.fluorideresearch.org). Furthermore, The US

Environmental Protection Agency recently announced proposed rules to limit fluoride level in drinking water to 0.7 milligrams of fluoride per liter of water due to risk of fluorosis for higher levels.[68]

It is unfortunate that water fluoridation, rather than promotion of sunlight and vitamin D fortification of food and the use of supplements, was adopted as the public health approach to reducing dental caries in the United States and elsewhere, especially since better vitamin D status has many additional benefits.[47,50] However, fluoridation of drinking water to 1 ppm entails an ~12.5% (95% CI, 7.0%–21.5%) risk of dental fluorosis, a fluoride-induced mottling of the enamel.[69] Thus topical application of fluoride, such as through the use of fluoridated toothpaste, seems to provide a useful alternative to drinking water fluoridation.[70]

Methods

Data sources. Solar UVB data for July 1992 are from NASA Goddard (http://toms.gsfc.nasa.gov/ery_uv/dna_exp.gif) and were digitized by state and adjusted for population distribution producing a data set already used in several ecological studies of cancer.[26,27]

Wintertime solar UVB availability is proportional to latitude and solar zenith angle. Previous work reports associations, best described by a quadratic function, between latitude and prevalence of multiple sclerosis in the United States.[71-73] Because of apparent exceptions to a simple latitudinal gradient of dental condition in the United States, especially at latitudes below 40° N, the present report does not use latitude in any analyses.

Fluorosis data were obtained from a map in a paper by Dean[25] showing locations throughout the United States where mottled enamel (fluorosis) had been reported in the literature or reported but not verified as of 1935. The regions with the highest density of locations were generally in the southwest (Arizona, Colorado, New Mexico and Texas), as well as North and South Dakota and Iowa. Very few states in the eastern US had mottling. The fluorosis index for each state was estimated by considering the density of data overlaid with population centers for each state. The index is, therefore, approximate.

Statistical analysis. Linear and regression analyses were carried out using SPSS 16.0; Graduate Student Version (SPSS, Inc., Chicago, IL). Graphs and additional analyses were made using Kaleida Graph version 4.0 (Synergy Software, Reading, PA).

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