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Recording Dental Caries in Archaeological Human Remains

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ABSTRACT Dental caries is an important condition to record in archaeological collections, but the way in which recording is carried out has a large effect on the way in which the results can be interpreted. In living populations, dental caries is a disease that shows a strong relationship with age. Both the nature of carious lesions and their frequency change with successive age groups from childhood to elderly adulthood. There is also a progression in the particular teeth in the dentition which are most commonly affected and, in general, the molars and premolars are involved much more frequently than the canines and incisors. Lower teeth are usually affected more than upper, although the condition usually involves the right and left sides fairly equally. In the high tooth wear rate populations represented by many archaeological and museum collections, there is a complex relationship between the form of lesions and the state of wear, which adds yet another range of factors to the changing pattern of caries with increasing age. In the same populations, chipping, fracture and anomalous abrasion of teeth are also common, and these contribute similarly to the distribution and forms of carious lesion observed. Amongst the living, the pattern of ante-mortem tooth loss is important in understanding caries and, in archaeological material, there is also the complicating factor of post-mortem tooth loss. Finally, there is the question of diagnosis. There are diagnostic problems even in epidemiological studies of living patients and, for archaeological specimens, diagenetic change and the variable preservation of different parts of the dentition add further complications. For all these reasons, it is difficult to define any one general index of dental caries to represent the complete dentition of each individual, which would be universally suitable for studying a full range of collections from archaeological sites or museums. Variation in the nature of collections, their preservation, tooth wear, and ante-mortem and post-mortem tooth loss mean that when such a general index appears to differ between sites, there could be many other reasons for this, in addition to any genuine differences in caries incidence and pattern that might have been present. It is suggested here that the best approach is instead to make comparisons separately for each tooth type, age group, sex, lesion type and potential lesion site on the tooth. Copyright © 2001 John Wiley & Sons, Ltd.

Key words: dental caries; recording schemes; epidemiology; periapical inflammation; dental wear

Introduction

Alongside the pattern of dental attrition and analysis of stable isotopes, dental caries epidemiology is one of the most important ways in which the diet of past populations can be reconstructed. It is fundamental to the understanding of transitions from hunter-gatherer to agriculturalist lifeways (Lubell *et al*., 1994). In addition, it is one of the few conditions which has been recorded unfailingly in almost all reports on human remains from archaeological sites (Rose *et al*., 1991). The difficulty is that methods used for diagnosis and recording dental status generally have lacked consistency, and also have often not provided enough detail to allow proper interpretation. It is only in the last 30 years that such detail has been recorded in any studies at all. A large step towards improving the situation has been taken in the so-called

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Chicago Standards (Buikstra & Ubelaker, 1994) for data collection which adopted the scheme of Moore & Corbett (1971). Yet caries epidemiology is difficult enough even amongst the living, and there is a need for continued debate on methods for recording and quantifying caries in archaeology.

The natural history and different forms of caries

It has been common practice to record dental caries simply as present or absent for each tooth, but the condition may be initiated in different positions on the tooth surface, to produce several classes of lesion with different aetiologies:

- *Coronal caries*. Carious lesions initiated in the enamel of the crown surface can be grouped together as coronal caries. As the lesions develop, they involve the dentine, which forms the main structure of the tooth underlying the enamel, and the character of the lesion changes with this transition. Ultimately, the pulp chamber may be penetrated, and in most cases, this results in an inflammatory response from the pulp, which may in turn lead to periapical inflammation. Nowadays, a lesion that had progressed to this point would usually be treated by extraction of the tooth, or a root filling. The original enamel lesion may be initiated in a variety of locations on the crown:
  - *Occlusal caries*. Many lesions are initiated in the complex systems of fissures, fossae and grooves that mark the occlusal surfaces of molar and premolar crowns (Figure 1). Others start in the buccal pits at the end of fissures on the molar crown sides, or in the pits which sometimes mark the lingual surfaces of upper incisors.
  - *Contact point or approximal smooth surface caries*. Lesions are frequently initiated on the mesial and distal crown surfaces, just below the contact point between neighbouring teeth (Figure 2).
  - *Other smooth surface carious lesions on the crown*. Caries may occasionally be initiated anywhere on the other crown sides, but such lesions are usually along the cervix of the crown just above the line of the gingivae, particularly on the buccal/labial side of the crown (Figure 3).

Figure 1. Carious lesion in the central fossa and distal fossa of the occlusal surface of a lower first molar crown. The lesions have progressed to the stage at which large cavities have been formed, involving the underlying dentine and, probably, the pulp chamber. The cusps of the crown have been worn by dental attrition to expose small areas of the underlying dentine, so what appears to be active caries is co-existing with moderately severe tooth wear. This specimen (and those of all the following figures) comes from the teaching collection of the Institute of Archaeology, University College London.

- *Root surface caries*. Usually later in life, the roots of the teeth are exposed by continuous eruption, or the recession of the gingivae and underlying supporting tissues related to periodontal disease. Carious lesions may then be initiated in the cement of the root surface either along the cement–enamel junction (Figures 4 and 5), or further down the root when this is exposed above the margin of the gingivae. Root surface carious lesions usually develop slowly, but the thin layer of cement is soon penetrated to expose the underlying dentine.

By far the majority of clinical studies have concentrated on dental caries in children from industrialized countries with diets rich in sugar, and, relatively speaking, a high level of dental care, amongst whom coronal caries is much the most common form. One of the key features of caries epidemiology since the 1970s throughout

Figure 2. Carious lesion at the contact point of an upper second premolar, represented by a clear cavity just below the point at which the tooth would have made contact with the crown of its neighbouring first premolar. The lesion also involves the cement–enamel junction at the cervix of the tooth. Its form suggests that the site of initiation was, in fact, the contact point, but strictly speaking, it should be classified as a gross contact point/cement–enamel junction lesion (see text).

Figure 3. Smooth surface carious lesion. A long irregular cavity runs along the crown of this upper first incisor, just below the point at which the gingivae would have been attached to the base of the crown.

the industrialized world has been a striking decline in caries rates, whichever way they are measured. This seems to have little to do with availability of dental care, but more to do with a less interventionist style of treatment, an even greater relationship with fluoride toothpaste and, most of all, with a range of changing social factors which also seem to be linked to improvements in general health indicators (Sheiham, 1997). The decline is shown in the average number of carious lesions per person (Decayed Missing Filled (DMF) scores—see below), and in the proportion of each age cohort in a population affected by caries. In all populations, there is an age-related trend line showing a progressive rise in the average number of lesions per person in successive age cohorts from childhood to adolescence and early adulthood. The effect of the caries decline has been to decrease the slope of that trend line, making it flatter. These changes in average caries rate are superimposed over a clear hierarchy of susceptibility in the tooth types and potential coronal lesion sites involved in the permanent dentition (Sheiham, 1997). Left and right sides are equally affected by coronal caries, and upper cheek teeth about the same as lower cheek

Figure 4. Carious lesion on the root, at the cement–enamel junction. A broad cavity runs around the root of this canine tooth, just below the base of the crown.

Figure 5. Another lesion on the root, at the cement–enamel junction, confined to the notch which characterizes the mesial side of the upper incisor crown. Lesions of this type are amongst the most common forms in Medieval British material.

teeth, but upper anterior tooth crowns are more frequently involved than lower. Cheek teeth are far more susceptible than anterior teeth, and the occlusal fissures of first molars (the earliest erupting permanent teeth) are generally the teeth affected in the lowest caries rate populations. At slightly higher caries rates, the occlusal sites in second molars are involved and, higher still, the approximal sites of the molar crowns (upper and then lower). At even higher rates, the occlusal sites of the premolars become involved—initially the second and then the upper first premolars—then the approximal upper incisor sites, approximal premolar sites and occlusal lower first premolars. Finally, at the highest rates, the upper canines are affected. This hierarchy appears to remain the same, regardless of fluorine in toothpaste and water, and level of dental care.

Only quite recently have there been large studies of caries in adults, including both coronal and root surface caries, and only rarely have there been such studies in communities where the level of surgical intervention seen in industrialized societies was effectively not available (Manji *et al.*, 1991; Thylstrup & Fejerskov, 1994). For this reason, it has been difficult to find modern examples which can be compared directly with the majority of archaeological material, and, on the contrary, archaeology may provide an important opportunity for studying the natural history of caries. There are now, however, a number of relevant studies of children and adults from Kenya (Manji *et al.*, 1988, 1989a,b, 1990, 1991), West Africa (Matthesen *et al.*, 1990), and rural China (Luan *et al.*, 1989a,b; Manji *et al.*, 1991; Baelum *et al.*, 1993). As with the studies of children and young adults described above, one of the main features of caries in these groups of people was a clear progression with age in successive cohorts from childhood right the way through to elderly adulthood. The proportion of an individual's teeth affected by coronal or root surface caries rose with age, as did the proportion of individuals in the study group affected (i.e. the prevalence of caries). At the same time, the caries experience of the members of such a study group was very varied, with only relatively few individuals having many teeth affected, or many lesions, in their mouths. As is seen in most archaeological studies, women tended to have more teeth affected than men, with a more strongly marked progression with age, although the difference was not great, especially in the younger age groups. The proportion of teeth with lesions penetrating to the pulp chamber rose gradually with age, as did the proportion of teeth missing because of caries. This was the most common cause of tooth loss/extraction in all age groups, followed by loss resulting from periodontal disease, and then trauma.

In these studies, the pattern of lesions changed progressively with age as well. Lesions confined to the enamel of the crown were the most common form in teenagers and young adults, and, although they decreased after this, they remained a common form of caries even in the oldest age groups. This means either that some enamel lesions progressed very slowly, or that new coronal carious lesions were initiated throughout life. Coronal lesions involving the dentine were uncommon in the youngest age groups, but increased into early/mid-adulthood and then fell somewhat. Root surface caries was also uncommon amongst teenagers and young adults, but showed a steady rise with age in older groups. This rise, however, was not nearly so marked as the age-related increase in root surfaces exposed by recession of the gingivae and continuous eruption. For all types of carious lesions, the molars were the most frequently affected teeth, although this was particularly marked in younger age cohorts (see above), and increasing numbers of incisors and canines were affected in older age cohorts. Caries was slightly more common in the lower molars than the upper molars but, even though carious lesions were much less common throughout all age cohorts in first premolars, incisors and canines, this group of teeth in the upper jaw were always considerably more affected than those in the lower jaw. These general patterns of change with age have been to some extent confirmed by studies of older adults in modern Europe and America, although here the position is complicated by widespread dental treatment, diet and fluoride (Chauncy *et al.*, 1989; Fejerskov *et al.*, 1993; Fure, 1997; Fure & Zickert, 1997).

Such studies may be of relevance to agriculturalist human existence in much of the past, but probably differ markedly from the caries epidemiology of hunter-gatherer existence. There have been some studies, mostly during the first half of the previous century and varying considerably in detail, of living people who had followed a relatively unaltered hunter-gatherer lifeway, at least during their childhood and early adulthood. P.O. Pedersen had a unique opportunity to examine the teeth of almost the whole population of Angmagssalik in East Greenland (Pedersen, 1938, 1947; Davies & Pedersen, 1955). The scientific communities of the western world were completely unaware of this isolated Inuit group until AD 1884, and, even in 1937 when Pedersen saw them, most still lived on their traditional diet of meat and fish, with practically no carbohydrate. The prevalence of caries was extremely low, with just over 4% of people being affected, and 0.3–0.6% of permanent teeth (0.7–0.8% of deciduous teeth) bearing a carious lesion. Most of these lesions were found in the fissure systems of third molars, particularly in adult females. Third molar occlusal fissures were often preserved into adulthood, because there was a very marked wear gradient along the tooth row, with the highest wear rate in the anterior dentition and the least in the most distal molars. Overall, tooth wear was extremely rapid, even in children, so that dentine was exposed in the permanent first molars of most people by 30 years of age, and secondary dentine in more than half the people over 50 years (Davies & Pedersen, 1955). In spite of this, pulp exposure by tooth wear was very rare (out of 6000 teeth only 2 showed this, Hilming & Pedersen, 1940), although large tooth fractures occurred frequently and did often expose pulps (Pedersen, 1947). Gingivitis was common, but bone loss in the jaws resulting from periodontal disease was practically non-existent. In no cases had any teeth been lost as a direct consequence of caries, and only rarely did tooth loss appear related to pulp exposure by attrition or alveolar bone loss resulting from periodontal disease. These observations fitted well with the dental condition of large collections of ancient Inuit skulls in Denmark and the USA (Leigh, 1925b; Pedersen, 1938), in which only 0.4–2.5% of individuals were affected by caries, with 0.08–0.35% of permanent teeth (and no deciduous teeth) bearing lesions, again mostly fissure lesions of little worn molars in adults. Other neighbouring Greenland Inuit settlements visited by Pedersen in 1930 had access to imported sugar and cereals, and had a considerably higher rate of caries (Pedersen, 1966), associated with a much lower wear rate (Davies & Pedersen, 1955). Similar contrasts have been noted for Inuit in North America (Mayhall, 1970, 1977).

