**Dental caries in a Portuguese identified skeletal sample from the late nineteenth and early twentieth centuries**

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## ABSTRACT

Dental caries was investigated in 600 adult dentitions belonging to the identified osteological collections of the Museum of Anthropology, University of Coimbra, Portugal (late 19$^{th}$ /early 20$^{th}$ centuries). The main advantage of this sample compared to an archaeological source is the presence of known demographic parameters - age, sex, occupation, etc. The aim of this study is to investigate the issues involved in comparing caries data derived from archaeological death assemblages with statistics compiled from clinical studies of the living. When only the upper dentition was considered, higher rates were observed in females than in males. No differences were found between sexes for lower teeth. In both sexes, both the percentage of carious teeth and the severity of lesions were found to increase with age, demonstrating that caries activity continued throughout life. The slight decrease observed for the age group 70-79 years is probably due to the increased ante-mortem tooth loss in the elderly. Caries was most common at contact areas (32.9%) and rarest at smooth crown surfaces (6.5%). Root surface caries was graphed in relation to the exposure of roots, and it was confirmed that the degree of root exposure was not strongly related to the frequency of carious lesions on the exposed root surface, although both increased with age. Molars were attacked more frequently by caries as a whole than premolars, canines or incisors. The results are similar to studies of recent living populations with a limited access to professional dental care.

Dental caries is one of the most widely studied pathological conditions in archaeological and anthropological collections. It produces highly characteristic changes that are distinguishable from other causes of tooth destruction, so it is possible to record lesions with a high degree of confidence in archaeological assemblages. It has also been the subject of widespread clinical research, so that the etiology and epidemiology of the disease during the latter part of the 20$^{th}$ century are well established. Caries has a multifactorial etiology but of prime importance is the amount and type of carbohydrate in the diet, which makes the disease a particularly useful tool in reconstructing dietary change in the archaeological record. In interpreting the palaeopathology of dental caries, it is logical to make comparisons with epidemiological studies of caries in living people, but there are several important issues that need to be taken into account. The aim of this study is to investigate the issues involved in comparing caries data derived from archaeological death assemblages with statistics compiled from clinical studies of the living.

The first issue concerns the nature of archaeological collections. Recent clinical studies are based upon dental examinations of living people. An archaeological collection of dentitions is fundamentally different – it is a death assemblage. This has a very different age distribution from that of a living population, with much higher proportions of young children and older adults. Further, such assemblages also encompass a particular subset of people – the sick and infirm – who might well have a different caries experience from the main bulk of the living. After all, caries in modern times shows a strong relationship with general health (Sheiham, 1997). Consequently, one may legitimately query whether the structure of a death assemblage produces a markedly different caries epidemiology from that seen in a living population.

The second issue is the patterning of caries between teeth, with different ages and sexes. Epidemiological studies of living people (Thylstrup and Fejerskov, 1994) have concentrated on caries in children. These studies have identified a strong pattern of susceptibility for different teeth within the dentition (Batchelor and Sheiham, 2004) that focuses on the permanent and deciduous molar crowns, so that the caries experience of modern children is clearly related to the sequence of dental eruption. These studies also identify sex differences in caries prevalence, usually with higher caries rates in girls, although this is not universal. There are far fewer reports on the epidemiology of caries in living adults (Luan et al., 1989; Manji et al., 1989). All, however, report a strong progression with age and this progression occurs for caries rate, the type of lesion and the specific teeth affected. Although these studies do not always distinguish between men and women, Luan et al. (1989) reported higher caries rates in Chinese women. By contrast, Mack et al. (2004) found no consistent differences by sex among elderly Germans. In yet another study, Manji et al. (1989) found no overall differences between the sexes among adult Kenyans. Nevertheless, older Kenyan women had higher caries rates than their male counterparts. In sum, patterning in children and rate differences among adults were found in some but not all studies.

Most archaeological studies of caries have calculated caries rates from the total number of teeth without distinguishing between different regions of the dentition. Those studies that have made this distinction (Moore and Corbett, 1971, 1973, 1975; Corbett and Moore, 1976; Varrela, 1991) report marked contrasts between different teeth. If this is so then, where all teeth are combined together, it is implicitly assumed that all teeth throughout the dentition have an equal chance of preservation, in all assemblages studied. This is not the case for most archaeological or museum collections. Teeth are quite often lost post-mortem and the single rooted anterior teeth are much more frequently lost than cheek teeth, which are held more firmly in their sockets. At the same time, ante-mortem tooth loss must complicate reliable comparisons of caries data because it is likely that many teeth with carious lesions would be lost earlier than those without lesions. This is not necessarily so, however, as teeth may also be lost through periodontal disease or, in heavy wear rate groups, through the processes of fracturing and rapid continuous eruption. For all these reasons, the assumptions made in archaeological studies are likely to have a profound influence on caries rates. So, for example, if caries rates are expressed as a proportion of total teeth, variation between sites could well be due to differential preservation of anterior versus cheek teeth. The only way to avoid this problem is to provide separate statistics for different teeth. Clinical studies make different assumptions, depending on the methodology used. Post-mortem tooth loss need not be considered, so all teeth absent at the time of examination are assumed to have been lost through the process of disease, trauma or congenital absence. Some studies also assume that missing teeth have been lost by extraction following a deeply penetrating caries lesion that exposed the pulp to infection (see discussion in Thylstrup and Fejerskov, 1994, p 184). While this may be true in children, which make up the bulk of epidemiological studies, in adults such assumptions ignore periodontal disease which is an important cause of tooth loss. Once again, it is important to be clear about the assumptions being made before comparing clinical studies.

Relatively few archaeological studies have examined caries affectation in relation to estimated age-at-death. In those studies where this has been attempted, such studies have found a marked progression in caries affectation that parallels indicators of increasing age-at-death (Moore and Corbett, 1971, 1973, 1975; Corbett and Moore, 1976; Varrela, 1991). Recent epidemiological studies are based upon carefully selected, equally sized groups representing a full range of ages from the living population. Archaeological and museum collections are often too small to allow selection of similarly sized groups throughout the full age range and, in any case, age estimation from the skeletal remains of older adults is not only uncertain but also often based on factors such as increasing tooth wear which are themselves not independent of dental caries. The nature of age groupings in most archaeological assemblages therefore differs fundamentally from age groupings in clinical studies.

