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The epidemiology of dental caries in relation to environmental trace elements

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Summary. This paper reviews the influence of the geochemical environment on the epidemiology of human dental caries. The best documented association is that between water borne fluoride and reduced caries prevalence. The influence of fluoride was first reported during the early decades of this century in Colorado, USA, and led to the fluoridation of some public water supplies in several countries. In all cases, fluoridation has been followed by significant improvements in dental health and no adverse effects in general health. Other trace elements in food and water have now been linked with dental caries. Molybdenum has been associated with reduced caries prevalence whereas selenium and lead appear to have adverse effects. Cavity formation in teeth probably involves a localised dissolution of the enamel surface by the products of bacterial activity. It is possible that the incorporation of trace metals into the apatite microcrystals of enamel may alter their physical properties, especially solubility, and hence their susceptibility to degradation.
Key words. Apatite; caries; enamel; fluorine; lead; molybdenum; selenium; trace metals; vegetables; water.

Introduction

It has long been believed that 'airs, waters and places' have a direct bearing on human health and environmental influences have been proposed to explain the localised prevalence of some non-infectious diseases[52]. Particular attention has been paid to the geochemical environment since many trace elements are either essential to mammalian metabolism or may interfere with metabolic functions[48, 57] and the trace inorganic composition of water can be influenced by the nature of bedrock and the composition of vegetables reflects that of the soil[56]. Unfortunately, to establish a link between environmental geochemistry and human health is not easy. Indeed, the mobility of people and their obtainment of food and drink from many different, often non-local sources justifies the apparently convincing conclusion that the local geochemical environment must have little influence on health.

Dental epidemiology, however, provides some of the most convincing evidence that trace elements can affect the health of communities.

A dental disease which lends itself for the purpose of the study is dental caries. It is epidemic in many countries and a large population is therefore always available for study. Diagnosis of the disease is through a visual inspection which maximises the willingness of individuals to assist in surveys. Where the survey population comprises children, typically 12-year olds, the time interval between cause and effect is short and it is possible to make direct associations between environmental quality and disease prevalence. In the case of fluoride, a direct link was established over 50 years ago[3, 20] and led to the successful fluoridation of public water supplies.

Caries and Enamel

The outer layer of the crown of a tooth is enamel, the hardest tissue in the body. Beneath it lies the dentine, the main tooth component, in the centre of which is the pulp containing the blood vessels and nerves. Cementum covers the root surface of the dentine and it attaches the periodental ligament to the tooth which in turn holds the tooth to the jaw.

Dental caries is the localised destruction of these tissues commencing with the enamel. The process of this destruction is not fully understood but it is thought to be due to the presence of micro-organisms on the enamel surface. They are responsible for the formation of plaque, in which the bacteria grow and proliferate. The presence of carbohydrate considerably increases the rate of proliferation as it is a substrate favoured by the organisms. As the substrates are metabolised, within the plaque, organic acids are produced which are held, by the plaque, against the enamel until they diffuse away. The initial phase of tooth destruction is most probably due to the dissolution of the mineral phase of the enamel by these acids[19].

The principal component of enamel is microcrystalline hydroxyapatite set in a protein matrix. The protein represents about 1% of the enamel dry weight and appears to resemble keratin except it contains less sulphur. The apatite fraction approximates to the composition
$(Ca_{9.5}Mg_{0.2}Na_{0.1}H_{0.5})\,(PO_4)_{5.7}(CO_3)_{0.5}(OH)_2$
But apatite, whether biogenic or geochemical, contains traces of many other elements which occur in the crystal structure through isomorphous replacement. That is, one ion can substitute for the normal ion if its size is similar and it does not differ in charge by more than one. Many