The teeth of living aboriginal Australians were studied during several expeditions of the University of Adelaide during the 1920s and 1930s (Campbell & Lewis, 1926; Campbell, 1928; Campbell & Moore, 1930; Campbell & Gray, 1936; Campbell, 1937, 1938a,c,b, 1939), and 1950s (Barrett, 1953; Campbell & Barrett, 1953; Cran, 1955; Barrett, 1956; Cran, 1957, 1959, 1960), and in association with the American–Australian Scientific Expedition to Arnhem Land in 1948–1949 (Moody, 1949, 1960). One of the features of these dentitions was again rapid tooth wear, associated with chipping of the enamel around the edges of the worn surfaces. Caries was uncommon in children, but showed a large increase in older adults—mostly lesions of the worn remnants of the molar crowns, and not root surface caries (although little detail is available). The rise of caries with age was paralleled by a rise in periapical inflammation and tooth loss (see section below). The situation was similar in museum collections of aboriginal Australian skulls (Campbell, 1925). The rise in frequency of lesions, therefore, appears to have been directly associated with increasing tooth wear in older adults, chipping (Moody, 1960) and abrasion at the neck of the tooth by using the teeth as tools for a variety of jobs (Campbell, 1925). The generally higher rate of caries amongst aboriginal Australians (compared with the Inuit described above) can be put down to the availability of sources of carbohydrate in the gathered plant foods exploited by many groups in Australia. Such foods also formed a substantial part of the diet of the !Kung bushmen of South Africa (van Reenen, 1964, 1966; du Plessis, 1986; van Reenen, 1992), who showed a remarkable similarity in the pattern of dental caries before they were settled on farms.

These studies of the natural history of dental caries, therefore, show that there may be strong contrasts between different cultures and different modes of subsistence in the types of lesion that occur, and their distribution. In order to identify this, studies of archaeological material need to differentiate between the various forms of caries, different stages of development (particularly of coronal lesions) different age groups, males and females, and between different classes of teeth. It is probably not necessary to distinguish left teeth from right, because caries is usually symmetical, but upper and lower dentitions show consistent differences (Thylstrup & Fejerskov, 1994). Another important aim is to recognize the possible effects of different patterns of tooth wear, chipping and fracture. If all these factors are not taken into account, any apparent differences in the pattern of caries between populations, or archaeological collections of material, could be explained simply by differences in the nature and derivation of the material studied.

DMF scores and percentages

Epidemiological studies of living people usually employ DMF scores to summarize an individual's caries experience (World Health

Organization, 1997). This idea was originally suggested by Klein *et al.* (1937, 1938) and, in its simplest form, is a count of the number of permanent teeth which have a carious lesion that are missing, or have been filled. The underlying, but unstated, assumption is that the count is out of the total 32 permanent teeth normally present, even though the total may vary for reasons which have nothing to do with caries. Such a count of teeth is known as the DMF-T score and, in many studies, the mean DMF-T score for the study group has been used to express the rate of caries in the population. In effect, this is the average number of teeth affected by caries, per person. It is *not* (as has sometimes been suggested) a prevalence for caries, which would be the number of individuals affected, expressed as a proportion of the total number of individuals in the population (Waldron, 1994). The mean is also not a very good way to summarize the distribution of DMF-T scores in a population, because this distribution is usually strongly asymmetrical (Thylstrup & Fejerskov, 1994). A further difficulty of basic DMF-T scores is that they must usually be an underestimate of caries severity, as they take no account of the possibility that a tooth might be affected by more than one carious lesion. Many studies have, therefore, used a variant of the idea, in which tooth surfaces are counted instead of teeth. Each tooth is reckoned to have five surfaces—occlusal, buccal, lingual, mesial and distal—totalling a possible 160 surfaces for a full permanent dentition. For each individual, the number of such surfaces which are carious, missing, or filled is counted to give the DMF-S score. Again, the mean DMF-S score is used as an index for caries experience in the population, even though the distribution of such scores is once more highly asymmetrical. In any case, there are problems with each of the elements of any DMF score:

1. The D element; decayed teeth or surfaces. The number of decayed teeth counted depends upon the diagnostic criteria used. Many surveys count only lesions in which a clear cavity is seen or felt, while others include stained or discoloured patches, or fissures in which the tip of a probe sticks. It is necessary to ensure that like is being compared with like in different surveys. In addition, even the DMF-S variant is an underestimate of carious lesions in some individuals, because it is quite possible for one surface to bear more than one lesion and an overestimate in others, where one lesion spreads over more than one surface. Finally, in their basic forms, DMF scores do not allow the different types of carious lesion to be recorded separately.
2. The M element; missing teeth or surfaces. This is one of the biggest problems. When most studies involved caries in the young, it was a fairly safe assumption that most teeth that were missing had been lost as a result of a carious lesion which penetrated to the pulp, and had resulted in an extraction, because tooth loss resulting from periodontal disease is very uncommon in children and young adults. Even so, there would be some variation because of congenital absence of teeth, trauma and variation in the sequence and timing of eruption. Studies of adults have more problems because, although several studies have shown that caries is the most common reason for tooth extraction throughout life, a substantial number are still lost to periodontal disease. The ratio of caries to periodontal disease tooth loss is likely to vary between populations, especially with the large contrasts in diet and behaviour, which are often investigated in archaeological material. In studies of the living, patients can be asked about the clinical history of their missing teeth (Manji *et al.*, 1989a). Carious lesions which penetrate the pulp and initiate periapical inflammation may cause great pain, but little bone loss or subsequent loosening. Periodontal disease rarely causes such pain, but involves bone loss, and one of the main signs for diagnosis is mobility of the tooth (MacPhee & Cowley, 1975). Even with such additional evidence, it can be very difficult to determine the cause of tooth loss and, in archaeological assemblages it is not possible to reach any definite conclusions. To some extent, it may be possible to form at least an opinion about the likely cause of tooth loss

with archaeological material, as caries is often symmetrical and teeth still present on the opposite side of the jaw may suggest pulp penetration by coronal caries. Similarly, bone loss resulting from periodontal disease may be evident around other teeth which survive in the jaw. For archaeological material, it is also necessary to take into account such factors as tooth wear and fracturing, which cause parts of teeth to be unscorable for caries and, therefore, effectively missing, even when the rest of the tooth is still present in the jaw. The most insuperable problem for archaeology, however, is the post-mortem loss of teeth and parts of the jaw. It is very difficult to adjust DMF scores to take account of this (below). In any case, there is a final over-riding difficulty with the M element even in living populations—DMF-S scores have an inbuilt error because, if a tooth is missing, then all five of its surfaces are counted as missing. This means that all five are assumed to be carious, when it is much more likely that only one or two surfaces were affected when the extraction took place. Some authors, therefore, advise that the missing category should be left out of DMF-S scores, to give DF-S scores instead (Thylstrup & Fejerskov, 1994).

3. The F element; filled teeth and surfaces. In studies of living patients, this causes problems because one filling frequently overlaps several surfaces, as a result of the need to give it a form which will be retained in the tooth under heavy load. With one large filling, there is no knowing how many surfaces were originally involved with carious lesions (Thylstrup & Fejerskov, 1994). In archaeological material, even into the beginning of the 19th century, there is often little evidence of dental work, so the F element causes fewer difficulties.

If all these difficulties are taken into account, then the epidemiologist is left with only a D-T or a D-S score. To allow for this, some studies now present scores for D-T, D-S, M-T, F-T and F-S separately (Manji *et al.*, 1989a, 1990, 1991). For all these reasons, there is considerable current discussion of DMF scores in the epidemiological literature, and various adjustments and statistical procedures have been proposed (Thylstrup & Fejerskov, 1994; Beck *et al.*, 1997; Burt, 1997; Kingman & Selwitz, 1997; Spencer, 1997).

DMF scores are rarely used in archaeology, because the first priority is to develop a methodology which is not affected by the pattern of jaw preservation and post-mortem tooth loss. With this in mind, most studies have expressed either the number of carious teeth as a percentage of the surviving teeth, or the number of individuals affected as a percentage of the total number of individuals in the collection. Expressing caries as a percentage of teeth present has a big practical advantage for archaeology, in that isolated teeth can be included in the study, and these make up a considerable proportion of the remains at some sites. As normally calculated, however, there are several serious difficulties:

- No distinction is made between tooth classes. This makes it impossible to discern any patterns which relate to the distribution of caries through the dentition and, as has been shown above, this is known to be highly variable. In addition, the pattern of post-mortem tooth loss has a strong effect. Caries rates are much higher in cheek teeth, but anterior teeth are more likely to fall out post-mortem, so that, in an archaeological collection where preservation is good and the anterior teeth survive, the caries rate is inevitably depressed relative to a collection with poor survival of this kind.
- The percentages are likely to be underestimates of caries experience, where the bulk of missing teeth were extracted ante-mortem as a result of caries because these, the most strongly affected of all, are not taken into account.
- No allowance is made for the development of dental caries with age. The age-at-death and sex composition of archaeological assemblages varies widely, and this could strongly affect the apparent caries rate.
- In most common usage, no distinction is made between the different forms of caries,

and there is no way in which the presence of two different forms of caries on one tooth could be recorded. This must mean an underestimate of caries amongst assemblages (such as those of some native North Americans) where both coronal and cervical lesions are important. In addition, the various forms are differently distributed in anterior and cheek teeth with age, and are differently affected by the contrasting wear patterns seen in archaeological assemblages.

With all these difficulties, it is unclear what the figure for percentage of teeth with caries in a group of archaeological material actually represents. Where, say, two assemblages are compared, there are so many potential alternative methodological explanations for any difference between them that it is very difficult to prove a real difference in caries rate. The depressing conclusion of this is that most of the caries data painstakingly collected over many years, and presented as percentages of total tooth counts, cannot reasonably be compared between studies of different collections.

In some studies, corrections have been applied to archaeological caries scores for the proportion of teeth missing ante-mortem, to make them directly compatible with DMF indices in modern epidemiological studies (Costa, 1980b). It is also possible to use the pattern of lesions in surviving teeth to estimate the number of teeth lost because of penetration of the pulp by caries, and add these on to the number of carious teeth present in the jaw (Lukacs, 1995). Caries rate can then be calculated as the total number of teeth estimated to have had caries, expressed as the proportion of the estimated total number of teeth originally present (teeth in the jaw plus teeth lost ante-mortem). Erdal and Duyar (1999) have proposed a further modification to this corrected index, which allows for the differential survival of anterior teeth and cheek teeth. Another possibility is to include all teeth missing ante-mortem by adding their count onto the number of carious teeth—the 'DM' index (Kelley *et al.*, 1991)—and then to express this as a percentage of the total number of surviving teeth plus the number of teeth lost post-mortem (Saunders *et al.*, 1997). This approach has also been called the 'I-CE' (index of *caries et extractio*; Caselitz, 1998). Procedures like this, however, make assumptions which are difficult to test and none address all of the problems outlined above, so it seems timely to re-examine the whole basis of recording carious lesions in archaeological material, and to look at alternatives to the traditional percentage rates.

Alternative caries recording systems in archaeology

One possible alternative is the so-called Moulage System, which grew out of large plaster-of-Paris models developed originally by P.A. Lindström for teaching purposes in the Royal School of Dentistry, Stockholm. In the first half of the 20th century it was common practice to use models made from impressions (French *moulage*, moulded reproduction) of bodies and organs for teaching anatomy and pathology. Between 1940 and 1942, the teaching series was developed into a recording scheme based on a series of 85 beautifully made models showing different types of carious lesion in varying degrees of severity (Dahlberg, 1940). The models were numbered:

- 1–9 represented fissure caries.
- 11–16 and 91–92 represented premolar contact area caries.
- 21–24 represented premolar combined fissure/contact area caries.
- 31–37 represented incisor contact area caries.
- 41–49 represented smooth surface caries at the cervix.
- 51–59 represented cement–enamel junction caries.
- 61–65 represented pit caries.
- 71–76 represented cusp tip lesions.
- 81–84 represented root surface caries.

The models themselves were never widely available outside Scandinavia, but small photographs were published in a number of journal articles (Lindström, 1940; Rönnholm *et al.*, 1951). When used for recording, carious lesions are matched with the models, and then the tooth involved is assigned the appropriate model number. This system was used in several epidemiological studies in the living, including the famous Vipeholm study (Gustafsson *et al.*, 1954), and in the ground-breaking archaeological study of Swärdstedt (1966). The results were presented as frequencies for the different categories of moulage, and could be combined in a variety of ways.

The main advantage of the Moulage System is that it counts the different types of lesions at various caries sites, rather than affected teeth. As originally described, it makes no provision to count the non-carious sites and, therefore, does not allow lesions to be expressed as a proportion of 'sites at risk', although this could easily be remedied. The models make an excellent shorthand for describing caries, and a good teaching aid, but are a little too cumbersome for routine use in archaeological material. Another difficulty is that the original large plaster models are not widely available, and the published photograph is too small for ease of use. In any case, the system needs to be used imaginatively because real carious lesions do not necessarily match any model exactly. Furthermore, archaeological teeth are often much more worn than those of modern people, and this gives rise to lesions which are not included in the system.

Another alternative was proposed by Moore and Corbett (Moore & Corbett, 1971, 1973, 1975; Corbett & Moore, 1976) in their study of the history of caries in Britain from the Iron Age to recent times. They recorded carious cavities at three groups of lesion sites:

(A) Occlusal. Fissure caries. Cuspal caries. Gross (below) occlusal caries.
(B) Interstitial. Contact area caries. Cement–enamel junction caries (distinguishing where possible between lesions initiated in enamel and those initiated in cement). Gross interstitial caries.
(C) Buccal. Fissure caries. Cement–enamel junction caries. Gross buccal caries.

Lingual sites were involved so rarely that they were not presented in the results. 'Gross caries' is the term used to describe a lesion that has grown to the point that it includes several possible sites of initiation, and, therefore, its original site cannot be determined (Figure 6).

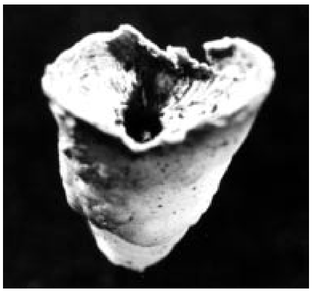

Figure 6. 'Gross gross' carious lesion, in which only the apical part of the root remains. The cavity exposes the open root canal in its floor, and there is no real evidence remaining which might suggest where this lesion was initiated.