By contrast, sexual dimorphism in the adult skeleton allows a reasonably confident identification of sex in many archaeological collections, and most archaeological studies report higher caries rates in females than in males (Lukacs and Thompson, 2008). As these studies are usually based on total tooth counts, no distinction is made between adults and children, although it seems reasonable to assume they were adults since it is difficult to distinguish between the skeletons of boys and girls. Archaeological collections often have fewer than expected female skeletons (see discussion in Waldron, 1994, p 23), perhaps due to a preference in burial, or to taphonomic factors. Furthermore, an examination of statistical tables in the United Nations Demographic Yearbooks (available online at http://unstats.un.org/unsd/demographic/products/dyb/dyb2.htm) shows that the sexes are never evenly distributed by age in death assemblages – there tend to be more girls than boys in the infant age group, fewer girls/women throughout most of child- and adulthood, and more women in the oldest age groups. This might well have an impact on the sex differences in caries rates seen in archaeological studies. Once more, clinical studies usually select carefully equal numbers of males and females for each age group. This is difficult to achieve in the typical archaeological collection and again, the nature of the assemblage needs to be borne in mind when comparing the age and sex variation of caries between different sites, and between archaeological and modern clinical studies.

Until the development of large urban centers following the industrial revolution, human dentitions appear to have been characterized by a much more rapid rate of wear than seen today. In addition, refined sugar was not readily available to all socioeconomic groups until after the 18th century, when there was massive growth in the international sugar market. These two factors – very light wear and high sugar consumption – set the past 200 years apart from the bulk of human history (Moore and Corbett, 1975; Corbett and Moore, 1976; Hillson, 2008). For example, Victorian era dentitions from Christchurch, Spitalfields in London (Whittaker, 1993) show a caries experience much more in common with the present day than with Medieval times. Like today, caries affected primarily the tooth crowns starting with newly erupted teeth in childhood, with adults accumulating more crown lesions and adding root caries as the root surfaces were exposed in the oral cavity by periodontal disease. By contrast, many ancient archaeological collections tend to be characterized by lesions that started at the cement-enamel junction as the roots were exposed in older adults – not by periodontal disease - but by continuous eruption to compensate for heavy wear (Hillson, 2008). Hence, the type of lesions and the pattern of occurrence with age contrast strongly between archaeological collections and recent clinical studies. Because of this, a simple comparison of caries rates calculated for all teeth and all ages combined is likely to be affected by many hidden factors. It is therefore important to take these fundamental changes in caries epidemiology into account.

In light of these issues, there are several important questions to be addressed when comparing archaeological collections with data collected from living people:

1. Are caries data gathered from a death assemblage consistent with data gathered from clinical studies of the living?
2. Does a death assemblage, in which teeth are lost post-mortem and there is a different distribution of ages, show similar differences in caries rates between different teeth to those shown in recent living populations?
3. Is there a similar progression of caries with age, despite the differences between a death assemblage and a living population?
4. What are the potential effects of the patterns of ante-mortem and post-mortem tooth loss in different age groups within the death assemblage?

5. Are there differences between males and females in the age-related progression of caries and do these vary between different age groups in a way that might be affected by the nature of the death assemblage?

To test for these, it is necessary to isolate, as far as possible, the different factors. Such a test requires a collection of dentitions from a death assemblage that represents a well-defined group of people who lived under conditions that differ little from those of living people, particularly in not being subjected to the very rapid wear, which characterizes most archaeological collections that antedate the early years of the 19$^{th}$ century. To be directly comparable to the demographic characteristics of a clinical study, ages-at-death and sex need to be known independently from the skeletal remains themselves. This is especially important for age-at-death since age is extremely difficult to estimate reliably in older adult skeletons. In addition, there should be a relatively even spread of age groups across the full range of adult life. Such collections are rare, but one exists in the Coimbra Identified Osteological Collections of the Museum of Anthropology at the University of Coimbra in Portugal. These collections encompass around 2,000 skulls and dentitions of people from the central region of Portugal, who were mostly of low socioeconomic status and who died during the late 19$^{th}$ and early 20$^{th}$ centuries. This places them at a point temporally intermediate between the large clinical studies of the 1980s and the archaeological collections of the 19$^{th}$ centuries in other European countries. The study presented here uses a sample selected from the Coimbra Identified Osteological Collections to address the six questions posed above.

## MATERIALS AND METHODS

### The Coimbra Identified Osteological Collections

The sample evaluated for this analysis comes from the Coimbra Identified Osteological Collections, curated by the Museum of Anthropology of the University of Coimbra (MAUC). There are three osteological collections at the MAUC that make up the Coimbra Identified Osteological Collections. These include the Medical School (MS, 585 skulls), the International Exchange (IE, 1075 skulls) and the Identified Skeletal (IS, 505 skeletons) collections. The skulls belonging to the Medical School collection were acquired from the Schools of Medicine in Lisbon and Porto and also from the Anatomical Theatre of the University of Coimbra, whereas skeletal material from both International Exchange and Identified Skeletal collections was recovered from the “Cemitério Municipal da Conchada” in Coimbra.

In Portuguese cemeteries it is common practice to perform exhumations after a period of five years. The bones are then required to be transferred for deposition in an ossuary. However, if relatives do not claim the remains following exhumation or cease payment of ossuary fees the remains are either placed in a communal grave or cremated. It was at that time that the Coimbra University intervened and asked to house the remains for research purposes (Cunha and Wasterlain, 2007).