such substitutions are known[23] and when they occur they alter the properties of the mineral, especially its solubility. For example, tetravalent uranium has a radius of 97 pm which is very close to that of divalent calcium (99 pm) and natural mineral apatites can contain up to 0.01% U. Other replacements for calcium which are common are by Mn, Pb, Ce, Th and Sr. An important series of replacements occurs between OH^- (140 pm), F^- (136 pm) and Cl^- (181 pm) to produce the almost pure end members hydroxyapatite, fluorapatite and chlorapatite, respectively. The structure of hydroxyapatite is a little expanded compared with that of fluorapatite and hydroxyapatite is relatively less stable. This is reflected in their different solubilities; the solubility product for hydroxyapatite is 1.6×10^{-58} and that for fluorapatite is 3.98×10^{-61}. PO_4^{-3} in the lattice can be replaced by SO_4^{-2} and MnO_4^{-1}. Finally, in the protein matrix of enamel selenium can readily replace sulphur. The composition of enamel is potentially very variable and it is interesting that many of the elements which geochemists recognise as common 'guests' in apatite have also been associated with differences in the prevalence of human dental caries.

Fluoride and caries

The relationship between environmental fluoride, especially in drinking water, and dental caries is probably one of the best established links between environment and disease. So strong is the relationship that the addition of 1 mg F/l to public water supplies has been undertaken regularly by some water utilities.

In 1901 Dr Frederick McKay opened a dental practice in Colorado Springs (Colorado, USA) and encountered a mottling and staining of teeth which was known locally as 'Colorado Stain'. The condition was so prevalent that other practitioners regarded it as commonplace and no reference to it could be found in the available literature. The area had been recently settled and a survey of school children in 1909 revealed that 87.5% of those born and reared locally had mottled teeth. It was also noted that although these children had fewer carious cavities their teeth were more brittle[14]. Enquiries established that an identical pattern of mottling in teeth had been observed in some other American areas and in immigrants coming from the volcanic areas of Naples, Italy[46]. Field work in South Dakota and reports from Italy and the Bahamas convinced McKay[43] that the quality of the water supply was involved in the aetiology of the condition. He subsequently found direct evidence for this in Oakley, Idaho, where, in 1908, a new piped water supply from a nearby thermal spring had been provided and within a few years it was noticed that children's teeth were becoming mottled. In 1925 McKay persuaded the local community to change their water supply to a different, cold spring after which stained teeth became rare[44,45]. A second case of the development of stained teeth following a change in water supply was identified in Bauxite, Arkansas[36], and that water supply, together with samples from other areas, was analysed for trace constituents. The results revealed that all the waters associated with mottled teeth had in common a high fluoride content (2–13 mg F/l)[20]. At the same time it was demonstrated experimentally that fluoride in drinking water could produce mottling in rats' teeth[49].

The work of McKay has been described in some detail because it provides a classical example of how a trace element can affect health and how the effect was noticed through diagnosis, survey and (unintended) direct experimentation. Reports of mottled teeth were published from other countries. In Britain, unusual mottling was described for patients in Maldon, Essex[47], where only 7.9% of the teeth of children in two of the town's schools were carious, compared with 13.1% in all districts examined, and white mottling was common. Water from the Maldon area contained between 4.5–5.5 mg F/l compared with 0.5 mg F/l elsewhere[3]. Subsequently, Weaver[58] reported mottled teeth in the Tyneside towns of North and South Shields. The incidence of caries in children in South Shields was 56% of that in North Shields while drinking water in North Shields contained less than 0.25 mg F/l compared with 1.4 mg F/l in South Shields.

The published reports on the protective role of fluoride led Dean[22] to suggest that 'the possibility of controlling dental caries through the domestic water supply warrants thorough epidemiological-chemical investigation'. The US Public Health Service concluded that a concentration of 1 mg F/l drinking water would be beneficial for dental health but would not be in any way injurious to general health. Fluoride was first added to public water supplies which were low in this element in 1945 in Grand Rapids, Michigan. Fluoridation schemes were subsequently introduced in Brantford, Ontario (1945); Tiel, The Netherlands (1953); Hastings, New Zealand (1954) and in 1955 in Watford, Anglesey and Kilmarnock in Great Britain. In addition to the fluoridation of water supplies, fluoride has also been administered systemically in tablets and salt and topically in solutions, toothpastes, gels and rinses. Its use has been reviewed comprehensively by Murray[49]. There is no doubt that whenever it has been used it has been associated with a reduction in the prevalence of dental caries. The effect can be lifelong and, at the recommended levels, has never been demonstrated to be associated with any other medical condition.