The prevalence of caries was calculated in a number of ways, but the real innovation was an index which expressed the number of carious teeth as a percentage of 'teeth at risk' of developing caries. In addition, indices were tabulated separately for different tooth classes and different age groups. These ideas were an important advance in recording dental caries for archaeological material, and have formed the basis of most detailed studies since (Lunt, 1974; Whittaker *et al.*, 1981; Kerr *et al.*, 1990; Varrela, 1991). They have been recognized as a standard for anthropological recording (Buikstra & Ubelaker, 1994), but can be applied in a variety of ways, and the methods proposed in the present paper have developed out of them.

General problems of recording and presentation of results

The progressive nature of caries

The cavities which make the most visible expression of dental caries are in fact a rather late stage of the disease. In coronal caries, the initial demineralization of enamel takes place under an apparently intact surface layer, and the changes can only be seen in microscope sections (Darling, 1963; Jones & Boyde, 1987). Some time later, the first outward sign may be a very small white or brown spot in the otherwise translucent enamel, which still has a smooth and glossy surface. It requires very careful examination of the surface, preferably with a low-power microscope, to see the first stages of such white or brown spot lesions. The localized demineralization often does not show itself as a radiolucency in a dental x-ray until much later and, in any case, the ability to demonstrate enamel lesions varies greatly with their position on the tooth crown. Gradually, the spot lesion may increase in size until it is readily visible to the naked eye. Eventually, the hitherto smooth enamel surface may become roughened (traditionally detected by feel, using a fine-pointed probe), and finally breaks down to produce a cavity. The lesion may then progress into the dentine, and then into the pulp. This opens the pulp up to an infection by a broad spectrum of micro-organisms from the mouth, and may result in pulp inflammation. Ultimately, the pulp usually dies (although some parts of the pulp in a multi-rooted tooth may continue to survive), and inflammation passes down the root canal, so that either the micro-organisms or the products of inflammation emerge from the apical foramen and initiate inflammation in the supporting tissues around the apex of the root. Pulpitis and acute periapical inflammation are painful, and the affected teeth are sensitive to cold, heat and pressure. Nowadays, teeth that have reached this stage are usually treated by extracting them or by root canal treatment, or sometimes by removing part of the pulp. Extraction is the simplest and surest treatment, and this operation has a long history (Hofman-Axthelm, 1981). Most people in the world today probably have recourse to basic treatment of this kind, even if it is from non-professional surgeons, and it is also likely that many groups of archaeological material include jaws from people who were treated in this way. In the absence of treatment, it is not clear that acute periapical inflammation inevitably leads to loss of a tooth, and many cases progress much more slowly anyway. The most typical form of such chronic inflammation is a periapical granuloma (below), usually associated with a small smooth walled cavity within the bone of the alveolar process. These are virtually symptomless, and involve very little loss of tooth support, even though they may look striking in archaeological jaws. In some instances, such granulomata may develop by the accumulation of pus into a chronic periapical abscess, but these are once again not usually painful, and would mostly be noticed by the foul-smelling discharge which emerges via a channel through the gingivae or into the nose. Chronic periapical inflammation of these kinds may persist for a long time, and is maintained as long as the open root canal provides a route for micro-organisms to enter from the mouth.

In most cases, even coronal caries, as described above, is a slowly progressive disease (Pine & ten Bosch, 1996), although a proportion of modern children show what is known as 'rampant caries', where newly-erupted and not-fully-matured crowns are covered in thick plaque deposits, and the child eats sugary snacks all day. In most other cases, it can take years for surface-visible signs to develop, and the lesion progresses irregularly, with faster development interspersed by quiescent phases (Pine & ten Bosch, 1996). Even when a cavity has formed, the lesion does not necessarily proceed to exposure of the pulp and it may remain stable for years, or even remineralize. Penetration of the pulp chamber itself can be delayed for a long time by the deposition of secondary dentine, which seals off the pulp, and inflammation of the pulp can be very localized and slow to develop. Chronic pulpitis of this kind sometimes does not lead to pain and may be unrecognized for years—it may even heal. Similarly, periapical inflammation may be virtually symptomless for much of the time, and often develops very slowly. All of these features and consequences of caries show a gradual progression with age, and the mouths of people who are susceptible to caries accumulate more carious lesions, more lesions which penetrate into the dentine, more exposed pulp chambers, more teeth affected by periapical inflammation, and more teeth lost by extraction. Root surface caries develops even more slowly, and shows a similarly strong pattern of development with age.

From this, it is clear that dental caries has no precisely defined fixed points at which a diagnosis of 'carious' or 'non-carious' can be made. It is a continuous development, which typically proceeds slowly and irregularly, so that any diagnostic criterion is arbitrarily selected, and there has been recent discussion in clinical literature about the best criteria to use (Ie & Verdonschot, 1994; Thylstrup & Fejerskov, 1994; Lussi, 1996; Pine & ten Bosch, 1996; Burt, 1997; Ismail, 1997; Nyvad & Fejerskov, 1997; Pitts, 1997). One issue is the inclusion of 'precavitated' lesions (sometimes called incipient lesions) in epidemiological surveys. It has been known for some time that enamel lesions in which an opaque spot or roughened surface is seen, without a cavity being apparent, are much more common than cavitated lesions (Ismail, 1997). Most surveys to date have however only recorded carious cavities (usually penetrating the dentine) about which the examiner was absolutely certain, because this reduces problems of variability between dentists, particularly in situations where the facilities for examination are not optimal. It is recognized that such procedures will underestimate the prevalence of caries, but consistency is usually considered more important (Burt, 1997). It has recently been suggested that recording of precavitated lesions is not necessarily as unreliable as had been believed when carefully trained and calibrated examiners are used to conduct the survey (Ismail, 1997), although some other studies have shown less encouraging results (Lussi, 1996). A related issue is the use of a dental explorer or probe to feel for roughened enamel surfaces, or fissures in which the tip sticks, to help detect precavitated lesions. In the first place, it is now suggested that sharp probes damage tooth surfaces and, second, that they are not a very effective aid to diagnosis (Penning *et al.*, 1992; Thylstrup & Fejerskov, 1994; Ismail, 1997). Another issue is so-called 'hidden caries', in which a lesion can be demonstrated in a section of the tooth to have affected the dentine, but is either not apparent at the crown surface, or the surface manifestation gives no clue that the lesion is so extensive. This is particularly a problem of occlusal caries (see below), and numerous laboratory studies of extracted teeth have been carried out (van Amerongen *et al.*, 1992; Tveit *et al.*, 1994; Ekstrand *et al.*, 1995), together with trials of various traditional and novel methods of examination (Ie & Verdonschot, 1994; Pine & ten Bosch, 1996; Huysmans *et al.*, 1998a,b; Eggertsson *et al.*, 1999; Lussi *et al.*, 1999). X-rays are not a very reliable basis for diagnosing hidden occlusal caries (van Amerongen *et al.*, 1992; Espelid *et al.*, 1994) because of the convolutions in the enamel in this part of the crown, but they are more useful for approximal caries, and still act as a useful additional diagnostic tool. Newer techniques include fibre-optic transillumination (FOTI), with a narrow beam of light that shows up dentine lesions as dark shadows, laser fluorescence where lesions fluoresce differently to the intervening enamel, and electrical resistance which is reduced in carious lesions because they are more porous and, thus, imbibe more fluid than intact enamel. Of these, electrical resistance seems to be one of the more promising approaches, but even this is not widely used for clinical purposes. Most dentists continue to use direct examination by eye and explorer, supported by radiography. Simple visual examination, in fact, does not perform badly for lesions hidden under occlusal surfaces, particularly when modest magnification can be used to examine extracted teeth carefully (Tveit *et al.*, 1994; Ekstrand *et al.*, 1995; Lussi, 1996). This latter situation is easy to duplicate in examination of archaeological material, where jaws can be held under a low-power stereomicroscope with optimum illumination, teeth are already dry and clean, and can often be tilted and manipulated in their sockets to show the approximal area better. The main additional difficulty for archaeological material is the possibility of diagenetic change, which may produce staining and even cavitation (Poole & Tratman, 1978) under some circumstances. This can be checked by simple sectioning (see below), through the presence of a secondary dentine reaction underneath.

A more serious problem, even in clinical studies, is that varying practice between different surveys and the contrasting nature of carious lesions in different populations make it difficult to ensure that like is being compared with like when surveys are compared. Furthermore, most surveys of caries in the living, and all archaeological studies, are *cross sectional*. They record caries in a group (not necessarily contemporaneous) of people of various ages, and it is necessary to infer the longitudinal development of caries throughout these people's lives from a snapshot of the group as a whole. Caries does not affect everyone equally, and the bulk of large carious lesions and tooth loss are found in only a quarter or less of the study group (see above). This uneven distribution makes it particularly difficult to infer a lifetime's development of caries from cross sectional studies, although modern clinical studies have shown that, at the level of the population as a whole, it is possible to extrapolate. Added to this is the fact that a collection of archaeological material from a large cemetery is by no means a random sample of all ages, sexes and conditions of people in the original living population. The group of people that die each year is itself not a random cross section, because it is generally those who are susceptible and succumb to disease, and the people buried in the cemetery would be drawn from such death assemblages over some years—maybe even hundreds of years. The collection that eventually reaches the anthropologist's work-bench has also been subject to a whole series of (probably) non-random factors of preservation and recovery. Caries is common enough in most archaeological material to make it the most profitable palaeopathological condition to study, but all the problems involved with determining prevalence in ancient, once-living populations need to be borne in mind (Waldron, 1994).

Occlusal caries and its diagnosis

Caries frequently develops in the complex of sloping cusp sides, grooves, fossae and fissures that make up the occlusal surface of the crown. The fissures in the occlusal surfaces of molars and premolars are often very deep, and reach down almost to the enamel–dentine junction. The initial stages of fissure caries may take place deep inside them, without being apparent at the surface. Within a complex fissure system in a large molar, lesions may be initiated at several separate points and, in any case, caries may spread rapidly through the whole complex of fissures and fossae. In some cases, the lesion has reached the enamel–dentine junction, and is undermining the enamel before there is any sign at the surface, which may result in a sudden collapse of a large area of the occlusal surface, to create a deep and steep-sided cavity. In other teeth, opacities, staining or small cavities may become visible in the grooves, fossae and fissures. These features are usually a reasonably good indication that there are carious lesions underneath, but it can be difficult to relate them directly to the extent of that lesion, or group of lesions. Penning *et al.* (1992) found that 94% of extracted teeth with stained fissures showed caries when they were sectioned and, on average, there were 2.3 lesions per tooth. Tveit *et al.* (1994) similarly found that 90% of molars and premolars with opaque or discoloured patches in occlusal fissures or pits, but no cavity, had histological evidence for caries in the underlying enamel (and in 23% of the teeth in the dentine also). All those teeth which had even a small cavity, with or without an opaque or discoloured patch, were carious on histological examination, although lesions involved the dentine in only 77% of them. Ekstrand *et al.* (1995) found a high correlation between the surface appearance of occlusal lesions and their progress into the enamel and dentine when they used a very detailed set of criteria for examination under a low-power stereomicroscope. In summary, it seems that staining and cavities in the occlusal surface can suggest a good deal about the progress of caries underneath, even if there are difficulties in interpretation.

In modern clinical practice, diagnosis of fissure caries is still augmented by the use of a sharp explorer or probe (see above). These instruments are run along the line of a fissure/groove and, where they stick or catch slightly, caries may be suspected even if there is no other sign. Penning *et al.* (1992) tested the efficiency of the explorer method against an examination of serial sections through the crown, but only 17% of carious lesions within the fissure systems were detected in this way. Another possibility is to use radiography. The difficulty here is that the deep fissures of the occlusal part of the crown are all superimposed over one another in the image on the x-ray film, so that it is impossible to disentangle details of the enamel. A carious lesion in this area shows only as a radiolucency when the dentine underneath is substantially affected. In a study by Espelid *et al.* (1994) of 84 extracted teeth, a panel of ten dentists failed to diagnose enamel fissure caries in 77% of the specimens, and fissure caries affecting a small area of dentine in 38% of specimens. They also falsely diagnosed caries in 12% of the teeth that had normal fissures, but they did diagnose correctly all those fissure caries lesions which affected a large area of the underlying dentine. Lussi (1996), on the other hand, found that the number of cavitated carious lesions detected in radiographs was about the same as those detected visually, and that diagnosis in radiographs was somewhat better than visual examination for precavitated lesions. A combination of the two methods gave the best results.

What can be suggested from such studies when methods for studying occlusal caries in archaeological material are to be developed? First, there seems little point in using an explorer on potentially delicate archaeological specimens, but the use of a low-power stereomicroscope seems well worthwhile, particularly when fibre-optic lamps can be used to adjust illumination precisely. Radiography of archaeological specimens is easy to accomplish, and high quality x-rays can be produced by the long exposure times that are possible, but they are only likely to be of limited use in studying early occlusal caries because lesions do not register as radiolucencies until they involve the dentine. Where possible, however, they should be used alongside visual examination under a microscope. Recording of precavitated occlusal lesions clearly produces variable results, but many lesions involving the dentine may well be missed if they are not recorded. It therefore seems best to record opacities and discolourations in occlusal fissures, grooves and fossae as a separate category which can be tabulated separately to cavitated lesions.

If specimens can be sectioned, then it is possible to check the diagnosis by examining the underlying dentine. A minimally destructive approach is to avoid grinding a thin section of the tooth, but instead to embed the tooth in methylmethacrylate resin, make a single cut, polish one side of it and then examine it either under a reflected light microscope, or in a scanning electron microscope, using backscattered electron mode. This shows the changes of demineralization and the dentine reaction very clearly, and is also an excellent means of distinguishing diagenetic changes (Boyde & Jones, 1983; Jones & Boyde, 1987). The resin can be removed afterwards by dissolving it in acetone, and the cut halves of the tooth are still available for study, with relatively little material lost in the sectioning process.