Individuals in the MS, IE and IS collections died between the years 1895-1903, 1904-1938 and 1904-1938, respectively. As these were fully identified individuals, detailed information about each, namely birthplace, sex and age at death, year and place of death, illness or cause of death, and occupation, amongst others, is compiled in a Record Book. These records make clear the low socioeconomic status of most individuals in the collections. According to these records, the women were almost exclusively engaged as housewives whereas men were employed mainly as rural workers and artisans. Furthermore, the provenance of their bodies can also be considered a sign of their low socioeconomic status, for in most cases their families could not afford adequate burials (Cunha and Wasterlain, 2007).

## The Sample

In some dental studies based on skeletal collections, the specimens were selected on the basis of degree of completeness or state of preservation (Whittaker et al., 1981; Kerr et al., 1990; Kerr, 1990; Whittaker and Molleson, 1996). However, exclusion of damaged specimens might result in an unrealistically low frequency of caries, as bones and teeth weakened by disease are more likely to suffer diagenic damage in the ground than those with normal structure (Watt et al., 1997). To avoid this, the individuals of the present study were selected regardless of the state of preservation.

Since previous studies (Kerr et al., 1990; Kerr, 1990) have shown an increase in the frequency of dental caries in adults with advancing age, it was important to analyze individuals by age group. Therefore, 600 specimens were randomly selected in order to have six age groups (age group 1: 20-29 yrs; age group 2: 30-39 yrs; age group 3: 40-49 yrs; age group 4: 50-59 yrs; age group 5: 60-69 yrs; and age group 6: 70-79 yrs) composed of 100 individuals, with 50 males and 50 females in each. The selected individuals died in the centre of Portugal between 1896 and 1938. Non-adults were deliberately excluded from the study due to the insufficient number of children and juveniles in the collections. Ideally it would be known if these individuals had life-long, or at least long-term, residence in the same geographic region, but this information was not available. It is known, however, that all of the selected individuals had been born and had died in the centre of Portugal.

The dental collection analyzed in this research (9562 permanent teeth) is one of the largest and best preserved studied anywhere. This is important because low numbers of individuals could easily result in false high or low values for caries statistics (Vodanović et al., 2005).

## Context of the collection in late 19th/early 20th century Portugal

Diet

The daily diet in the centre of Portugal at the beginning of the 20th century was very simple, consisting essentially of bread (mostly made of maize, but also wheat, barley, and rye), green and dry vegetables eaten as soups and broths accompanied by potatoes. Soups were also prepared with maize flour (Roque, 1982). Additionally, a small (but not daily) intake of fish (usually sardine and salted codfish), bacon, olive oil and honey could complement the dietary staples (Bocquet-Appel and Morais, 1987).

Oral hygiene

Despite the availability of some modern methods of cleaning teeth during the 19th and early 20th centuries, such methods were certainly not widely used in Portugal. Based on general accounts of the history of oral hygiene, toothbrushes were already manufactured in France and England by the 18th century (Mattick, 1992 in Saunders et al., 1997), and even though described in great detail in the Portuguese literature by A. De Vitry Júnior in 1843, they remained luxury items due to the high cost of production (Boléo, 1965).

Access to professional dental care

Professional dentistry was available in the late 19th and early 20th centuries, though on a limited basis. As in Europe in general, there were only a very small number of practicing dentists in Portugal (in 1887, only two medical doctors practiced dentistry in Portugal). Gradually, others began to practice, but dental treatment, mainly dental extraction, was predominantly provided by people without any qualification and as a sideline to other primary businesses, such as barbering (Ribeiro, 1935; Costa, 1961; Capelas and Pereira, 1976). Tooth extraction is one of the oldest surgical procedures, and would quite possibly have been performed by many people in the past, particularly when pulp exposing lesions led to periapical inflammation which can produce the most violent toothache (Hillson, 2000, 2008). More complex procedures, such as fillings and crowns, would have been limited, even for qualified dental practitioners, since there were no anesthetics, the instruments and materials were unsophisticated and, most importantly, there was a lack of knowledge of the etiology and pathology of caries. Consequently, preventive practices hardly existed (Capelas and Pereira, 1976) and the treatment offered by qualified practitioners would have been limited by their cost and the ability of patients to pay.

Fluorine levels

The cariostatic properties of fluorine are well known (Thylstrup and Fejerskov, 1994), but fluoridation was never introduced in Portugal, despite some experiments in a few places later in the 20th century. Natural soil fluorine levels in Portugal are generally very low (ranging between 0.03 mg $F^-$/l and 0.19 mg $F^-$/l in the region of Coimbra) (Pinto et al., 1999). In fact, a recent study performed in 275 Portuguese “concelhos” (administrative division) reveals that in only one (*Vila Flôr*, district of *Bragança*, Northeast region of the country) are the natural soil fluorine levels sufficiently high to dispense fluorine supplements (Pinto et al., 1999). Consequently, aside these few exceptions, the individuals living in Portugal would probably not have ingested fluorides in any significant amounts, until more recent times, when fluoridated toothpastes were introduced.

## Dental examination

Initially, teeth were examined for presence, post-mortem absence, ante-mortem absence, partial eruption, anomalous eruption, or no eruption (as a result of young age, impaction or agenesis). The assessment of which teeth had been lost before death and which after death was done by considering the condition of the socket margins. It was assumed that a tooth had been lost post-mortem if there was an empty alveolus with no sign of remodeling. Ante-mortem tooth loss was assumed when there was at least a trace of remodeling in the socket or alveolar process. Third molars were only recorded as lost ante-mortem when they had left distinct traces of approximal wear on the distal surface of the adjacent second molar. All retained roots were recorded as remaining teeth. Only fully erupted teeth were used for further calculations because there is the possibility that partially erupted teeth may have been covered by soft tissue (Lingström and Borrman, 1999). In all, 19188 tooth positions and 9562 permanent teeth were analyzed.

In this paper the phrase “tooth type” is used to refer to a specific tooth in the dentition regardless of side (e.g., mandibular first molars) rather than to an entire class of tooth (e.g., molars).

## Recording dental caries

For a detailed comparison with modern epidemiological studies of living adults, it was necessary to record caries in more detail than has been the case in many archaeological studies. For this reason, the caries recording scheme of Hillson (2001) has been adopted here.