The mode of action of fluoride is not entirely clear[49]. The most likely mechanism is a reduction in enamel solubility through the formation of fluorapatite. But Jenkins[35] has reported that only one molecule in 20 converts to fluorapatite at the highest, normal fluoride intake. Other mechanisms proposed include a bactericidal effect and an enhanced repair mechanism in which small areas of decalcification become refilled with apatite rather than other, more soluble calcium compounds.

Dental caries and other trace elements

Inevitably, the recognition that water containing fluoride was protective against caries led to investigations of the possibility that other trace constituents of food or water might affect dental health. Nizel and Bibby[51] surveyed the dental records of 22,117 soldiers in the USA and found increased caries prevalence in the New England and Middle Atlantic states but lower incidence in the South Central states. They proposed comparative analyses of soils from these areas since deficiency or excess of other trace elements besides fluoride might be important. Adler and Straub[2] compared caries rates in two adjacent Hungarian villages. In one the incidence in the school population agreed with the rate expected from the fluoride level of local drinking water but surprisingly low rates were recorded in the other village despite a much lower water fluoride content. Since there were no dietary, social or racial differences between the two study groups the authors proposed that some other constituent, perhaps molybdenum, was responsible. This report was followed up by Hadjimarkos[27,28] who concluded that water supplies do not constitute a major source of ingestion of trace elements and that food as a source ought to be studied. Nonetheless investigations of water composition in relation to the incidence of caries have continued. Adkins and Losee[1] attempted to find correlations between caries incidence and trace elements in water supply and found that copper and manganese were always associated with high caries prevalence. In two isolated villages in Colombia, South America, where there was less than 0.1 mg F/l in the drinking water there were marked differences in caries prevalence. Low prevalence was associated with raised concentrations of Ca, Mg, Mo and V while concentrations of Cu, Fe and Mn were higher in the samples from the village with the higher prevalence[25]. Losee and Adkins[39] reported that reduced caries incidence was associated with higher water concentrations of B, Li, Mo and Sr as well as F. They were also concerned whether when water was used for cooking vegetables there could be a transfer of trace metals from water to food and they found that these elements were taken into green beans in considerable quantity.

A direct association between caries incidence and soil rather than water composition has been demonstrated by several authors. Barmes and co-workers[11,12] have described an extensive epidemiological study in Papua and New Guinea. The population was basically Melanesian and still living in primitive village communities that formed self-sufficient units relying on locally produced or caught food. Refined foods were virtually absent from their diet. A strong inverse relationship was found between caries prevalence and the contents of Sr, Ba, K, Mg, Ca and Li in garden soils and a possible direct association with soil Cu and Pb. There was consistent evidence of an inverse association with concentrations of V, Mo, Mn, Al, Ti and P and of direct association with concentrations of Pb, Cu, Cr, Zn and Se in the staple foodstuffs (sago, sweet potato and Chinese taro). The role of fluorine was very indefinite and differences between frequencies of caries could not be explained by the fluorine contents of food and soils.