Cement–enamel junction and root surface caries

Carious lesions initiated on the surface of the cement which coats the roots create a number of difficulties for archaeologists. Clinical studies of living people record caries as present when an area of the root surface is discoloured or stained, sometimes with a surface that is soft to the explorer, and sometimes with the formation of a cavity (Fejerskov *et al.*, 1993). Such cavities, however, are not like those of the enamel in the crown, where the sides are usually steep and the outline clearly marked. Root surface caries cavities instead tend to be shallow depressions that spread around the cervix in a band, and are difficult to recognize in archaeological material. Most archaeological studies, in fact, show a considerably higher frequency of cement–enamel junction caries than cement caries of the root surface itself (Moore & Corbett, 1971). This may be because they are difficult to diagnose on ancient root surfaces. It is also possible that diagenetic changes in archaeological teeth may mimic the discolourations used to diagnose the condition in the living and, for this reason, discolouration should either be excluded from the criteria used in archaeology (noting only definite cavities) or be recorded as a separate category. In addition, considerable care needs to be taken in distinguishing post-mortem erosion of the root surface from, particularly, the cavities of cement–enamel junction caries (Moore & Corbett, 1971). Whilst in coronal caries it may be relatively easy to confirm the status of the lesion histologically by identifying a patch of reparative secondary dentine lining the pulp chamber, root surface caries typically occurs in older individuals who often (in archaeological material) have much more worn teeth, with a pulp chamber and root canal already filled in by secondary dentine. This means that the tell-tale patch of reparative secondary dentine, which might prove that the demineralization occurred during life, cannot be distinguished.

The role of tooth wear and fracturing in caries

The prevalence of fissure caries tends to be low in populations that have a high rate of occlusal attrition. Amongst some rural Africans today, it has been noted that caries occurs at a lower rate in first molars than in second molars, which is the opposite way round to most studies of town-dwelling people. It is suggested (Manji *et al.*, 1990) that this is a result of the higher fibre content and abrasive quality of the diet, promoting rapid wear which would remove the fissures of the earlier erupting first molar before they became carious (although it could also be a result of a change from childhood to adult diet—A. Sheiham, personal communication). In heavy wear populations, such as recent hunter-gatherers or early agriculturalists, wear in molar teeth could theoretically obliterate fissures, even in the young, and might therefore remove carious tissue, but it would have to be very rapid indeed to outstrip the type of caries development deep in the fissures, which is seen in many populations today. It might also be expected that approximal attrition (between neighbouring teeth in the same jaw) could remove carious tissue in contact area lesions (Kerr *et al.*, 1990). Once again, however, caries often proceeds rapidly to a deep cavity in this region, and approximal attrition is relatively much slower than occlusal. Indeed, one of the main areas for initiation of contact area caries is along the cervical edge of an approximal attrition facet, which must represent a discontinuity in the protective surface layer of enamel. Similarly, it is not uncommon in archaeological material to find a carious lesion in quite heavily worn teeth (Figures 1 and 7), or even involving the dentine in the middle of a large attrition facet.

An alternative view is that, far from having a protective effect against dental caries, the rapid attrition of hunter-gatherers was intimately involved in the development of carious lesions. Amongst the recent !Kung bushmen and aboriginal Australians, caries seems to have been positively related to attrition, and was a disease particularly of the worn molars in older adults (Moody, 1960; van Reenen, 1964, 1966). This is because increasing attrition predisposed to chipping of teeth, ranging from small chips to more major breaks, and creating traps for dental plaque to accumulate, as well as exposing lines of weakness for the extension of a carious lesion, or exposing areas of dentine. In worn teeth, where all the enamel of the occlusal surface had been removed so that the enamel of the sides stood up as a raised rim above the softer dentine in the centre, small chips of enamel flaked away under the powerful forces applied to the teeth (Turner II & Cadien, 1969; Milner & Larsen, 1991). These areas of exposed dentine were particularly susceptible to caries in older adult aboriginal Australians (Campbell, 1925, 1937; Moody, 1960), and this would be

Figure 7. Gross carious lesion, bridging the whole mesial side of an upper first incisor. It involves the heavily worn occlusal surface, the contact area and the cement–enamel junction. Apart from being able to say that the lesion was initiated on the mesial side of the tooth, it is not possible to determine the site of initiation with any certainty, although, in Medieval British material, this type of lesion commonly seems to result from a cavity of the type shown in Figure 5.

expected, because the demineralization of dentine does not require such a low pH as that needed to demineralize enamel (A. Sheiham, personal communication). Another effect of heavy wear was to create approximal spaces in which food could be trapped, and thus encourage plaque accumulation. These factors may also be at work in the natural history of caries amongst those other primates that regularly eat sugars. In the wild great apes, for example, dental caries is most common in the approximal region of the incisors, rather than the molars, but also seems to develop in association with increased attrition. Thus, in the chimpanzee, orang utan and gorilla, it is mostly a disease of the worn incisors of older individuals (Miles & Grigson, 1990; Kilgore, 1995).

Root surface caries is also related to wear, but in a different way. Rapid occlusal attrition may lead to rapid exposure of root surfaces, over and above exposure resulting from periodontal disease. Teeth continually erupt throughout life, as part of a mechanism by which the dentition and jaws adjust and remodel in response to the changing height of the tooth crowns, and alterations in the form of the occlusal plane (Levers & Darling, 1983; Whittaker *et al.*, 1990). In a rapid attrition population, it might be expected that this eruption could expose roots to carious attack at an earlier age than a population with lower attrition rate (Kerr *et al.*, 1990). There may also be other factors at work in cervical caries. Campbell (1925) noted that almost all carious lesions in aboriginal Australian skulls were associated with 'erosions' worn in the cervix on the mesial and distal sides of many of these teeth. Similar features are well known from Middle Pleistocene hominid fossils, as well as later archaeological material, and are often referred to as approximal or interproximal grooves (Frayer, 1991; Milner & Larsen, 1991; Bermudez de Castro *et al.*, 1997). There is ethnographic evidence that they were caused amongst aboriginal Australians by stripping fibres between the teeth (Brown & Molnar, 1990), but a variety of other explanations is possible for archaeological material.

Some cases of pulp exposure (see below) might also be the result of carious lesions developing in combination with advancing attrition—the exposed pulp chamber may be stained and it can sometimes be difficult to be sure that it is a simple open chamber rather than a poorly defined carious cavity. Carious lesions develop slowly over time, with arrested and active phases, and the actual exposure of the pulp might have occurred during a period when there was an active lesion in the occlusal surface. Further attrition could remove evidence of the original site of the lesion. It is also possible (although perhaps less likely) that the dentine above the pulp chamber area might have cracked and fractured away under load, exposing a trap in which plaque might accumulate. There are many possibilities and practically no data for the way in which very worn teeth may be involved in caries and behave mechanically. How can a 'pulp chamber exposed by attrition' be positively diagnosed? It is surely better to record what is actually seen—the stage of attrition, the exposure of an open pulp chamber whose sides and floor can clearly be distinguished, the exposure of an apparently open root canal, the presence of secondary dentine, the presence of discolouration or of any clearly defined carious cavity, fracturing or cracking, or the existence of bone loss around the apex of the root. Anything else is an interpretation rather than an observation, and should be kept separate.

The heavy attrition seen in many archaeological collections, therefore, creates difficulties in defining the best way to record carious lesions, because the usual recording schemes have been defined for the much less worn teeth of modern Europeans and Americans. The marked attrition of archaeological material and recent hunter-gatherer groups exposed rather different sites for the initiation of caries. How should a carious cavity in the middle of the dentine of a large occlusal attrition facet be recorded? It cannot be assumed that the lesion was originally initiated in the fissure system, before it was worn away, because it may just as well have been initiated in the worn surface—for example, along the edge of one of the remaining patches of enamel which mark some of the intermediate phases of wear. There is also the question of interaction between attrition and caries. Attrition exposes vulnerable tissues, and caries itself weakens those tissues and potentially renders them liable to more rapid attrition. At the risk of further complication, it seems best to include separate categories of caries in relation to attrition facets. In addition, it is clearly necessary to make some record of both occlusal and approximal attrition, not only for the purposes of age estimation (see below), but also to relate the surfaces exposed in the attrition facets to the pattern of dental caries. For similar reasons, in heavy wear groups, it is also necessary to record tooth chipping and fracturing as a separate category of potential site for the initiation of carious lesions.

Calculus and caries

Dental calculus is mineralized plaque, which frequently builds up around the cervix of the tooth crown (supragingival calculus), or coats the exposed surfaces of roots as a thinner layer (subgingival calculus) when they are exposed in a periodontal pocket by the development of periodontal disease. As calculus is formed through mineralization, and caries involves a net demineralization, it is not surprising to find an inverse relationship at the population level between the two conditions. A population with a high caries rate is likely to have less frequent calculus deposits, and vice versa (Manji *et al.*, 1989b). The relationship, however, is not a strong one, and does not apply at an individual level. It is quite common to see calculus deposits on a tooth with a well developed carious lesion, and not only can arrested or remineralizing lesions be covered with calculus (Thylstrup *et al.*, 1989), but active lesions may continue underneath a calculus deposit (Jones, 1987). A number of factors may be involved. The chemistry of dental plaque changes greatly between adjacent regions of a plaque deposit and shows, for example, a strong gradient with depth. Caries involves very localized changes in the chemistry of the plaque, and so it is quite possible to imagine active caries proceeding in one region whilst calculus mineralization occurs in an adjacent region. Dental caries also involves cycles of both demineralization and remineralization, so that calculus deposition could well be part of the long term development of a lesion.

It is thus clear that the presence of a calculus deposit on a tooth surface is no guarantee that the surface underneath is caries-free. Such surfaces should be recorded as 'no information' rather than 'non-carious'.

The relationship of caries with hypoplasia and fluorosis

Enamel hypoplasia is a defect of enamel matrix formation that may (very rarely) be inherited, or (much more commonly) results from a disruption to development, such as a childhood fever or a dietary deficiency. Developmental defects of this latter kind form a band around the circumference of the tooth crown, representing the interval during which the growth disruption occurred. The bands of defective enamel can be traced from tooth to tooth across the dentition, so that one disruption marks several teeth, each in a different place relating to differences in the ages at which particular teeth form. It has long been known that these bands form a line of weakness, along which enamel can be preferentially demineralized, and, therefore, they predispose to caries (Mellanby, 1927, 1929, 1930, 1934, 1941). It is essential to take account of them but, as they occur at intervals during the development of the teeth, only some initiation sites for carious lesions on particular teeth will be affected. Similarly, depending upon the timing of growth disruption, different sites on different teeth will be involved. A further difficulty is that the prominence of defects produced by one growth disruption varies between teeth, in relation to the geometry of crown formation. Any relationship between prominence of defect and the vulnerability of the crown surface to initiation of a carious lesion is not at all established, but the effect of hypoplastic defects will only be serious for the statistics of caries prevalence if there are common features in growth disruption for all children in a particular population. It used to be thought (Massler *et al.*, 1941) that the development of the dentition could be divided into a number of phases, characterized by a different 'quality' of enamel which rendered particular parts of the dentition either more or less vulnerable to carious attack. This

Table 1. Parts of different permanent tooth crowns in which the formation times overlap

Upper and lower first incisors	Lower second incisor	Upper second incisor	Canines	Premolars	First molars	Second molars	Third molars
Occlusal	–	–	–	–	Occlusal	–	–
Contact	Occlusal	–	–	–	Contact	–	–
Lower crown side	Contact	–	Occlusal	–	Cervical	–	–
Cervical	Cervical	Occlusal	Contact	Occlusal	–	Occlusal	–
–	–	Cervical	Lower crown side	Contact	–	Contact	–
–	–	–	Cervical	Cervical	–	Cervical	–
–	–	–	–	–	–	–	Occlusal
–	–	–	–	–	–	–	Contact
–	–	–	–	–	–	–	Cervical

Following this table, for example, a hypoplastic enamel defect level with the contact point area of the lower first incisor crown would be expected to match with a defect in the occlusal (incisal edge) part of the lower second incisor, and in the contact point area of the first molar. If this defect decreased the resistance of the enamel to development of carious lesions, it could affect all these teeth in those particular regions of their crowns. Data from Table 6.3 in Hillson (1996).

interpretation has not stood the test of time, but the general idea of relating caries to enamel structure warrants serious consideration. An index of dental enamel defects has been defined for clinical purposes (Commission on Oral Health, 1982), but it is not really suitable for the present purpose, and the simplest way to take account of hypoplastic defects is to create a table of the dental development sequence, in relation to the various sites of initiation for potential carious lesions on different teeth (Table 1). Distributions of caries and hypoplasia can then be tabulated together, so that relationships between them can be recognized. Even so, there are varying types of hypoplasia, some more prominent than others (Hillson & Bond, 1997), and it is not in any way clear that all types predispose to caries in the same way.