The dentitions were examined under standardized lighting conditions by careful visual inspection, with the aid of a low-power microscope. When possible, teeth were removed from the alveolus for better evaluation. Lesions were judged to be caries if there was a discernable, even if small, white or brown spot in the otherwise translucent enamel, which serves to identify the early stages of the condition (Hillson, 2001). Most surveys to date have only recorded carious cavities about which the examiner was absolutely certain (O’Sullivan et al., 1993; Whittaker and Molleson, 1996; Watt et al., 1997; Lingström and Borrman, 1999;

Cucina and Tiesler, 2003; Vodanović et al., 2005). It is now recognized that such procedure underestimates the frequency of caries and that recording of non-cavitated lesions is not as unreliable as had been believed when carefully trained and calibrated examiners are used to conduct the survey (Ismail, 1997). Radiographs could not be made of all specimens in this very large collection but their use was not considered essential. The visual method of caries identification has previously been shown to be reliable when compared to both radiographic and histological studies (Whittaker et al., 1981) and serves to minimize inter-observer error (Rudney et al., 1983). Also the dry surfaces, bright lighting and use of a microscope greatly improve the visibility of lesions.

The position, site of origin, stage of development and extent of lesions were recorded where possible. Several locations were considered: occlusal surfaces, pit sites, mesial and distal contact areas, mesial and distal root surfaces, buccal/labial and lingual enamel smooth surface sites, and buccal/labial and lingual root surfaces. A cavity was classified as gross when it was too large for the initial location of the site of attack to be determined with certainty, and as gross gross when involving the loss of so much of the tooth that it was not possible to determine whether the lesion was initiated in the crown or root.

Root exposure on each side of the tooth was assessed by measuring maximum vertical distance (to the nearest millimetre) between the cement-enamel junction (CEJ) to the alveolar bone lining the socket (ABLS) with a graduated periodontal probe (roots were considered exposed when CEJ-ABLS > 2mm).

Prior to commencement of the main study, several calibration exercises were carried out to ensure that diagnostic criteria were precisely defined and a high level of reproducibility achieved. Data were collected by one observer (SW). Every two weeks, checks for intra-examiner variability were made by repetition of the first individual recording made during that time period. In all, 22 repeats were involved in this intra-observer assessment. The kappa statistics on intra-examiner consistency in the diagnosis of caries lesions was 0.93.

### Calculating caries occurrence

The expression of caries frequency in an assemblage of skeletons has always been problematic. Given the fragmentary nature of osteological material, it is rather difficult to estimate the proportion of individuals affected by dental caries, as the status of missing teeth can never be known. For the same reason, modern caries indices such as DMFT (decayed, missing and filled teeth) or DMFS (decayed, missing and filled surfaces) are unsuitable (Watt et al., 1997). The most accurate method of expressing caries rate would appear to be the calculation of the number of teeth observed to be affected by caries as a percentage of all teeth present that have erupted into functional positions (Kerr et al., 1990). Some individuals are likely to have lost some teeth during their lives and it is reasonable to think that some of these had been lost due to dental caries. Some researchers (Whittaker et al., 1981; Lukacs, 1995) have felt that to exclude those teeth would yield caries rates lower than the true ones and have attempted to apply corrective factors derived from the numbers of teeth lost ante-mortem. However, teeth are frequently lost ante-mortem due to reasons other than caries; namely periodontal disease and trauma. Most frequently, it is impossible to know what proportion of ante-mortem tooth loss may have resulted from dental caries, and the current view appears to be that such corrections should not be applied (Kerr et al., 1990; Whittaker and Molleson, 1996; Watt et al., 1997; Hillson, 2001; Oxenham and Matsumura, 2008). This was the position adopted in this study.

In life the teeth are held in the jaw by the soft tissues. However, after death, as these decay, the teeth become more susceptible to loss in the burial environment. Some researchers have considered the proportion of post-mortem tooth loss to be a useful measure of the ‘quality’ of the dentitions in excavated skeletal material. If, however, as in the present study incisors and canines are more often lost post-mortem than cheek teeth and at the same time they are much less affected by caries than cheek teeth (Varrela, 1991; Watt et al., 1997; Lingström and Borrman, 1999), then the pattern of loss must have a strong effect on caries statistics.

With all this in mind it was decided that a single index of caries rate could not express the true complexities of dental caries and would be affected by differential preservation of different tooth classes, parts of teeth, age groups and sexes (Hillson, 2001). Separate tabulations for the different categories of carious lesions, at the different sites where they may be initiated on different teeth were made. Ante-mortem tooth loss was calculated as the percentage of tooth positions in the jaws from which the tooth had been lost during life. The statistical significance of the recorded values was tested with independent samples chi-square.

## RESULTS

### Missing teeth

Of the 19188 observable sockets, 2222 teeth were lost post-mortem (11.6%) and 7131 (37.2%) were lost before death. Additionally, two roots remained as support to prosthetic crowns. Partial eruption was observed in 38 teeth (third molars only) whereas anomalous eruption was found in 32 teeth (third molars and upper canines). Much more common was complete failure to erupt (as a result of young age, impaction or agenesis), registered in 109 tooth positions (mainly third molars, but also upper lateral incisors, lower canines and lower premolars). Of the 9654 fully erupted teeth, 92 were excluded from the present study due to severe post-mortem damage that prevented evaluation. Therefore, it has been possible to study caries in 9562 teeth. The percentages of teeth present, ante-mortem losses, post-mortem losses, post-mortem fractures, and those with eruption related problems (with sides pooled) by age group are provided in Figure 1 (Table S-1).

In age groups 1 and 2, between 53% and 95% of all teeth were present. The number of teeth present decreased with age particularly in the posterior region, as ante-mortem tooth loss (AMTL) increased. In fact, AMTL increased steadily from 4.6% in age group 1 to 73.2% in age group 6. Loss of molar teeth was especially marked from age group 5 onwards. Canines were the least frequently missing teeth as age progressed. Post-mortem tooth loss was higher between age groups 2 and 4 whereas tooth damage was broadly similar in all age groups. In age group 6, between 6% and 28% of all teeth were present. Molars suffered AMTL with higher frequency but were lost post-mortem less often than incisors or canines. In general, premolars occupied an intermediate position in both types of tooth loss.