There have been several accounts of the relationship between soil conditions and caries prevalence in New Zealand. Cadell[17] reported a national survey of the prevalence of caries in rural areas of New Zealand the results of which were plotted on the national soil map. Levels of naturally occurring fluoride in New Zealand waters are generally within 0.10 to 0.25 mg F/l and the study excluded those areas where fluoridation of water supplies was carried out. A significantly high caries rating was shown to be associated with wet (gley), sandy or podzolised soils. Outstandingly low prevalence rates were associated with gley soils with saline deposits, northern yellow brown earths and yellow grey earths west of Canterbury. No common factor, other than soil, appeared to be present within the low-prevalence areas. It was hypothesized that the soils might be differentiated by their plant-available concentrations of trace elements. A standard strain of sweet vernal grass was grown on the soils and analysed. High caries rates were associated with soils deficient in Mo, B and Sr and high in Ca, Al, Fe and Ti. Earlier, Ludwig et al.[40] and Healy et al.[33] had written an account of one phase of this investigation involving the prevalence of caries on recent saline soils at Napier, Hawke's Bay. In 1931 a major earthquake resulted in the uplifting of a land mass some 60 miles (97 km) long and at least 10 miles (16 km) wide to heights ranging up to 9 feet (2.7 m). The epicentre was in the vicinity of Napier and resulted in the draining of more than 5 square miles (13 km^2) of a lagoon adjacent to the city. The exposed saline soils were subsequently brought into agricultural production and used for residential housing development. During 1954–55 dental examinations were undertaken of children in Napier and the adjacent city of Hastings in order to establish a baseline before fluoridation of the Hastings water supply. The 5–8 year old Napier children had a considerably lower caries experience than children of similar age in Hastings. The findings were unexpected in view of the similarities of the two cities. Both had populations of approximately 20,000, both were adjacent coastal towns and both had the same supply of low-fluoride water (mean 0.15 mg F/l). The most likely differentiating factor appeared to be soil type. Vegetables grown on the recent marine soils at Napier showed no marked differences in major elements but major differences in trace elements. Napier vegetables were higher than Hastings vegetables in Mo, Al and Ti and lower in Cu, Mn, Ba and Sr. Differences in susceptibility could not be related to a higher intake of fluoride[41] since urine fluoride was low (mean 0.15 mg/l). It was concluded that the factor involved was most likely to be molybdenum in the diet. Ludwig and co-workers[42] analysed teeth from children in the two cities, and those from Napier contained higher levels of molybdenum. When rats were fed with a cariogenic diet supplemented at the 1% level with ash from French beans grown on either Napier or Hastings soils, the ash of the Napier vegetable produced a large reduction in caries in the test animals. This effect was also observed when the Hastings ash was enriched in molybdenum to a concentration equivalent to that in the Napier ash.

These reports associating dental caries with environmental molybdenum[2,40–42] were followed up in a series of investigations in Britain by Anderson[5–7]. These took place in Somerset, England, in an area which has now become the benchmark area for investigating molybdenosis in cattle. The area was described by Lewis[38] as approximately 75,000 acres (30,400 ha) of flat, low lying country where cattle are liable to scouring when turned out on to certain pastures. Both the pastures and the condition are locally known as 'teart' and the disorder arises because of very high molybdenum contents in both soil and grass. The underlying parent rock is a molybdenum-rich black shale of Lower Lias age. In a pilot study 270 children were examined from the teart district compared with 163 children from other parts of southern England. The mean

D. M. F. score (i.e., the sum of the number of teeth which were observed to have decay, or had experienced decay and had been extracted (missing) or were filled was 4.3 in the teart area compared with 6.2 elsewhere ($p < 0.01$). Similar results were obtained for a larger study population from the teart and control areas. If molybdenum was involved in the aetiology of caries in the area then the element was probably not water borne but might have been ingested in milk.

The role of molybdenum in protecting against caries has been reviewed by Jenkins[34, 35]. Evidence from human epidemiological studies strongly suggested that molybdenum, either in drinking water or in food, reduces caries in man. Animal experiments in which molybdate was given either in diet or in water confirmed that molybdenum possesses anti-caries properties. But in some of these experiments very high doses were used and their relevance to human caries was therefore doubtful. None of the known enzymatic functions of molybdenum has any relation to caries but experimental work has suggested that molybdenum can increase the absorption of fluoride from the rat stomach. But animal experiment data were contradictory and did not clarify the molybdenum-fluoride interaction. An unusually high molybdenum intake during tooth formation influences the morphology of teeth and this might account for its anticaries effect. In vitro experiments indicated that the paramolybdate, but not the molybdate, ion inhibited acid production by salivary bacteria and molybdate reduced the solubility of whole teeth. But neither effect was likely to be important in the mechanism in which molybdenum reduces caries prevalence.