Fluorine is found naturally in varying concentrations in the water of different regions, depending upon the local geology. The particular fluorine analysis of a given region, therefore, characterizes not only the drinking water, but also any food plants and animals raised on it, and it is passed on into the human body. Fluorine is absorbed into the bloodstream, from which it is taken up by mineralized tissues as they develop. Within enamel, it typically shows highest concentrations near the surface of the crown, with much lower values underneath (Weatherell *et al.*, 1977). In dentine, it occurs in highest concentrations near to the pulp chamber, and falls off steadily through the thickness of the dentine towards the enamel–dentine junction. Fluorine has a considerable effect on dental caries. Enamel that contains fluorine is protected because it is less soluble and, therefore, resistant to demineralization, and the presence of fluorine in food and drink has a further protective effect in inhibiting plaque microorganisms and enhancing the remineralization of carious lesions. The relationship of fluorine in water to the epidemiology of caries has long been recognized, and the introduction of fluoridation to water supply, together with fluoride toothpaste, are today major factors in the control of dental caries. It is clear that fluorine should be taken into account in any study of caries, archaeological or otherwise, but its effect can be difficult to establish. Large concentrations of fluorine in the water supply can cause enamel defects of a characteristic type, which usually involves a pattern of opacity, called fluorosis (Møller, 1982; Fejerskov *et al.*, 1988). There are rare reports of fluorosis in archaeological material (Lukacs *et al.*, 1985), but it is difficult to distinguish them from potential diagenetic effects, and, in any case, it does not make a very precise marker of fluorine concentrations in water. Similarly, analysis of fluorine in teeth is unlikely to be helpful, partly because the distribution of fluorine in enamel and dentine is complex anyway, and partly because fluorine levels change markedly after burial as a result of interaction with ground water. Instead, it may be best to examine the water catchment of different sites studied, obtain water analyses, and consider possible derivation of drinking water in the past.

The problem of post-mortem missing teeth (and parts of teeth) in archaeology

Teeth, or parts of them, may be have been lost post-mortem from archaeological jaws for a variety of reasons. Each has different implications for the recording of caries:

1. Tooth and socket missing. A whole segment of jaw may have broken away, taking the sockets and teeth with it. In such cases, nothing can be recorded about caries, attrition or the bone of the alveolar process.
2. Tooth missing, socket present. In archaeological material, teeth may fall out of the jaw, leaving an empty socket. This particularly affects the single-rooted incisors, canines and premolars. Study of such specimens involves much fitting of isolated teeth into the correct sockets, but many teeth may simply have been lost. In such cases, although caries and attrition cannot be recorded, any alveolar or periapical bone loss can still be detected.
3. Part of the tooth broken away during burial, excavation or laboratory work. Archaeological teeth have a number of lines of weakness (Hillson, 1996) which cause them to break up, particularly when they dry out after cleaning. The main line of weakness in incisors, canines and lower premolars divides the crown along a buccolingual plane, whereas molars tend to break into quadrants along the lines of the main fissures. In post-mortem fractures, the broken surfaces are usually clean and sharp. Again, these fragments may be present in the bottom of a skull box and can, therefore, be re-fitted, but they may be lost altogether. Where this has happened, it may be possible to record caries in some initiation sites, but not others. Frequently, the root trunk and roots of molars remain in the socket, because another line of weakness runs along the base of the crown.

Reckoning with teeth that never erupted

One or several of the expected 32 permanent or 20 deciduous teeth may never have appeared in the mouth, and, therefore, must be reckoned out in calculating caries statistics. There could be four possible reasons for this:

1. Congenitally absent teeth. A proportion of people in most populations have some teeth which are missing because they never developed. Most commonly, this involves the third molars (up to one third of people may have one or more missing), followed by the upper second incisor, second premolars, lower first incisor and first premolars. In jaws where there has been significant bone loss (below), it may be difficult to decide whether or not teeth were originally there.
2. Impaction of teeth within the jaw. There are many different anomalies of dental eruption, and some teeth (often the third molars again) never emerge from their bony crypts. Radiography is required for detection.
3. Teeth not yet erupted in young individuals. The permanent teeth erupt between 5 years and the early 20s in three phases—first molars and incisors, then canines/premolars/second molars, and finally, third molars. DMF scores rise through childhood and into early adulthood, simply because more teeth gradually arrive in the mouth to become carious. As each new tooth erupts, a succession of sites for the accumulation of plaque appear.
4. Exfoliation of deciduous teeth. As they are replaced by their permanent conterparts, all information about caries in the deciduous teeth is lost. Those people who died in infancy, and, therefore, preserved their deciduous teeth, may not be representative of caries experience amongst the healthier people that survived to an older age.

These difficulties are minimized when caries statistics are kept separately for each tooth type.

Mechanisms of ante-mortem tooth loss

Once erupted, permanent teeth are lost only when they are removed mechanically through injury or surgery, or when so much supporting bone is lost through remodelling of the alveolar process that they can no longer be sustained in position. This remodelling takes place in relation to continuous eruption, the changing occlusal relationships between teeth resulting from attrition, periodontal disease, and periapical bone loss relating to exposure of the pulp to infection.

After the initial establishment of a tooth in occlusion, continued eruption takes place throughout adult life at a slow rate. The 18th/19th century crypt at Christ Church, Spitalfields, in London, contained a much-studied group of people whose age-at-death is known from parish records. There was a steady increase with age in the vertical distance between the inferior mandibular canal (chosen as a reference point inside the body of the mandible) and the root apices, cement–enamel junctions and occlusal surfaces of the molars (Whittaker *et al.*, 1990). At the same time, the distance from the canal to the crest of the alveolar process remained relatively constant with increasing age, so the roots of the teeth appear to have been progressively exposed. The Spitalfields people, like several other groups of post-Medieval Londoners, had very little occlusal wear, and so the net result was that the overall height of the face in older individuals was greater than in younger individuals. Continuous eruption thus occurs whether or not the teeth are worn rapidly (Clarke, 1990) but, in people where the rate of attrition is more rapid, it is thought that the rate of continuous eruption may be increased to compensate (Danenberg *et al.*, 1991). The inferior mandibular canal to occlusal surface measurement in earlier groups of archaeological material remains relatively constant for increasing wear (Levers & Darling, 1983; Whittaker *et al.*, 1985), as does the distance to the crest of the alveolar process. This implies that the wear rate is at least partially balanced by the eruption rate. By contrast, the distance to the root apex and cement–enamel junction increases (by 10 mm from youngest to oldest age groups at the Romano–British site of Poundbury, compared with 2–3 mm at Spitalfields), and the root surface of the teeth is progressively exposed. It is this shortening of the socket as wear progresses down the roots that apparently resulted in the loss of teeth amongst recent aboriginal Australians and Inuit (above). In very worn teeth, where only a fragment of root is left, this may be housed in such a shallow socket (or practically no socket) that the tooth becomes loose and can be pulled out simply in the fingers—'The teeth of the old people are generally worn down by attrition and when loose are generally removed by themselves' (Cran, 1957, p 280) and 'Excessive use results in loosening the teeth only when the roots have become so shortened by attrition at one end and by root absorption from the other that only short stumps not surrounded by bone are left' (Pedersen, 1947, p 731).

In addition to this gradual upward migration of the tooth sockets through the alveolar process, there is also a change in their position relative to one another, and to the outer compact bone plates of the alveolar process. This results partly from 'mesial drift' of the teeth in response to approximal wear (Begg, 1954; Kaul & Corruccini, 1992), but the supporting bone is known to respond by remodelling to a whole range of changing forces acting on the dentition (MacPhee & Cowley, 1975). In some cases, the alveolar bone lining the socket comes very close to the labial/buccal compact bone plate at the surface of the process. Remodelling may remove part of the bony covering of the root, so that it is covered only by the gingivae and, in dry skulls, this is seen as a notch known as a dehiscence, or window-like opening, known as a fenestration (Muller & Perizonius, 1980; Clarke & Hirsch, 1991). Even if an opening was not present during life, the surface bone may have been so thin that it fractures away easily in archaeological specimens and exposes the root (Brothwell, 1981). It is important to be able to recognize this post-mortem effect by the sharp edge exposing different coloured bone at the edge of a pseudo-fenestration.

It may be difficult to disentangle the root exposure of continuous eruption (and other remodelling of the alveolar process) from active bone resorption, which relates to inflammatory conditions. The most common condition of this kind is periodontal disease. This involves an irregular inflammatory response to the presence of micro-organisms and antigens in the plaque, in the supporting tissues of the teeth, throughout life. It progressively disrupts the periodontal ligament, which binds the root into the socket, and this results in loss of the alveolar bone lining the socket, starting at the crest of the alveolar process. This is seen first of all as a porosity and then as a deep, narrow trench around the root as the thin alveolar bone lining of the socket is resorbed (Kerr, 1991), followed by a more generalized remodelling of the alveolar process which reduces its height as a whole. The distinguishing feature of bone loss relating to periodontal disease (in contrast with general remodelling of the jaw, continuous eruption and periapical inflammation) is the trench-like nature of the defect in the alveolar process in its early stages, around the roots of each tooth. The amount of general bone loss gradually increases with age so that the roots of the teeth are progressively exposed. Patterns of bone loss are variable, but it generally involves a whole segment of the dentition together and, in recent populations, is more marked around the molars and premolars than anterior teeth (Watson, 1986). Eventually, so much support is removed that teeth are lost. Today, periodontal disease is an important cause of tooth loss in older adults. It also seems to have been common in, for example, 19th century Londoners (Molleson & Cox, 1993), but evidence for it is rare in Medieval and earlier human remains (Alexandersen, 1967b), and it appears to have been uncommon amongst the recent Greenland Inuit, aboriginal Australians and !Kung Bushmen. It is related to the presence of long-standing plaque deposits, so some of the conditions that predispose to caries must also predispose to periodontal disease, but the connection with diet is not clear.

The micro-organisms of the mouth may gain access to the pulp through a rapidly developing carious lesion, a narrow crack which opens up in the tooth crown (and may leave little surface evidence), a more extensive fracture or, perhaps, rapid occlusal attrition. Whatever the mechanism of pulp exposure, a broad spectrum of micro-organisms initiates an inflammatory reaction in the pulp. In some cases, this produces few symptoms, whereas in others there is pain, sensitivity to cold and pressure. The pulp may contain the infection and recover, but is more likely to die and the bacteria, their products, or the products of the inflammatory process pass down the root canal, to emerge through the apical foramen. This initiates an inflammatory response in the bone around the apex of the roots (periapical inflammation). Even at this stage, the infection may be contained, but it often settles down to a chronic (slowly developing) inflammation, typically a periapical granuloma (Soames & Southam, 1993; Dias & Tayles, 1997). This is seen initially as a small radiolucency (typically less than 15 mm across—Whaites, 1992; Goaz & White, 1994) in a dental x-ray, as bone is resorbed to accommodate a growing mass of granulation tissue. The radiolucency represents a cavity within the bone, extending a few millimetres radius around the apex of the root, and with a smooth, compact bone wall. In some tooth roots, there are lateral canals which branch off to the side from the main root canal (Carlsen, 1987), and these may in a few cases give rise to a granuloma at the side of the root instead (Clarke, 1990; Dias & Tayles, 1997). Most periapical granulomata cause little pain or other symptoms. In dry bone specimens, as in the jaws of living people, many require radiography for detection, but general remodelling of the alveolar process (see above) may reduce the distance between the periapical region and the surface of the bone to the extent that the side of the cavity is exposed at the surface in a fenestration (above). The edges of the opening are formed by delicate wafers of thinned bone from the buccal plate of the alveolar process, and are often damaged in archaeological specimens. In a small number of cases (possibly one quarter to one third), the granuloma may develop into a periodontal cyst, through the replacement of the granulation tissue by fluid, and an increase in size of the cavity. It still has a smooth bony lining and, as it starts to bulge out the periosteum which covers the surface of the bone, a thin shell of bone may grow out beyond the alveolar process (usually only a few remnants of this shell survive in archaeological material). Periodontal cysts look very impressive, but are relatively uncommon in archaeological jaws and are likely to have been practically symptomless in life.

Another type of periapical inflammation involves the accumulation of pus. This is a periapical abscess, and produces much more noticeable symptoms than the granuloma. An acute (rapidly developing) periapical abscess is marked by the rapid build up of pus around the root apex, with little bone resorption, to invade the spaces within the bone and emerge into the overlying soft tissues and form a swelling which bursts. It is very painful and usually associated with a fever. By contrast, a chronic (slowly developing) periapical abscess is not usually painful and, in most cases, does not make the patient feel ill, but does produce an unpleasant discharge from a channel or sinus into the mouth or nose. It may produce its own rough walled small cavity at the blind end of the sinus within the alveolar process at the tooth apex, but a larger cavity with rough walls is more likely to represent an abscess which has developed in a pre-existing granuloma. Dias and Tayles (1997) have pointed out that chronic abscesses with a proper sinus are considerably rarer than most anthropologists suppose, and that most small bony cavities in archaeological jaws are probably periapical granulomas, exposed by thinning of the overlying buccal plate of the alveolar process.

For the purposes of this paper, the distinction between granulomas, abscesses and cysts may not matter much, but the loss of bone involved does, because of its possible relationship with ante-mortem tooth loss. Chronic periapical inflammation on its own is unlikely to cause sufficient bone loss in archaeological jaws to destabilize a tooth. Exposed cavities in the alveolar process are common in many collections, but they are usually small and limited to the area of the apex (or occasionally at the side of the root in relation to a lateral canal; above). Similarly, the chronic forms of inflammation which produce such bony changes are not usually painful, and are less likely to have resulted in tooth extractions. It is acute inflammation, not typically marked by bone loss, that is painful, and has, for centuries, been treated by extraction (thereby causing tooth loss). Periapical bone loss is therefore unlikely in most cases to have been a direct factor in ante-mortem tooth loss. It may, however, have been a contributing factor in jaws with extensive bone loss resulting from periodontal disease, or remodelling in relation to continuous eruption of teeth. Clarke (1990) maintained that many cases of localized bone loss adjacent to the side root are a result of inflammation of pulpal origin which occured in relation to a lateral canal, rather than periodontal disease.