## Caries experience

Though dental caries may attack one side of the dentition to a greater degree in an individual, there is no reason why it should systematically favor one side or the other in a population (Watt et al., 1997). A pilot comparison showed no consistent side-specific differences in caries frequency in the current sample, and hence data from both sides were combined as is normal for most epidemiological studies (Thystrup and Fejerskov, 1994).

In the whole assemblage, 62.0% (5932/9562) of the surviving permanent teeth and 99.4% (511/514) of individuals with permanent teeth were affected by caries. If only cavitated lesions are considered, these values drop to 27.9% (2666/9562) and 92.6% (476/514), respectively. Of 514 individuals with dentitions, only 17 (3.3%) had only one decayed tooth.

When consideration is limited to the upper dentition, higher rates were observed in females than in males (Chi-square = 28.451, df = 1, $p$ = 0.000). No differences were found between the sexes for lower teeth (Chi-square = 0.087, df = 1, $p$ = 0.768).

In Figures 2 and 3 (males and females, respectively; Tables S-2 and S-3), caries and ante-mortem tooth loss frequency rates are presented for each tooth by age group. Although the frequency of carious lesions was age-associated it was still remarkably high among members of age group 1. In the youngest males some 49.1% of all teeth were carious. This rose to a maximum of 74.7% in age group 5 and fell to 72.8% in age group 6. In females, the percentage of carious teeth rose from 53.6% in age group 1 to 71.7% in age group 2, than fell to 64.2% in age group 3 to increase again until age group 5. As with men, caries experience decreased in the oldest group of females. This decrease in the oldest age group may have been influenced by increasing levels of ante-mortem tooth loss, for the most carious teeth would also be the ones most likely to be lost. In both sexes, the eldest age group showed a marked increase in ante-mortem tooth loss, an unknown proportion of which may have been due to caries. Furthermore, a slight trend was evident towards a more anterior location of the lesions from molars, to premolars, to canines and incisors in the older age categories. In the younger age classes caries attacked the incisor and canine teeth less frequently than the molars and premolars, whereas in the older age groups caries progressed from posterior to anterior teeth, so that in some cases posterior and anterior teeth were affected by caries with almost equal frequency. This pattern may be a consequence of ante-mortem tooth loss. With preferential loss of the molars, often due to caries, more anterior teeth are the only ones left to be at risk of caries in older individuals. Hence, caries frequency tends to increase. Caries occurred more frequently in the upper than in the lower jaw, both in males (Chi-square = 34.859, df = 1, $p$ = 0.000) and females (Chi-square = 110.227, df = 1, $p$ = 0.000).

The overall coronal and root surface caries frequency for all incisors and canines was 44.6%, for premolars 70.6%, and molars 77.2%. The most caries-involved teeth were first molars, independently of sex. Nevertheless, the largest value for caries frequency in a particular tooth class was 100%, observed in maxillary second molars and mandibular third molars among 70-79 year-old males. By contrast, the least affected teeth were the lower incisors.

In Figures 4 and 5 (for males and females, respectively), caries frequency rates are presented for each tooth by age group, according to the severest lesion type on any surface of the tooth (Table S-4). The pattern of lesions changed progressively with age as well. Lesions confined to the enamel of the crown were the most common form in young adults, declining with age, particularly from the age group 4 in females and from age group 5 in males onward. On the other hand, the proportion of teeth with lesions penetrating to the dentine and to the pulp chamber rose gradually with age. Overall, enamel lesions, fillings, and pulp exposing lesions predominated in the posterior teeth, while in the anterior teeth dentine lesions predominated. Fillings were extremely rare in all age groups and were not found in any individual in the oldest age class (age group 6). Only 12 individuals possessed fillings. These include three individuals (2 males, 1 female) with three filled teeth, four individuals (3 males, 1 female) with fillings in two teeth, and five males had a filling in a single tooth. Overall, only 0.4% of the carious teeth (22/5932) and 2.3% of the individuals had fillings. First molars were the most frequently filled teeth (11), followed by the second molars (4). The remaining filled teeth were incisors (1), canines (2), first premolars (2), and second premolars (2). Fifty per cent of those teeth had fillings on only one surface: 7 teeth had fillings involving the occlusal surface, and 4 teeth had the approximal area filled.

Since carious lesions fall into several different categories, in relation to their site of initiation on the tooth surface, and that these categories have contrasting etiologies, and develop in different ways with increasing age, they are also presented separately here. On the crown, it is possible that a carious lesion might have initiated in the enamel of the occlusal fissures, grooves or fossae, in a buccal or lingual pit, in an occlusal attrition facet, at either the mesial or the lingual contact point, or in the enamel of the smooth surface.

For occlusal caries (Table 1), the percentages of surfaces involved were calculated as a percentage of fissure and fossa occlusal sites (only molar and premolar teeth have them) present in each individual and at risk. As no sexual differences were found for occlusal caries (Chi-square = 0.660, df = 1, $p = 0.416$), males and females were pooled. Of all the occlusal surfaces examined, some 22.9% (1189 of 5197) showed evidence of caries. Overall, molars were significantly more affected by occlusal caries (37.4%) than premolars (5.3%) (Chi-square = 751.720, d.f. = 1, $P = 0.000$). The teeth most affected were second molars and the teeth least affected were first premolars. Interestingly, the frequency of occlusal caries increased between age-groups 1 and 2 then remained relatively stable until showing another rise in age group 5. No differences were found between lower teeth (22.8%) and upper teeth (22.8%), for occlusal caries (Chi-square = 0.003, df = 1, $p = 0.955$).