A third element which has been studied in some detail in relation to its effect on dental health is selenium. Selenium toxicities in animals have long been recognised in western areas of the USA and in parts of Ireland. Subacute poisoning is known locally in the USA as 'blind staggers' in which lameness, loss of hair and abnormal growth of hooves is prominent. These defects can be traced to a replacement of sulphur by selenium in the cystine linkages of the protein keratin. A possible role for selenium in the aetiology of caries was studied by Hadjimarkos et al.[32]. They had observed that children resident west of the Cascade Range in the state of Oregon showed high rates of caries experience and those east of the mountains low rates. Social factors, dietary habits and water fluoride content did not differ between the two groups. Earlier investigations of selenium in residents of the western zone, where selenium poisoning of stock was a continuing agricultural problem, had revealed elevated urine selenium levels accompanied by poor dental health. Two groups of high school children were examined. Those of Clatsop County west of the Cascade Range had a mean D. M. F. score or 14.4 in contrast with children in Klamath county east of these mountains whose mean D. M. F. score was 9.0. The mean value of urinary selenium for Clatsop County was 0.049 mg Se/l and for Klamath County it was 0.037 mg F/l; the means were different at $p = 0.05$. This work was confirmed by a second study in Oregon and subsequently extended to South Dakota, Wyoming and Nebraska[26, 29]. In a later paper, Hadjimarkos[30] reviewed experimental work on rats which confirmed that selenium added to drinking water at levels as low as 2.3 mg Se/l and consumed at the time of tooth development increased the incidence of caries. He suggested that selenium might alter the protein component of enamel and reported some experimental work which suggested that the initial point of attack in the development of a carious lesion involved the protein of enamel. In another study, Tank and Storvick[55] surveyed high school children in Wyoming which has extensive seleniferous areas and widespread vanadium deposits. Vanadium was of interest because the vanadate ion can replace phosphate in apatite. When vanadium was administered in drinking water to rats and hamsters maintained on a cariogenic diet conflicting results had been reported. In one experiment a decrease in caries was observed but in other work caries was seen to increase. Dental caries rates of permanent teeth was significantly higher in seleniferous areas than in nonseleniferous areas and increasing vanadium content of the drinking water was accompanied by decreasing caries rates.

Environmental lead and dental caries

The fluoride, molybdenum and selenium contents of soil, as well as other elements, vary from place to place according to the nature of the local bedrock and because of differences in soil conditions. Accumulations of these elements in soil are reflected in the composition of locally grown food and the discussion so far has demonstrated that they can be associated with differences in the prevalence of dental caries. In addition to natural geochemical differences some areas have been and are subject to urban and industrial pollution leading to trace metals accumulating in soil. Lead is of particular concern and has influenced dental studies in two ways. The first is the possibility that dental health might be affected by environmental factors and the second is the use of teeth as monitors of the body burden of lead.

Brudevold and Steadman[13] noted in 1956 that lead is normally present in small amounts in teeth, but at that time it was not known to what extent lead found in teeth had been incorporated during tooth formation or deposited after eruption. Nor was it known whether lead in teeth might influence the development of caries. They found that there was an increase in the lead concentration of the surface enamel in fully formed unerupted teeth but the concentration was less than in the outer enamel of erupted teeth. Lead concentration increased with age. Altshuller et al.[4] noted that teeth were much more readily available as biopsy specimens than bone and investigated their use as an index of body burden of lead. They analysed 82 deciduous teeth from normal children, 18 deciduous teeth from children who had died of lead poisoning and 15 teeth from children who had survived lead poisoning. The lead content of the control set of teeth rose linearly with time after eruption and lead was higher in the survivors' teeth and higher again in those from the dead children. Steenhout and Pourtois[54] also found that the lead concentration in permanent teeth rose linearly with age. Analysis of teeth has now become common as a means of assessing exposure to lead and hence relating exposure to human health[15, 18, 24, 37, 50, 53, 59].

