Deciduous enamel 3D microwear texture analysis as an indicator of childhood diet in medieval Canterbury, England

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Abstract

This study conducted the first three dimensional microwear texture analysis of human deciduous teeth to reconstruct the physical properties of medieval childhood diet (age 1-8yrs) at St Gregory's Priory and Cemetery (11th to 16th century AD) in Canterbury, England. Occlusal texture complexity surfaces of maxillary molars from juvenile skeletons (*n*=44) were examined to assess dietary hardness. Anisotropy values were calculated to reconstruct dietary toughness, as well as jaw movements during chewing. Evidence of weaning was sought, and variation in the physical properties of food was assessed against age and socio-economic status. Results indicate that weaning had already commenced in the youngest children. Diet became tougher from four years of age, and harder from age six. Variation in microwear texture surfaces was related to historical textual evidence that refers to lifestyle developments for these age groups. Diet did not vary with socio-economic status, which differs to previously reported patterns for adults. We conclude, microwear texture analyses can provide a non-destructive tool for revealing subtle aspects of childhood diet in the past.

Keywords

Dental microwear; medieval childhood diet.

1. Introduction.

Human diet during the 11th to 16th century in medieval England is best understood for adults, higher status families, or ‘closed-communities’ such as monastic settlements (Dyer, 2000: 83; Slavin, 2012: 8; Woolgar, 2010). Knowledge of childhood diet during this period is generally more limited because it was not a focus for medieval writers. Although limited, there is some historical textual evidence that provides weaning and other childrearing advice related to food consumption (Fildes, 1986: 213, 1988: 76). A few isotopic studies have also reported dietary weaning age and subsequent protein consumption for medieval village and urban centres in the north of England (Burt, 2013, 2015; Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002), but not for the south-east. Neither is anything known about the physical properties (hardness, toughness) of medieval childhood diet.

Here, we conduct the first intra-specific three dimensional (3D) dental microwear texture analysis (DMTA) of human deciduous teeth to reconstruct the physical properties of childhood diet in medieval Canterbury, south-east England (Fig.1). DMTA is a non-destructive methodology that provides evidence of the hardness and toughness of foods eaten by an individual (Scott et al. 2005, 2006; Ungar et al., 2003) in the days and weeks preceding death (Grine, 1986). For example, dietary hardness and toughness has been reconstructed from DMTA of permanent tooth enamel for archaeological samples of hunter-gatherers, fossil hominins, and Neanderthals (El Zaatari et al., 2011, El Zaatari and Hublin, 2014; Schmidt et al., in press; Ungar et al., 2008a, 2010). However, few studies have examined microwear surfaces of deciduous enamel (e.g., Bullington, 1991). Our study is the first to apply the 3D methodology to human deciduous teeth.

1.1 Childhood diet in Medieval England

Physicians in sixteenth century Europe advised the introduction of mixed-feeding (gradual introduction of non-milk foods leading to a relative decrease in the contribution of breast milk to total diet: Humphrey, 2014) between seven to nine months of age (Fildes, 1986: 245). Historical records from this period indicate that a child was finally weaned (removal of breast milk) between 12-18 months (Fildes, 1986: her Table 15.3-4; 1995: her Table 4.7). This latter age range is compatible with isotopic evidence from the medieval village of Wharram Percy and the urban Fishergate House cemetery in the north of England, which suggests weaning occurred in the second year after birth (Burt, 2013, 2015; Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002).

Pap (flour, milk, egg yolk) or panada (bread in broth with butter or oil) were popular supplementary foods during mixed-feeding (Fildes, 1986: 213; Orme, 2003: 71). Insights into early childhood diet after mixed-feeding have been gained from historical textual accounts. Grain products were an important component of medieval diet (Slavin, 2012: 169; Stone, 2006:11), and bread with butter, porridge, and gruel, were typical early childhood foods (Orme, 2003: 71-72). However, little is known about dietary variation with age. Isotopic evidence from Wharram Percy indicates that children may have consumed a post-weaning diet that that was lower in protein compared to older individuals (Richards et al., 2002).

Socio-economic status could determine the quality, variety, and type of foods consumed by adults (e.g., Dyer, 2006: 201-9; Powell et al., 2001: 298; Woolgar, 2006: 196; Woolgar et al., 2006: 270). Outside of periods of religious observance (primarily Advent and Lent) wealthier lay households and monastic communities regularly consumed meat, but other than pork, it contributed less to the peasant diet (DeWitte and Slavin, 2013; Dyer, 2000: 84-86; Powell et al., 2001: 308). Higher social strata preferred white bread made from wheat, while those of lower socio-economic status usually consumed coarser whole grain bread (Campbell, 2010; Stone, 2006: 17; Slavin, 2012: 180).

It is unclear if the relationship between adult status and food consumption extends to children from this period (Burt, 2013). In medieval York, lower status children consumed higher status and more expensive foods after weaning (Burt, 2015). Furthermore, a study of gross dental wear on deciduous teeth from medieval sites in the south of England, including Canterbury, reported no differences between higher and lower status burials of similarly aged children (Dawson and Robson Brown, 2013). Thus, the relationship between food consumption and status for children in this period might be more complex than that reported for adults.

1.2. Study Aims

This study conducts the first intra-specific microwear texture analysis of human deciduous teeth to reconstruct the physical properties of childhood diet in Medieval Canterbury (Fig. 1). All dental samples were from human juvenile skeletons (*n*=44) aged between one to eight years of age, which were recovered during excavation of St Gregory's priory and cemetery (11th to 15th Century AD) in Canterbury (Hicks and Hicks, 2001). The site is unique in south-east England as it contained a large number of well-preserved juveniles. It has two burial areas, a priory and a cemetery, which correspond with higher and lower socio-economic status respectively (see section three).