For pit caries (Table 2), each discrete pit present in the dentitions was counted and evaluated. Not all dentitions have them, but there is often one buccal pit on molars and, sometimes, a lingual pit in upper incisors (rarely canines) (Hillson, 2001). The frequency of pit caries was lower than that of occlusal caries, totaling 17.8% of 533 sites at risk. Central incisors were never affected by pit lesions, neither were lower canines. No pits were even present in lower lateral incisors. Overall, molars were significantly more affected by pit caries (24.2%) than anterior teeth (5.1%) (Chi-square = 29.743, df = 1, $p = 0.000$). Besides, the frequency of pit caries in lower teeth (22.6%) was higher than that of upper teeth (9.0%) (Chi-square = 15.290, df = 1, $p = 0.000$). In males, the percentage of pit caries rose from 9.0% in the 20-29 yr-olds to 66.7% in the oldest group. In females, the frequency of pit caries increased more or less steadily through the age groups from 11.3% in age group 1 to 21.4% in age group 5. Males had a significantly (Chi-square = 5.179, df = 1, $p = 0.023$) greater involvement of pit sites (21.0%) than females (13.4%).

For occlusal attrition facet dentine caries (Table 3), 5906 facets were at risk and of these 16.0% were involved. For both males and females, occlusal attrition facet dentine caries was more common in upper than in lower teeth (Chi-square = 100.055 df = 1, $p = 0.000$). No differences were found between anterior and posterior teeth (Chi-square = 2.069, df = 1, $p = 0.150$), nor did occlusal attrition facet dentine caries show any significant preference for a particular tooth type. In the youngest men (age group 1), 15.6% of attrition facets were carious and, as with occlusal caries, the frequency rose to a maximum of 27.5% in age group 5 only to fall to 20.3% in age group 6. In females, the frequency of attrition facet caries was lowest among age group 2 (10.6%) and highest in age group 5 (19.5%). Males had significantly (Chi-square = 17.579, df = 1, $p = 0.000$) more involvement of attrition facets (17.8%) than females (13.8%).

Contact areas between neighboring teeth (Table 4) were the most frequently sites attacked by caries. Of the 17617 approximal surfaces (mesial and distal) at risk, 5800 (32.9%) were carious. In both sexes, contact caries was significantly more common in posterior (60.0%) than in anterior teeth (28.8%) (Chi-square = 813.248, df = 1, $p = 0.000$) and in upper (54.2%) than in lower teeth (41.4%) (Chi-square = 143.500, df = 1, $p = 0.000$). Overall, contact caries was more common in first molars and premolars. Interestingly, the frequency of contact caries was much lower in third molars. Even so, central incisors were the least affected of all teeth. In males, a trend towards increasing caries frequency on the approximal surface with age until age group 4 was noted. In females, 28.5% of contact areas were caries-involved in age group 1, rising to a maximum of 47.2% in age group 2, a rate very different from that in age group 6 (32.9%). Females had a significantly greater involvement (Chi-square = 57.115, df = 1, $p = 0.000$) of distal and mesial surfaces (both upper and lower) than did the males.

Smooth surfaces (Table 5) were the least affected by caries. As no sexual differences were found for smooth surfaces caries (Chi-square = 1.934, df = 1, $p = 0.164$), males and females were lumped together. Lesions were seen on the buccal or lingual surfaces in only 1174 cases of 18148 surfaces observed (6.5%). Overall, third molars were the most commonly affected teeth. By contrast, second premolars and the incisors were the least involved teeth in the upper and lower jaws, respectively. In men, smooth surfaces caries was more frequent in age group 5 whereas in females it was more common in age group 2.

In living individuals, it is possible to determine whether a root surface carious lesion was initiated at the cement-enamel junction or on the root surface nearby, but in archaeologically-derived specimens 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). A root caries index (Kerr, 1990) was calculated from the number of lesions in each sex and age group related to the surfaces at risk (Table 6, Figs. S-1 and S-2). Of the 36567 root surfaces analyzed, 55.9% were presumably exposed (maximum vertical distance between cement-enamel junction to alveolar bone lining socket > 2mm) by continuous eruption, or the recession of the gingivae and underlying supporting tissues related to periodontal disease. Although root exposure affected all tooth classes, a characteristic pattern could be identified in both sexes. In upper teeth, root exposure was more commonly seen in molars whereas in lower teeth affected mainly incisors and canines. The percentage of exposed root surfaces increased steadily with age, in both sexes, from 26% in age group 1 to around 89% in the oldest individuals. Of the 20432 exposed root surfaces, 2161 (10.6%) were carious. Overall, molars were more affected by root surface caries than anterior teeth, but this was not evident for every age group. Root surface caries was relatively uncommon amongst young adults, only 7.4% and 7.9% of male and female surfaces being affected, but showed a steady rise with age, reaching the maximum of 16.6% and 11.4%, respectively, in age group 4. In age group 6, the frequency of root caries was 13.2% for males and 10.5% for females. Root caries was lower in females (9.7%) than in males (11.3%). In both sexes, buccal root surfaces were more heavily affected by caries (men: 10.0%; women: 7.4%) than lingual surfaces (men: 3.2%; women: 2.4%).

Overall, caries was most common at contact areas (32.9%) and rarest at smooth surfaces (6.5%). In some teeth the lesions were so large that they involved more than one surface. Of the 9562 analyzed teeth, 252 (2.6%) had gross cavities. Of these, the great majority (49.6%) were gross contact area or cervical caries (where a carious cavity bridged the cement-enamel junction and the edge of the approximal attrition facet), 15.9% were gross buccal or lingual caries (where a carious cavity bridges the cement-enamel junction and the buccal or lingual smooth surface), 14.3% were gross coronal caries (where the lesion has progressed so far that it was only possible to say that it was initiated on the crown), 11.9% were 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), and 8.3% were gross contact area/occlusal caries (where it was not possible to tell whether it was initiated in the occlusal surface or at the contact point). Gross gross lesions where there was no indication where the lesion was initiated affected 4.2% of all teeth.