The cause of the initial pulp exposure may not always be easy to determine. Often, there is a large carious cavity in a tooth which has periapical bone loss. Sometimes, however, there may be a gross carious lesion which has removed most of the crown, but no surface sign of periapical inflammation (although there may, of course, be an undetected granuloma inside). It has long been noted that periapical inflammation can be found in association with the exposure of the pulp chamber in a large occlusal attrition facet, without clear signs of a carious lesion, so that it has seemed reasonable to suppose that the pulp was exposed by rapid attrition (Campbell, 1925; Leigh, 1925b,a, 1928; Brothwell, 1963; Alexandersen, 1967b; Costa, 1980b,a; Clarke & Hirsch, 1991; Lukacs, 1995). The evidence that this actually happens, however, is not very clear. Secondary dentine is deposited in the pulp chamber as a reaction to disruption of the overlying enamel covering, and it seems unlikely that attrition could proceed so fast that the rate of secondary dentine deposition was outstripped (see plates in Campbell, 1925). In the Greenland Inuit, there was little evidence of pulp exposure by wear, even though attrition was the most severe seen in any group of people, archaeological or recent (Pedersen, 1938; Hilming & Pedersen, 1940; Pedersen, 1947; Davies & Pedersen, 1955). On the other hand, Elvery *et al.* (1998) noted, in a radiographic study of jaws from a low caries/ heavy wear aboriginal Australian group, that teeth with associated periapical bone loss were more often heavily worn than teeth without such bone loss. They also found, however, that the same teeth frequently had pulp chambers which were almost completely filled by secondary dentine deposition and, in such cases, it could hardly be said that the pulp was being exposed by attrition. Other factors must have been at work.

On occasion, periapical bone loss may be unaccompanied by any sign of a carious lesion or exposure of the pulp chamber in the occlusal attrition facet. In such cases, it is reasonable to assume that there is a crack in the crown. The heavy loads applied to teeth of hunter-gatherers might create fine cracks, through which micro-organisms could still infect the pulp (Pedersen, 1938; Alexandersen, 1967b), as well as large fractures right through the tooth, especially when the softer dentine was exposed at the centre of the occlusal surface. 'Extensive fractures exposing the pulp are rather frequent' (Pedersen, 1947, p 729) in recent East Greenland Inuit. In some very worn teeth, the roofless pulp chamber or open root canal is exposed in the attrition facet, but this does not in itself prove that the pulp was originally exposed by rapid attrition. Populations in which teeth wear rapidly often also commonly chip and fracture their teeth, and it is rather more likely that such fractures are responsible for the pulp exposure (see above), as well as contributing to the rapid loss of the crown during wear of that tooth. Similarly, there is no reason why the initial exposure should not have occurred during the development of an earlier carious lesion which was arrested and then worn away. In some archaeological groups, it is not uncommon to find an exposed pulp chamber, associated with dark staining, in the centre of a very worn tooth.

One possibility that should not be forgotten is ante-mortem tooth loss resulting from trauma to the jaw itself. Most jaw fractures track along the tooth sockets and, thus, communicate with the oral cavity so they are, in effect, compound (Alexandersen, 1967a; Banks, 1991). The infection and inflammatory reaction involve the bone around the roots, and the processes of fracture consolidation and remodelling also affect the alveolar process. All this may remove support for the tooth, so that it is eventually evulsed, even if it was not lost at the time of the fracture. It should, however, be possible to recognize the site of such a fracture, unless it has been extensively remodelled.

Even in living people, information about the distribution of caries may also not be recordable for some parts of a tooth which is actually still present in the jaw. So far as the compilation of caries statistics are concerned, these parts of the tooth are effectively missing ante-mortem:

- Wear. Occlusal and approximal attrition may remove large parts of the tooth, and it is not possible to make any assumptions about their history in relation to caries.
- Dental fracture. Ante-mortem breaks in the tooth may be recognizable by their worn and rounded appearance, and, again, may remove caries initiation sites.
- Calculus. Some parts of the tooth may be covered with calculus deposits, and no assumptions can be made about caries in the underlying enamel.
- Caries. A gross carious lesion itself removes evidence of where it was initiated.

It is, therefore, clear that ante-mortem missing teeth and missing surfaces need to be considered very carefully in archaeological studies of caries. In view of their place in a whole network of factors involved in the pattern of caries, it is probably just as dangerous to ignore them as it is to put them into caries scores and indices.

Conclusion: desiderata for a caries recording scheme in archaeology

With all this in mind, what is needed for recording archaeological caries?

1. There seems little advantage in trying to arrive at a recording scheme which attempts to be compatible with the mean DMF commonly used to summarize caries experience in epidemiological studies of the living. There is currently debate about the validity of DMF scores in any case (see above), and the only studies with which archaeological collections are directly comparable use variants that quantify caries for individual tooth classes, and give separate figures for

different categories of caries, for filled and for missing teeth. These are closer to the figures which can be produced from fragmentary archaeological material, in which there is no possibility of estimating a reliable mean DMF-T or DMF-S.

2. In view of the particular difficulties of post-mortem archaeological tooth loss, it would be best to carry out an analysis of missing teeth separately from the tabulation of data on caries. Figures for missing teeth in modern populations normally relate to extractions by dentists, so it is not clear that ante-mortem archaeological tooth loss would follow similar patterns. In any case, the roles of such factors as tooth wear and fracture and periodontal disease may well have been very different. Careful records need to be made of the pattern of attrition, pulp exposure, discolourations and carious cavities on attrition facets, and loss of alveolar and periapical bone. Caries also needs to be reckoned in relation to the preservation of sites on the teeth that would be capable of registering the different types of lesions. In other words, the scheme needs to take account of the fact that parts of teeth may be missing in archaeological material, as well as whole teeth.
3. The scheme needs to take into account the much higher rate of occlusal and approximal attrition in archaeological material relative to modern populations. This gives rise to different potential sites of caries initiation, and a different pattern of lesion development. It is also important to take into account such factors as crown chipping and fractures, together with abrasions on the crown sides and at the cervix.
4. Different tooth classes must be recorded separately, because of their different patterns of caries and differential survival in archaeological material. This is particularly true of anterior teeth versus cheek teeth. Upper teeth should, similarly, be recorded separately to lower teeth. There is no substitute for separate statistics on different teeth.
5. Different age groups need to be recorded separately, because of the clear development with age of caries in living populations which would lead to artificial contrasts between archaeological sites where there was differential preservation of juvenile and young adult remains versus older adults. There is, however, a difficulty with archaeological material, because the best age estimation methods for adults are based upon occlusal attrition of the teeth. Attrition is strongly related to the pattern of dental caries in adults so, without care, it is possible to enter a circular argument in which dental caries shows apparent trends with age which are actually trends with attrition. Alternative age estimation methods based upon the pubic symphysis, auricular surface and sternal articulation of the rib should be used instead (or as well) where possible. If these alternatives are not available, it is better to abandon any attempt to define 'age groups' and, instead, to make explicit definitions of groups in terms of dental development and occlusal attrition scores. In this way, it is immediately clear what is being compared with what.
6. The dentitions of men and women should be recorded separately, because there are at least some differences between the sexes in the pattern of caries development with age. Most archaeological studies in which the sexes have been separated show that women are more frequently affected by caries than men. Thus, the differential survival of the sexes on many archaeological sites will potentially create differences in caries statistics between sites if they are not kept separate.
7. It is necessary to consider the effects of hypoplasia, because the dental enamel defects seen at some archaeological sites are very strongly marked and would almost certainly have had an effect on the progress of carious lesions. The difficulty lies in defining a method which takes into account the irregular distribution of hypoplastic defects over the different potential caries initiation sites of different teeth.

It is not possible to arrive at a single index of caries prevalence that expresses the true complexities of the condition, or is not affected by differential preservation of different tooth classes, parts of teeth, age groups and sexes. Instead, it is best to make separate tabulations for the different categories of carious lesions, at the different sites where they may be initiated on different teeth (it is possible to present these quite compactly as graphs—Luan *et al.*, 1989a; Fejerskov *et al.*, 1993).

If counts of the various categories of lesions need to the expressed in relation to the survival of those parts of the tooth capable of showing the different initiation sites, then the site totals, out of which percentages or proportions are calculated, are likely to be different for each category. Each total will relate not only to be survival of whole teeth, but to the loss of parts of them as a result of fracture, wear and the development of carious lesions themselves. A large lesion removes all signs of its original initiation site just as effectively as heavy occlusal wear or fracture. It is, therefore, necessary to record such large lesions in a way that makes no assumptions about their original initiation site. This leads to various categories of gross caries, which recognize the range of possible initiation sites that might have been involved. On the crown, it is possible that a carious lesion might have been initiated in the enamel of the occlusal fissures, grooves or fossae, in a buccal or lingual pit, or at either the mesial or the lingual contact point. If the lesion has progressed far enough, it may not be possible to tell whether it was initiated in the occlusal surface at all, or at the contact point, and, in some cases, it may only be possible to say that it was initiated on the crown. For coronal caries, therefore, it is necessary to present the frequency of caries as a number of different percentages:

- Occlusal fissure/groove/fossa caries as a percentage of the total number of fissure/groove/fossa complexes with any part surviving—it is only practicable to count just one complex per tooth because there are often several lesions hidden deep in fissures.
- Pit caries as a percentage of the total number of buccal pits (in the case of molars) and lingual pits (in the case of incisors and canines) surviving.
- Contact area caries lesions as percentages of the total numbers of mesial and distal contact points surviving—two per tooth.
- Gross contact area/occlusal caries as a percentage of the number of mesial and distal crown elements surviving—similarly, an intact tooth would have two of these.
- Gross coronal caries as a percentage of the number of tooth crowns with any part surviving.

At the cervix, it is often possible to see that a root surface carious lesion was initiated either at the cement–enamel junction, or on the root surface nearby, but in archaeological material, it is usually not possible to distinguish between the two initiation sites. It is, therefore, more practical to combine the two as 'root surface caries', as in clinical studies (Fejerskov *et al.*, 1993). In some groups of archaeological material, it is common for mesial or distal lesions to overlap the root surface, cement–enamel junction, and the contact area or cervical crown side. Further, where there is pronounced occlusal wear, there may be one single gross mesial or distal carious lesion running from the root surface up the crown to the edge of the attrition facet. In such cases, it is not possible to determine the original site of initiation. It is, therefore, necessary to represent root surface lesions as a number of separate percentages:

- Root surface caries as a proportion of the mesial, distal, buccal and lingual sites, for which the cement–enamel junction or root surface is present or visible.
- Gross cervical caries (where the lesion is so advanced that it is not possible to tell whether it was initiated in the cervical enamel, along the cement–enamel junction, or in the cement) as a percentage of the number of teeth with any part of the root surviving on mesial, distal, buccal and lingual sides.
- Gross contact area or cervical caries (where a carious cavity bridges the cement–enamel junction and the edge of the approximal attrition facet) as a percentage of the number of mesial and distal cervix

elements surviving—an intact tooth would, therefore, have two of these.

- Gross mesial or distal caries (where a carious cavity bridges the entire crown side from the cement–enamel junction to the edge of the occlusal surface, or occlusal and approximal attrition produced a similar outcome in combination with the cavity) as a percentage of the number of mesial and distal cervix elements surviving (Figure 7).

In addition, it is necessary to have two further categories, to cope with all the possibilities:

- Occlusal attrition facet dentine caries as a percentage of the total number of teeth with attrition facets that expose dentine (at the early stages, there may be fissures and grooves remaining at the centre of the facet and these may still be scored separately).
- Occlusal attrition facet enamel edge chipping and caries, in populations where this occurs.
- Gross gross caries (where there is no indication where the lesion was initiated) also as a percentage of the number of teeth with any part surviving.

A scheme for recording caries, together with all the essential related information about attrition, remodelling of the alveolar process, hypoplasia, ante-mortem and post-mortem tooth loss, is proposed in Appendix A. It incorporates the principles outlined above, and is being tested on a variety of projects.

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Appendix A: Caries recording scheme

Dental features related to caries

Caries and attrition are most easily recorded per tooth on recording forms (Appendix B). If the records are to be entered into a computer database, then it makes sense to use the Fédération Dentaire Internationale (FDI) system of tooth numbering (Fédération Dentaire Internationale, 1971), as given on the forms shown in Appendix B. Each row of the form is numbered and these row numbers are referred to below in the titles of each section. The different categories of observation are noted as number codes, which can be entered into the forms.

General

Row 1. Presence/absence of tooth, and score for gross gross caries

Some aspects are recorded for the whole tooth, rather than particular sites on it. The numbering of this category has deliberate gaps in it, to match the numberings of other categories.

BLANK = missing post-mortem and jaw with socket missing too.
0 = tooth present, without gross gross caries.
7 = gross gross carious cavity, involving the loss of so much of the tooth that it is not possible to determine whether the lesion was initiated in the crown or root.
8 = gross gross carious cavity, involving the loss of so much of the tooth that it is not possible to determine whether the lesion was initiated in the crown or root, and there is a clear opening into an exposed pulp chamber or root canal.
10 = tooth missing, leaving an empty socket in the jaw without any sign of remodelling.
11 = tooth missing, leaving an empty cavity in which there are signs of remodelling, but the bone is not fully remodelled to a level contour.
12 = tooth missing, with full remodelling of the jaw to leave a level contour.

13 = no evidence that the tooth has ever erupted (as a result of young age, impaction or agenesis).
14 = tooth partly erupted (crypt communicating with crest of alveolar process, or tooth not yet in wear).
15 = anomalous eruption, so that the tooth has not reached its normal position in the tooth row.

Occlusal crown lesion sites

Row 2. Occlusal surface caries in premolars and molars

Fissure system, groove and fossa sites. Count the whole occlusal fissure system of premolars and molars as one site, when any part of it remains and can be seen unobscured. Score the deepest lesion, if there is more than one.