Barmes and colleagues[11, 12] reported in 1969 and 1970 that soil lead appeared to be directly associated with increased dental caries in Papua-New Guinea. At the same time Buttner[16] reviewed the published literature on the effects of trace elements on caries incidence in rats and hamsters and he identified lead as having a cariostatic effect. Anderson et al.[9] investigated a possible lead effect by examining dental caries prevalence in 12-year-old children resident in the Tamar Valley in the west of England. The Tamar Valley is an old metal mining area now characterised by widespread heavy metal contamination. The results revealed an apparent small reduction in caries associated with the mineralised area with the exception of one part, the Bere Peninsula, where children had a raised caries level. The Bere Peninsula was the principal producer and refiner of lead ore in the nineteenth century and all the agricultural soils are contaminated by lead. Subsequently, Davies[21] demonstrated that garden soils in the same area are also contaminated by lead and the elevated metal levels are reflected in the composition of home-grown potatoes. A similar dental survey was subsequently conducted[8] in west Wales and included the Pumlumon lead mining district where soils are extensively contaminated by lead. The dental caries prevalence in 12-year-old children was significantly higher for those resident in the contaminated areas. In contrast, a similar study undertaken in Somerset included a small area with some of the highest reported soil cadmium levels[10] and where the soils were also lead polluted, but there was no statistical difference between the dental health of 12- and 15-year-old children resident in the affected village compared with neighbouring, uncontaminated areas.

Conclusions

The addition of fluorides to public water supplies has proved to be a successful exercise in preventative dentistry. The epidemiological and experimental work upon which fluoridation is founded comprise one of the best attested links between environmental geochemistry and human health. Epidemiological evidence also indicates that environmental molybdenum is associated with reduced caries whereas an increased selenium intake may have an adverse affect on dental health. The evidence for dental health effects from other elements is less clear but where there is lead pollution which is not accompanied by unusually high levels of other elements there is also an adverse association with dental caries.

The mechanism through which these trace elements act is not clear. Since cavity formation probably involves localised dissolution of the enamel surface by organic acids it is tempting to hypothesize that the incorporation of trace elements into the apatite structure or into the protein matrix alters the physical properties of enamel, such as solubility, and thereby renders it more or less susceptible to attack by organic acids. But this is simplistic and all that can be said is that those elements which have been identified as affecting the incidence of dental caries are those which do alter the properties of protein and apatite.

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Geopsychology and geopsychopathology: Mental processes and disorders associated with geochemical and geophysical factors

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Summary. Temporal and regional variations in psychological processes have been associated with three geological factors. They are geochemical profiles, geomagnetic variations, and tectonic stresses. In the geochemical domain, copper, aluminum, zinc, and lithium may influence the incidence of thought disorders such as schizophrenia and senile dementia. These common elements are found in many soils and ground water. Geomagnetic variations have been correlated with enhanced anxiety, sleep disturbances, altered moods, and greater incidences of psychiatric admissions. The effects are usually brief but pervasive. Transient and very local epidemics of bizarre and unusual behaviors are sociological phenomena that sometimes precede increases in earthquake activity within a region; they have been hypothesized to be associated with tectonic strain. Many of the contemporary correlations between geological factors and human behavior are also apparent within historical data. The effects of geophysical and geochemical factors upon human behavior are not artifactual, but they are complex and often not detected by the limited scope of most studies.
Key words. Geochemistry; psychology; pathology; geomagnetism; seismicity; psychiatry.

Introduction

Although the idea that geological factors should contribute to human behavior has intuitive appeal from evolutionary and biochemical arguments, empirical support has been less clear. This discrepancy is not unusual for phenomena whose demonstration depends upon factors (in a statistical sense) because they are rarely reflected by a single measure. The available evidence and the conceptual potency of a complex link between geological factors and mental processes are sufficiently compelling to at least entertain the question. This article reviews the concepts, methodological issues, theoretical bases, and empirical support for a causal relationship between changes in human behavior and the three major sources of variance: geochemistry, geomagnetism, and tectonic stress.

1. Psychopathology and soil chemistry

The supposition that chemical constituents within the soil and the underlying bedrock can influence mental processes appears to be based upon two principles: 1) ground water and dependent food sources that are consumed by local residents strongly reflect soil chemistry, and 2) many of the chemical constituents (trace elements) that demonstrate regional variations are also integral components of blood, RNA, DNA and various enzymes. These constituents are effective in microquantities that might be influenced by passive ingestion through the water and food supply.

1.1 The soil concept

The chemical constituents of soil are a function of the