## DISCUSSION

In summer, our study of the Coimbra collection found that:

1. The proportion of teeth lost ante-mortem increased markedly with age particularly in the molars and premolars. In the oldest age group, the great majority of cheek teeth were missing. Post-mortem tooth loss or fracturing stayed at a similar level throughout, with anterior teeth affected substantially more than cheek teeth.
2. A larger proportion of molars and premolars was affected by carious lesions than incisors and canines. There was no significant difference between left and right, but upper teeth were more often carious than lower. The proportion of surviving teeth

affected by caries increased with age (particularly in the cheek teeth), but reduced slightly in the oldest group. As the number of surviving teeth decreased markedly with age, when caries and ante-mortem tooth loss are considered together the proportion of tooth positions showing a carious lesion fell. Both males and females showed a similar pattern of lesions – only in upper teeth did females show significantly higher frequencies of lesions than males.

3. Overall, in both males and females, cheek teeth lesions were most often confined to enamel or penetrating the pulp, while in anterior teeth they were more commonly confined to dentine. There was, however, a progression with increasing age. For most teeth, enamel lesions were commonest in the youngest age group and declined steadily to the oldest group. Dentine and pulp penetrating lesions were least common in the youngest group and increased to the oldest. This trend was particularly marked in anterior teeth. Even in the oldest age group, a substantial proportion of lesions was confined to the enamel. This might be taken to imply that lesions were slowly developing but, given that the proportion of teeth lost ante-mortem increased markedly with age and that many of those teeth are likely to have been heavily affected by caries, it suggests that new lesions continued to develop in the crown enamel.
4. Molar occlusal fissures were much more commonly affected by carious lesions than those of premolars, and there was no significant difference between upper and lower teeth. There was no strong trend with age and the oldest age group had just as many fissures affected as the youngest. Pits on the crown sides were much less commonly affected than occlusal fissures and mainly the buccal pits of lower molars were involved. In males, lesions at these sites showed a pronounced increase with age.
5. Contact areas were the most common sites of all carious lesions. A greater proportion of cheek teeth than anterior teeth was involved, especially the first molars and the

premolars.  Females showed slightly higher proportions of contact areas with caries than males, while males showed a stronger trend with age than females.

6. The smooth surfaces of crown sides just above the gingivae were the least common caries sites.  This type of lesion could be found in any tooth, but the most commonly affected were the third molars.  There was no significant difference between males and females and there was not a strong trend with age.
7. Root surface caries lesions were strongly related to exposure of the roots through continuous eruption or periodontal disease.  Both exposure and caries showed a steady increase until 50 years of age.  Males showed a somewhat larger proportion of exposed root surfaces with caries than females.

One of the main aims of this study was to test the effect on caries statistics of a death assemblage, with its very different age distribution to a living population.  It was therefore necessary to find comparative studies of adults of all ages, divided into age groups.  In addition, because of the uneven distribution of teeth lost post-mortem, it was necessary to find studies which reported caries rates separately for different teeth.  Relatively few studies fit these criteria.  Manji et al. (1989; 1991) studied a full range of adult ages in a sample of 1131 living people examined during 1985/6 in rural Kenya.  They were divided into five age groups (ten years in each), starting with 15 years and ending with 64 years.  This makes a good comparison with the present study because the data were plotted separately for different teeth and different ages.  In addition, as with the people in the Coimbra collection, the Kenyan patients lived in an area with limited access to dental care.  Luan et al. (1989; Manji et al., 1991) published a similar study of 1744 Chinese people from the Beijing area, divided into six age groups (again with ten year interval) from 20 years up to 70 or more.  The age groups are closer to those of the present study, but this study group may be less directly comparable as it combined people living both in rural and urban conditions.

Manji et al. presented their Kenya study in two ways. In their original paper (1989), they plotted a graph in which ante-mortem tooth loss was included with caries, showing the most severe lesion (divided into enamel, dentine, pulp or root) for each tooth, for each age group. The rationale for including ante-mortem loss was that the principal cause was extraction as a result of caries, except in the case of lower incisors which were often ritually extracted (Manji et al., 1988). In a later book chapter (1991) they excluded ante-mortem tooth loss and instead plotted the most severe lesion (divided into enamel, dentine, pulp, root, filling) for each tooth and each age group. This type of graph has become the standard for studies of this kind, and has been used in presenting the results of the present study.

In Manji et al.'s study in Kenya (1989) the molars were the most commonly affected teeth, with 60% carious or missing, in all age groups. Premolars, canines and incisors were little affected in the youngest 15-24 year group, but in older groups progressively larger proportions had lesions or were missing. By the 55-65 year age group, some 40% of upper premolars had carious lesions or were missing, and up to 30% of anterior teeth. Upper premolars, canines and incisors were much more affected than lower in all age groups. Carious lesions became progressively larger with increasing age, involving the dentine and pulp as well as enamel, and more teeth missing. In the oldest age group, up to half of the teeth in each part of the dentition were missing. Root caries became more common in older age groups although enamel caries remained the most common, at least in cheek teeth. Overall, there was no significant difference between men and women, although particularly in the oldest age group women tended to be more affected by caries and tooth loss than men.

When ante-mortem tooth loss was excluded from the graph (Manji et al., 1991) there was an even stronger contrast between the high proportions of caries affected molars (40-60% or more) and low proportions of anterior teeth (mostly 20% or less), with premolars in between. In progressively older age groups, a larger proportion of anterior teeth and premolars were carious, and this was much more marked in the upper dentition than the lower. Enamel caries dominated throughout, although root caries, and more deeply penetrating dentine and pulp lesions increased with age.

Luan et al.’s (1989; Manji et al., 1991) study in rural and urban areas of Beijing was presented in same way, excluding ante-mortem tooth loss. It showed very similar patterns of carious lesions, with molars again the main teeth involved. The age progression was more strongly marked than in the Kenya study. This was emphasized by the inclusion of an older 70+ year age group. The younger age groups, under 50 years, had much lower caries rates than for the Kenya group with less than 40% of molars affected. This increased to more than 60% in the oldest 70+ year group. The proportion of premolars and anterior teeth rose steadily with increasing age to 20-40% in the same oldest group. At all ages, enamel lesions were less common than in the Kenya study. Except in the youngest 20-29 year group, most lesions penetrated the dentine or pulp, or were root lesions (and thus would also have penetrated dentine). In the 70+ year age group only a small minority of lesions was confined to the enamel, mainly in the molars. These trends were shown both in the upper and lower dentitions, but a higher proportion of upper teeth was carious, particularly the anterior teeth. Overall, the caries rate in women was slightly higher than that in men.