BLANK = sites missing for any reason, or fully obscured.
0 = sites present but enamel is translucent and with a smooth surface.
1 = white or stained opaque area in enamel of fissure/groove/fossa, with smooth glossy or matte surface.
2 = white or stained opaque area, with associated roughening or slight surface destruction.
3 = small cavity, where there is no clear evidence that it penetrates to the dentine.
5 = larger cavity, which clearly penetrates the dentine.
6 = large cavity which was clearly initiated in a fissure/groove/fossa site within the occlusal surface (it does not involve the contact areas), within the floor of which is the open pulp chamber, or open root canals.
7 = gross coronal caries, involving the occlusal crown surface and contact area or pit.
8 = gross coronal caries, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Row 3. Pit sites in molars and upper incisors

Count each discrete pit present. Not all dentitions have them, but there is often one buccal pit on molars and, sometimes, a lingual pit tucked in above the lingual tubercle of upper incisors (rarely canines). It would be uncommon for there to be more than one pit site per tooth, but it may happen.

BLANK = pit site not present or not visible (for any reason).
0 = site or sites present, but enamel is translucent and with a smooth surface.
1 = white or stained opaque area in enamel of pit, with smooth glossy or matte surface.
2 = white or stained opaque area, with associated roughening or slight surface destruction.
3 = small cavity, where there is no clear evidence that it penetrates to the dentine.
5 = larger cavity, which clearly penetrates the dentine.
6 = large cavity, which was clearly initiated in a pit site, within the floor of which is the open pulp chamber, or open root canals
7 = gross coronal caries, involving a pit and the occlusal crown surface (Row 2 above).
8 = gross coronal caries, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Row 4. Occlusal attrition score

The Smith (1984) system is simplest to use.

BLANK = occlusal surface not present, or obscured, for any reason.
1–8 = Smith attrition stage.
10 = tooth fractured, leaving a surface which shows some wear.

Row 5. Occlusal attrition facet dentine caries and pulp exposure

Count whole facet as one site, and record the most severe lesion if there is more than one.

BLANK = worn dentine surface, either not yet exposed, missing or obscured (for whatever reason).
0 = dentine exposed in occlusal attrition facet, but without any stained areas, or cavitation.
4 = stained area of dentine and/or enamel, which may or may not be a carious lesion.
5 = clear cavity in dentine.
6 = pulp chamber, exposed in the attrition facet, which is stained or appears to have

been modified by the development of a cavity.
8 = exposed pulp chamber in which there is no sign of either staining or irregular formation of a cavity.

Row 6. Occlusal attrition facet enamel edge chipping and caries

This category may only be important in some collections—particularly hunter-gatherer groups. Count the enamel rim of the attrition facet as one site.

BLANK = worn enamel rim not yet exposed at any point on the perimeter of the occlusal surace, missing or obscured (for whatever reason).
0 = enamel rim of occlusal attrition facet exposed at any point, but intact with no chipping.
1 = chipping which appears to be post-mortem in origin.
2 = chipping which appears to be ante-mortem, but is not affected by caries.
3 = chipping associated with carious lesion.
7 = gross carious lesion (scores 7 or 8 in Rows 2, 3, 8, 12, 15, 18), involving the enamel rim of the occlusal facet, but not clearly associated with any chipping.
8 = gross carious lesion, as defined in score 7 above, involving the enamel rim, within the floor of which is the open pulp chamber, or open root canals.

Mesial or distal side lesion sites

Rows 7 and 11. Mesial and distal approximal attrition score

BLANK = contact point missing (for whatever reason).
0 = no attrition facet around contact point.
1 = approximal attrition facet confined to the enamel.
2 = approximal attrition facet exposing dentine at its centre.
3 = approximal attrition facet exposes dentine all the way down to the cement–enamel junction.
4 = occlusal attrition has proceeded down into the roots of the teeth, so that there is no longer any contact between neighbouring teeth.

Rows 8 and 12. Mesial and distal contact area caries

BLANK = contact area missing, or not visible, for any reason.
0 = contact area present, but enamel is translucent and with a smooth surface (and any exposed dentine is unstained and not cavitated).
1 = white or stained opaque area in enamel, with smooth glossy or matte surface (or stained patch in dentine).
2 = white or stained opaque area of enamel, with associated roughening or slight surface destruction.
3 = small enamel cavity, where there is no clear evidence that it penetrates to the dentine.
4 = discolouration in exposed dentine of an approximal attrition facet.
5 = larger enamel cavity which clearly penetrates the dentine (or clear cavity in dentine of approximal attrition facet).
6 = large cavity, clearly initiated in the contact area or approximal attrition facet, within the floor of which is the open pulp chamber, or open root canals.
7 = gross cavity in the contact area or approximal attrition facet, which involves neighbouring occlusal sites (Rows 2 or 6) and/or root surface sites (Rows 9 or 13).
8 = gross cavity, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Rows 9 and 13. Mesial and distal root surface caries

Count one site per mesial or distal surface. The site may run into a buccal/labial or lingual site.

BLANK = no part of mesial/distal root surface or cement–enamel junction preserved, or at least not visible if present.
0 = root surface/cement–enamel junction present and visible, with no evidence of staining or cavitation.
1 = area of darker staining along cement–enamel junction, or on root surface.

5 = shallow cavity (stained or unstained), following the line of the cement–enamel junction, or confined to the surface of the root.
6 = cavity involving the cement–enamel junction, or root surface alone, within the floor of which is the open pulp chamber, or open root canals.
7 = gross cavity, including the cement–enamel junction or root surface, which involves the neighbouring contact area site (Row 9 or 13), occlusal sites (Row 2) or occlusal attrition facet sites (Row 6).
8 = gross cavity, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Rows 10 and 14. Mesial and distal root exposure
Maximum vertical measurement (to the nearest millimetre) from cement–enamel junction to alveolar bone lining socket, using a graduated periodontal probe. Do not take the measurement if there is evidence that the alveolar process has been damaged post-mortem.

Buccal/labial or lingual side lesion sites

Rows 15 and 18. Buccal/labial and lingual enamel smooth surface site
One site, just above the margin of the gingivae in life. Count as present only when it is clearly separate from the cement–enamel junction. Only score if the lesion clearly does not involve the cement–enamel junction, the fissure system, a pit or any worn occlusal attrition facet. Rare in archaeological material, and may not be worth recording.

BLANK = site not present or not visible (for any reason).
0 = site present, but enamel is translucent and with a smooth surface.
1 = white or stained opaque area in enamel, with smooth glossy or matte surface.
2 = white or stained opaque area, with associated roughening or slight destruction of the enamel surface.
3 = small enamel cavity, where there is no clear evidence that it penetrates to the dentine.
5 = larger cavity, which clearly penetrates the dentine.
6 = large cavity, which has exposed the open pulp chamber, still without involving the cement–enamel junction.
7 = gross cavity, which involves neighbouring occlusal sites (Rows 2 or 6) and/or root surface sites (Rows 16 or 19).
8 = gross cavity, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Rows 16 and 19. Buccal/labial and lingual root surface caries
Count one site per buccal/labial or lingual surface. The site may run into a mesial or distal site.

BLANK = no part of the buccal/labial/lingual root surface or cement–enamel junction preserved, or at least not visible if present.
0 = root surface/cement–enamel junction present and visible, with no evidence of staining or cavitation.
1 = area of darker staining along cement–enamel junction or on root surface.
5 = shallow cavity (stained or unstained), following the line of the cement–enamel junction, or confined to the surface of the root.
6 = cavity involving the cement–enamel junction, or root surface alone, within the floor of which is the open pulp chamber, or open root canals.
7 = gross cavity, including the cement–enamel junction, or root surface, which involves the neighbouring crown side (Rows 15 or 18), occlusal or pit sites (Rows 2 or 3) or occlusal attrition facet sites (Row 6).
8 = gross cavity, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Rows 17 and 20. Buccal/labial and lingual root exposure
Maximum vertical measurement (to the nearest millimetre) from cement–enamel junction to alveolar bone lining socket, using a graduated periodontal probe. Do not take the measurement if there is evidence that the alveolar process has been damaged post-mortem.

Defects of dental enamel

Row 21. Defects in the occlusal region, above the contact area
Score defects in the region of the cusp sides, occlusal fissures, fossae or pits, or mamelons on the incisal edge of anterior teeth.

BLANK = appropriate surface missing from the present tooth or corresponding surfaces from other teeth in the dentition (refer to table in Appendix B).
0 = appropriate surfaces present, but enamel surface smooth, or with only minor undulations.
1 = furrow-like defect follows around the circumference of the crown.
2 = band of pitted defects follows around the circumference of the crown.
3 = plane-form defect, in which layers of enamel matrix are missing from the tips of the cusps, and a prominent step runs around the edge.

Row 22. Defects involving the contact area
Score defects on the crown side that may predispose to caries in the contact area.

BLANK = appropriate surface missing from the present tooth or corresponding surfaces from other teeth in the dentition (refer to table in Appendix B).
0 = appropriate surfaces present, but enamel surface smooth, or with only minor undulations.
1 = furrow-like defect follows around the circumference of the crown.
2 = band of pitted defects follows around the circumference of the crown.
3 = plane-form defect, in which there is a prominent step running around the crown.

Row 23. Defects below the contact area or involving the cervical crown
Score defects on the crown side that may predispose to caries in the cervical region.

BLANK = appropriate surface missing from the present tooth or corresponding surfaces from other teeth in the dentition (refer to table in Appendix B).
0 = appropriate surfaces present, but enamel surface smooth, or with only minor undulations.
1 = furrow-like defect follows around the circumference of the crown.
2 = band of pitted defects follows around the circumference of the crown.
3 = plane-form defect, in which there is a prominent step running around the crown.

Bone remodelling in the alveolar process which may provide evidence for the progress of caries or the causes of ante-mortem tooth loss

Changes to the alveolar process are not so easily codified into a series of scores, and are mostly recorded by descriptions for areas of the jaw, rather than necessarily per tooth. The recording sheets included here (Appendix B) consist of a diagram of the alveolar process and teeth which can be annotated, together with boxes for scoring bone loss using the Karn *et al.* (1984) and Kerr (1991) systems (see below). Dehiscences, fenestrations and cavities within the alveolar process can be drawn on the diagrams, and the positions of dental radiographs marked. They are drawn roughly twice life-size, but the variation in size, shape and internal organization means that they can only work as an approximate guide.

General thinning of buccal and lingual plates

The process of remodelling for continuous eruption and occlusal adaptation leads to thinning of the buccal and lingual cortical plates of the alveolar process. The changes are usually more pronounced in the buccal plate than the lingual plate. There are no published standards for describing them, but a range of terms is commonly used.

Thinning of the buccal plate
The buccal plate remodels around the tooth sockets to create depressions between them, so that the bone above the roots appears to bulge outwards. In advanced cases, the whole outline of the roots can be clearly made out through

the thin 'skin' of bone. The sockets of some roots are, in any case, normally prominent, such as in the upper canines and incisors, but their level of prominence becomes much greater. At the same time, the bone around the cervix of the tooth shows wafer thin against the root, rather than making a stout edge.

Dehiscence
A dehiscence is a 'V' shaped opening in the alveolar process, extending down a root from the alveolar margin at the cervix of the tooth (Muller & Perizonius, 1980; Clarke & Hirsch, 1991). The edges of a dehiscence are usually wafer thin. Care must be taken to distinguish the dehiscence from post-mortem damage (look for a sharp edge with a different colour to the surrounding bone surface), and from irregular defects of periodontal disease (look for involvement of the alveolar bone in other parts of the tooth socket).

Fenestration
A fenestration is similar to a dehiscence, but is a circumscribed opening, further down the root (Muller & Perizonius, 1980; Clarke & Hirsch, 1991). It may expose a granuloma and, in such cases, it is important to distinguish it from the sinus of an abscess (see below).

Hypercementosis
Hypercementosis, and irregular over-production of cement on the root surface, is common in the jaws of people with heavily worn teeth. The irregular swelling of the roots is accommodated by resorption, and they may be exposed in a fenestration or dehiscence. Hypercementosis can be detected in x-rays as a swollen and irregular root outline.

Defects of the approximal wall between sockets

Periodontal disease is an important alternative cause of tooth loss. It is most easily monitored by examining the wall of bone which separates neighbouring sockets in the same jaw (the 'approximal wall'), consisting of the thin layer of compact alveolar bone lining each socket, with a thin zone of trabecular bone sandwiched between. As alveolar bone is lost through periodontal disease, the crest of the approximal wall first becomes porotic, and then irregularly removed, to create a gap between the teeth. Use number scores from Kerr (1991) to record the profile of the top of the approximal wall, porosity and destruction (see also Hillson, 1996).

Deformities of the alveolar process

Bone remodelling associated with periodontal disease causes gross changes to the alveolar process. The characteristic change is a selective removal of the thin alveolar bone lining to the socket, either just along one side of the root or around several sides to make a trench-like deformity. The buccal and lingual plates of the alveolar process may be involved as well, to produce a more general deformity. Use letter scores (C, T, R, P, CR and RC) from Karn *et al*. (1984) to describe changes from normal morphology in both jaws (see also Hillson, 1996).

Periapical/periradicular bone loss

Both direct observation and x-rays should be used to look for periapical bone loss, or similar loss at the sides of a root in relation to a lateral canal. The record should distinguish between different ways in which the area of bone loss has been exposed to view, or otherwise detected. Strictly from the point of view of a caries study, differential diagnosis of granuloma, cyst or abscess is not a large issue because, when associated with a carious lesion, all three imply that the pulp has been exposed. Similarly, their role in ante-mortem tooth loss is unclear, although a granuloma or cyst may cause enough bone loss to contribute to the loss of tooth stability, in combination with continuous eruption and periodontal disease.

Visible cavity within the alveolar process

Bone loss resulting from a granuloma or cyst is seen as a cavity in the bone around the apical foramen at the apex of the root, or occasionally around a lateral foramen at the site of a root.

Record different roots in multi-rooted teeth separately.

Visibility of cavity

- Visible through an ante-mortem opening in the thinned buccal or lingual wall of the alveolar process (i.e. a fenestration or dehiscence, rather than a sinus).
- Seen through a sinus (definition below).
- Seen on extracting a loose tooth from its socket.
- Seen through a post-mortem break in the bone (look for a line of different coloured bone along the break)—a post-mortem break may enlarge a pre-existing fenestration.

Location

- At the apex of one or more roots.
- In relation to a lateral canal part way up the root.
- In the cervical part of the root, or the root trunk of a multi-rooted tooth (Clarke & Hirsch, 1991).
- To buccal, lingual, mesial or distal of the root, or centrally under the apex.

Size

Measure radius with a graduated probe, and make allowance for the root protruding into the cavity.

- Less than 3 mm radius (from the side of the root to the wall of the cavity).
- More than 3 mm radius.

It is also possible to estimate the overall maximum diameter, including the root (see radiolucencies below).

- More than 15 mm diameter.
- More than 25 mm diameter.

Wall of cavity

- Smooth and well-demarcated.
- Slightly roughened.
- Clearly roughened, with a ragged appearance.

Sinus

Defined as a well-demarcated tube or canal, whose blind end is at the side or apex of the root, and whose open end emerges at the surface of the alveolar process, maxillary sinus, or nose. To be sure, it should have substantial walls and a well-defined opening, distinct from a fenestration fringed by delicate wafer-like bone (see above). Most apertures around the apex in archaeological specimens are probably a fenestration, rather than a sinus, and care also needs to be taken to recognize an opening made or enlarged by post-mortem damage. Where there is a clear indication that it *is* a sinus, however, the nature of the opening should be recorded:

- Through the buccal/labial or lingual plate of the alveolar process.
- Through the angle of the palatine process of the maxilla into the floor of the nose.
- Into the maxillary sinus.
- Onto the buccal or lingual aspect of the mandibular body.

Interpretation

Dias & Tayles (1997) have defined a periapical granuloma as a small cavity (< 3 mm radius as measured above) with smooth walls, and a radicular cyst as a larger cavity of the same type. It is, however, possible for a granuloma to be larger and a cyst smaller. An acute abscess developing in a granuloma or cyst may show as a slight roughening of the wall of the cavity. A chronic abscess is recognized by its sinus, which may have no real cavity at its blind end near the tooth root. A large cavity with rough or ragged borders, especially in the cheek tooth region of the mandible, is distinguished as chronic osteomyelitis, and may show the classical signs of multiple cloacae, sequestra, and involucrum.

Periapical radiolucency

The size and appearance of the radiolucency depends on the projection of the image (orientation of specimen, x-ray source and film), and may be explained by normal features, such as the maxillary sinus, incisive foramen, mental foramen and mylohyoid line, as well as the presence of a zone of bone removal within the alveolar process. Detailed descriptions of normal radiographic anatomy are given in Whaites (1992), Goaz & White (1994) and Wood & Goaz (1997). The same texts give details of the usual projections used for clinical work, and the terminology used below follows theirs.

Normal

The root and apex are outlined by a narrow radiolucent band, which represents the space occupied in life by the periodontal ligament, and outside this is a thin, clearly demarcated line of radio-opacity (the lamina dura) representing the alveolar bone lining the socket. Between adjacent sockets, and within the body of the alveolar process, an irregular, dense granular texture is created by the trabeculae.

Lamina dura

As alveolar bone is resorbed, there is local loss of the lamina, often apparent without a wider area of radiolucency. It may, however, be difficult to discern, and sometimes the lamina is poorly defined even in normal jaws.

Radiolucent area

A radiolucency of varying size and shape may be apparent within the trabecular texture surrounding the lamina dura. It may be circular to pear-shaped, and centred on the apex or side of a root, or it may be more widespread. It may be diffuse, without clear margins, or sharply demarcated by a clear radio-opaque line. The approximate diameter can be measured on the radiograph, but factors of magnification and distortion need to be taken into account (Whaites, 1992; Goaz & White, 1994).

Sclerosis

Sclerosis is a thickening of trabeculae, and deposition of isolated areas of denser bone. These are seen as isolated radio-opacities within the trabecular texture of the jaw, either as a diffuse area of opacity, or more sharply defined. It may occur right next to the lamina dura, or outside the margin of a radiolucency. Occasionally, sclerotic patches occur adjacent to teeth which do not have any evidence of pulp exposure—the cause is unknown.

Secondary dentine infilling of pulp chamber and root canal

Primary and secondary dentine cannot be distinguished radiographically, but the pulp chamber/root canal size is reduced by secondary dentine deposition, starting at its roof (infilling the horns first), followed by more general reduction in width. The chamber/canal may appear to be infilled completely, but there is often a thread-like radiolucency running down the root, so it cannot be assumed that the tooth is dead.

Interpretation

Circular or pear-shaped radiolucencies centred on a root (usually the apex) are usually interpreted as granulomata or cysts. The overwhelming majority in modern clinical practice are granulomata. Size may help to distinguish them, as very few granulomata give a radiolucency over 25 mm in diameter, whereas most radicular cysts are larger than 15 mm in diameter, but in many cases the radiolucency is smaller than 5 mm. With reference to dry bone specimens (see above), it should be noted that the measurement on a radiograph includes the root within the total area of radiolucency, whereas the direct measurement on the specimen is made from the side of the root and, therefore, is a smaller value. Cysts usually have a well-defined radio-opaque border, but granulomata may not do so. A periapical abscess may not give rise to any radiographic features, but may be associated with a radiolucency created by a pre-existing granuloma or cyst. Sclerosis is taken to indicate chronicity of the condition. Osteomyelitis is seen as a much larger, diffuse, ragged radiolucency of 'moth-eaten' appearance, and is almost always confined to the cheek tooth area of the mandible.

Appendix B: Recording forms for caries

The columns of the forms are numbered according to the FDI system and the rows are numbered, as explained in Appendix A.

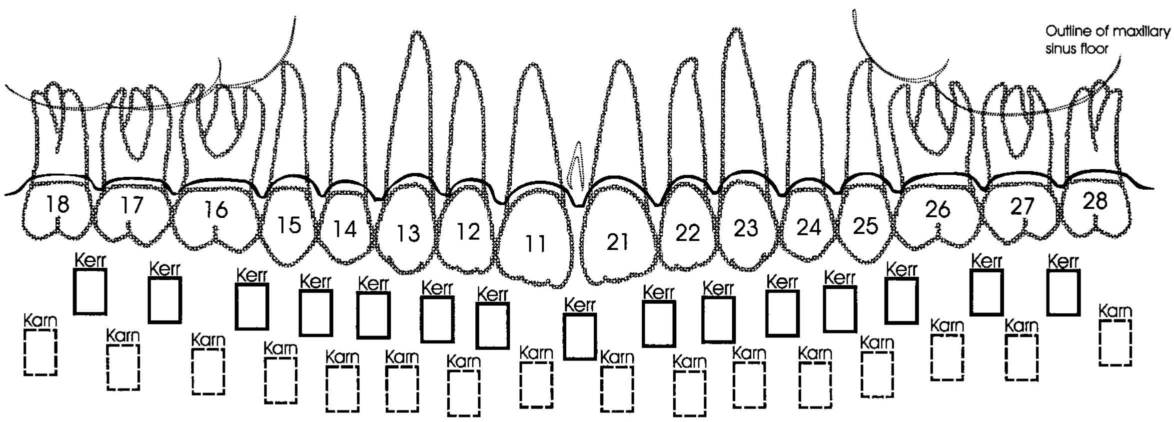
	18	17	16	15	14	13	12	11	21	22	23	24	25	26	27	28	
1																	1. Tooth presence, absence, carious
2																	2. Occlusal surface caries (fissure, groove, fossa sites)
3																	3. Pit caries
4																	4. Occlusal attrition score
5																	5. Occlusal attrition facet dentine caries
6																	6. Attrition facet enamel rim chipping/caries
7																	7. Mesial attrition score
8																	8. Mesial contact area caries
9																	9. Mesial root surface caries
10																	10. Mesial root exposure, CEJ-AC (mm)
11																	11. Distal attrition score
12																	12. Distal contact point caries
13																	13. Distal root surface caries
14																	14. Distal root exposure, CEJ-AC (mm)
15																	15. Buccal smooth surface enamel caries
16																	16. Buccal root surface caries
17																	17. Buccal root exposure, CEJ-AC (mm)
18																	18. Lingual smooth surface enamel caries
19																	19. Lingual root surface caries
20																	20. Lingual root exposure, CEJ-AC (mm)
21																	21. DDE in the occlusal region
22																	22. DDE in the contact area
23																	23. DDE lower down crown side or in cervical area

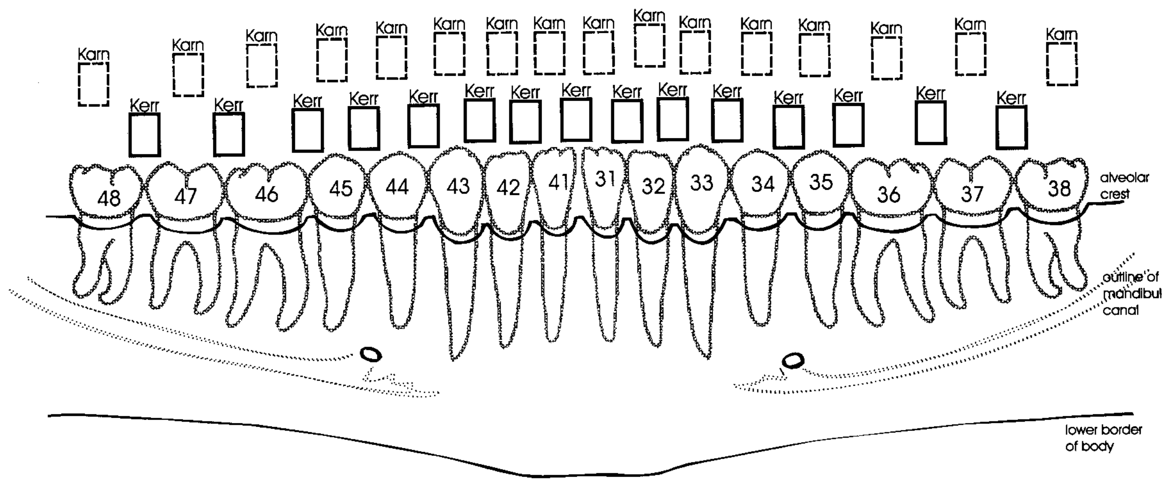
	48	47	46	45	44	43	42	41	31	32	33	34	35	36	37	38	
1																	1. Tooth presence, absence, carious
2																	2. Occlusal surface caries (fissure, groove, fossa sites)
3																	3. Pit caries
4																	4. Occlusal attrition score
5																	5. Occlusal attrition facet dentine caries
6																	6. Attrition facet enamel rim chipping/caries
7																	7. Mesial attrition score
8																	8. Mesial contact area caries
9																	9. Mesial root surface caries
10																	10. Mesial root exposure, CEJ-AC (mm)
11																	11. Distal attrition score
12																	12. Distal contact point caries
13																	13. Distal root surface caries
14																	14. Distal root exposure, CEJ-AC (mm)
15																	15. Buccal smooth surface enamel caries
16																	16. Buccal root surface caries
17																	17. Buccal root exposure, CEJ-AC (mm)
18																	18. Lingual smooth surface enamel caries
19																	19. Lingual root surface caries
20																	20. Lingual root exposure, CEJ-AC (mm)
21																	21. DDE in the occlusal region
22																	22. DDE in the contact area
23																	23. DDE lower down crown side or in cervical area

	55	54	53	52	51	61	62	63	64	65	85	84	83	82	81	71	72	73	74	75	
1																					1. Tooth presence, absence, carious
2																					2. Occlusal surface caries (fissure, groove, fossa sites)
3																					3. Pit caries
4																					4. Occlusal attrition score
5																					5. Occlusal attrition facet dentine caries
6																					6. Attrition facet enamel rim chipping/caries
7																					7. Mesial attrition score
8																					8. Mesial contact area caries
9																					9. Mesial root surface caries
10																					10. Mesial root exposure, CEJ-AC (mm)
11																					11. Distal attrition score
12																					12. Distal contact point caries
13																					13. Distal root surface caries
14																					14. Distal root exposure, CEJ-AC (mm)
15																					15. Buccal smooth surface enamel caries
16																					16. Buccal root surface caries
17																					17. Buccal root exposure, CEJ-AC (mm)
18																					18. Lingual smooth surface enamel caries
19																					19. Lingual root surface caries
20																					20. Lingual root exposure, CEJ-AC (mm)
21																					21. DDE in the occlusal region
22																					22. DDE in the contact area
23																					23. DDE lower down crown side or in cervical area

Appendix C: Diagrams for recording morphology of the alveolar process

Only diagrams for the permanent dentition are given here, as the changes described in the text are less relevant to the deciduous dentition. The teeth are numbered according to the FDI system (see Appendix A) and the boxes are for adding scores for pathological changes according to the Karn *et al*. (1984) and Kerr (1991) systems (also in Appendix A). Space is provided for notes on the condition of the alveolar process. The outline of the alveolar crest is drawn as a black line, and the approximate line of the alveolar crest relative to the roots can be drawn onto the diagram. Similarly, the relative amount of crown/root worn away can be indicated, with the positions of periapical bone loss, fenestrations and dehiscences. The same diagrams are also useful for noting post-mortem changes to the alveolar process, with the positions of x-rays and other details.





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