Luan et al. (1989) also plotted root surface caries separately for their China study, for each tooth in the dentition and for each age group, with plots for buccal, lingual and interproximal sides of the teeth. On the same graph, they plotted the proportion of root surfaces which were exposed and therefore at risk of root caries, and the proportion of roots surfaces which were both exposed and had a carious lesion. Once again, this has become the accepted way to present root caries data. The proportion of exposed root surfaces increased steadily with age so that, in the oldest 70+ year group, 80-100% of buccal surfaces were exposed in all teeth. Molars were more strongly affected than premolars and anterior teeth, although the proportion of the latter teeth with exposed roots increased strongly with age so that they were more nearly equal to the molars in the oldest group. For buccal and interproximal root surfaces, the upper teeth were more strongly affected than lower, particularly in the younger groups. For lingual surfaces, the opposite was true. Exposed root surfaces with carious lesions increased with age, but only a small proportion of exposed surfaces became carious. In addition, the lesions were not strongly related to the pattern of root exposure – the teeth with most frequently exposed roots did not necessarily show the highest root caries rates.

In general, the pattern of caries through the dentition and with age is rather similar in the Kenya and China studies. They are very different parts of the world, with a contrasting background in climate, foodstuffs and social conditions. It is supporting evidence for the idea that caries progresses in a similar pattern (even if the rate may vary) through the dentition (Thystrup and Fejerskov, 1994), and with age, in most 20$^{th}$ century populations with a nutrition based on carbohydrates, including both starches and sugars. In this context, it is reasonable to compare the Coimbra study with them.

In the Coimbra study (Figs. 2 and 3, Tables S-2 and S-3), the proportion of teeth missing ante-mortem at each potential tooth position in the dentition rose much more sharply with age than in the Manji et al. (1989) Kenya study. In age group 5 (60-69 year), approximately 80% of Coimbra molars were missing ante-mortem, whereas some 40% of the Kenya molars in the 55-64 year age group were missing. For Coimbra, as the surviving teeth decreased in number, the proportion of tooth positions occupied by a carious tooth also fell off more sharply in the older age groups than was the case for Kenya, although the effect is emphasized by the inclusion of an older 70-79 year age group 6 for Coimbra. Equivalent data were not published for the China study, so no comparison can be made.

When the surviving teeth are considered without ante-mortem tooth loss for the Coimbra study (Figs. 4 and 5, Table S-4), the picture is very different. In the youngest age group 1 (20-29 year), some 40-80% of molars had carious lesions, which compares well with Kenya. Both studies had a higher proportion of affected molars than the China study in the youngest group. The Coimbra study, however, showed a much higher proportion of anterior teeth and premolars with carious lesions in group 1 than either the Kenya or China studies. As in the Kenya study, the proportion of the Coimbra molars affected by caries remained at a similar level for older age groups, whereas the proportion of premolars and anterior teeth affected rose with age up to age group 5 (60-69 years), with a slight fall to group 6 (70-79 years). Lesions penetrating the dentine were more common in the Coimbra study than Kenya or China but it was similar to Kenya in the smaller proportion of lesions exposing the pulp chamber. The China study showed a much more marked rise of dentine and pulp exposing lesions with age.

Exposure of root surfaces showed a similar pattern in the Coimbra and China studies, with molars slightly more affected than anterior teeth and a pronounced increase in older age groups (Table 6, Figs. S-1 and S-2). In both, the proportion of exposed surfaces with a carious lesion was relatively small with no clear pattern to the distribution of lesions. For Coimbra, the proportion of carious surfaces is larger, approximately double that of the China study.

It is now possible to address the first five research questions outlined above:

1. The results of the Coimbra study are consistent with the most appropriate studies available for caries in living adults, conducted some 60-80 years after the Coimbra people died. The results are most like those of the Kenya study and in other respects they fit between the Kenya and China findings.

2. The pattern of caries around the dentition in the Coimbra study is similar to both Kenya and China, with the molars most affected, anterior teeth least and premolars in an intermediate position. It departs mainly in the larger proportion of anterior teeth affected by caries. In older age groups, this might be related to the pattern of ante-mortem tooth loss (below). There were also more dentine lesions in all age groups than in the modern studies. This might possibly reflect the relationship between poor health and caries, as a death assemblage is likely to contain individuals with a poorer record of health than the living populations as a whole.
3. There was a strong progression with age-at-death, following a similar path to that seen in the Kenya and China studies. Not only did carious lesions become more common, but they became more deeply penetrating and more anterior teeth were involved. Once again, the death assemblage results are consistent with studies on the living. The results make it clear that both age progression and distribution of carious lesions in the mouth are just as important to consider in archaeological studies as they are in studies of the living.
4. Ante-mortem tooth loss was more strongly marked in the Coimbra study than in either the Kenya or the China study. As with both of these, it affected the molars more than the premolars or anterior teeth and showed a marked progression with age. Post-mortem tooth loss was not marked but affected particularly the single-rooted anterior teeth. The pattern of caries through the dentition may have been affected by ante-mortem tooth loss, with anterior teeth surviving preferentially in the older groups and thus showing higher caries rates simply because they were the only teeth in the mouth. It might be expected that the preferential post-mortem loss of anterior teeth would reduce this effect, but it is difficult to unravel the two phenomena.

5. The differences in caries rates between men and women are small, both in the Coimbra study and in the Kenya and China studies. There is some variation between different types of lesion and different age groups, but where there is a significant difference it is generally the women that have slightly higher rates. The similarity between the results suggests that the nature of the death assemblage had little effect on them.

It would be interesting to compare the figures presented here with caries distribution in modern Portugal. It is presumed that, given the increasing availability of dental care over the last decades, there would be some differences. Unfortunately, this will have to wait until there are Portuguese epidemiological studies that follow caries into adult life.

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