The *study aims* are, 1) to search for microwear evidence of dietary weaning in the youngest children. 2) Determine if variation in the physical properties of diet correlates with age. 3) Compare microwear from those buried in the higher status priory to those buried in the lower status cemetery. Prior to these analyses, we conduct a preliminary experimental study to explore microwear texture formation processes on human deciduous enamel compared to permanent enamel.

1.3. Dental microwear texture analysis

Microscopic wear in the form of scratches and pits is laid down on the occlusal surface of tooth enamel as hard particles are sheared between or compressed into opposing crowns as the jaw moves through the chewing cycle (Gordon, 1982). Food contaminated by grit that is harder than enamel, such as quartz inclusions, is one microwear causal agent (Lucas et al., 2013; Peters, 1982; Teaford and Lytle, 1996). Two dimensional (2D) dental microwear analyses have been used since the 1950's to explore jaw movements of extinct mammals and modern humans (Butler, 1952; Dahlberg, 1960; Mills, 1955). Subsequent 2D studies described microwear patterns by their frequency, size, and orientation in extant and fossil mammals (Grine, 1981; Puech, 1979; Walker, 1976; Walker et al., 1978) leading to a range of quantitative studies that sought to infer aspects of diet in past human populations (e.g., Mahoney, 2006; Pastor, 1993; Schmidt, 2001; Teaford et al., 2001). Methodological developments led to DMTA, the 3D characterization of microwear surfaces (Scott et al. 2006). This automated quantification of microwear in three dimensions minimizes inter-observer measurement error (Grine et al., 2002), and thus holds great potential for the future of dietary reconstruction in an archaeological context.

Dental microwear texture analysis is based upon the principle that an enamel surface can look different when observed at different scales. A surface may appear smooth when observed at a coarse scale but can appear rough at a finer scale. The texture of an enamel surface can be quantified in three dimensions by combining white-light confocal profilometry with scale-sensitive fractal analysis (Scott et al. 2005, 2006; Ungar et al., 2003). In this study we focus upon two texture variables that have been previously related to dietary hardness and toughness in extant primates:

- Area-scale fractal ***complexity*** (Asfc) (Scott et al., 2005). Values for complexity measure changes in surface topography across different scales. Enamel with pits and scratches of different sizes superimposed onto each other, or a surface that is heavily pitted, would typically have higher complexity values (Ungar et al., 2008b, 2010). Consumption of hard abrasive foods, which are 'crushed' between opposing enamel surfaces, and correlated with frequent dental pits in 2D microwear analyses (Teaford, 1985; Teaford and Walker, 1984), tends to produce relatively higher Asfc values (and lower levels of anisotropy) in some primate hard seed and hard fruit eaters (Scott et al., 2005, 2006, 2012). Thus, a tooth surface that is dominated by dental pits with a high Asfc value has been used to infer a hard and abrasive diet (Scott et al., 2012; Ungar et al., 2010).

- Exact proportion length-scale ***anisotropy*** (epLsar) (Scott et al., 2005). Values for the anisotropy of microwear texture surfaces measure the orientation of surface features. Enamel dominated by scratches all orientated in the same direction produces a high anisotropy value (Ungar et al., 2008a). Low anisotropy values indicate low similarity in wear feature orientation. Tougher foods which are 'sheared' between opposing enamel surfaces, and correlated with frequent dental scratches in 2D microwear analyses (Teaford, 1993; Teaford and Walker, 1984), can produce comparatively higher epLsar values (and lower levels of Asfc) in some primate species that consume leaves, stems and other tough fibrous foods (Scott et al., 2005, 2006, 2012). Therefore, enamel covered with scratches mainly orientated in the same direction with a high epLsar value has been used to infer consumption of tough abrasive foods (Scott et al., 2012; Ungar et al., 2010). Jaw movement also has been reconstructed from dental scratches (Butler, 1952; Gordon, 1982; Scott et al., 2006; Young and Robson, 1987), whereby high epLsar values indicate more consistent rather than varied jaw movements during chewing (Ungar et al., 2010).

While texture values within a species are variable, and texture surfaces for harder or tougher diets will often overlap (Strait et al., 2013), the key correlations between microwear and the physical properties of a diet established in the 1980s (Teaford, 1985; Teaford and Oyen, 1989; Teaford and Walker, 1984), have been confirmed more recently in studies of texture surfaces from mammals, and in experimental studies (e.g., Schubert et al., 2010; Schultz, 2013, Xia et al., 2015; Hua et al., 2015). Thus, DMTA distinguishes between extant primates of known diet, and these correlations provide a base-line from which to infer diet in historic and pre-historic populations.

1.4 Potential sources of deciduous microwear texture variation in Medieval Canterbury.

Breast feeding will produce no microwear and the introduction of abrasive foods should produce tooth wear. After weaning, flour prepared using traditional milling methods could introduce hard abrasive grit into cereal foods, which has been identified as a source of microwear in 2D studies (e.g., Teaford and Lytle, 1996). In medieval Canterbury, cereal foods such as these came from regional farmlands, demesnes, and local grain traders (Campbell, 2010; Slavin, 2012: 52-55, 2014). During the Middle Ages, grain was ground and prepared for consumption by local mills in Canterbury, one of which was owned by St. Gregory's priory (Hastead, 1800; Somner, 1703). Mills in medieval Kent often used limestone and sandstones querns for milling (Farmer, 1992; Keller, 1989), which can introduce a residue of grit into foods (Teaford and Lytle, 1996).

Consumption of meat can alter microwear texture surfaces (El Zaatari, 2010). 19th century Fuegian hunter-gatherers with a diet that consisted mainly of meat had a lower mean Asfc but higher epLsar value, relative to other hunter-gatherer populations (El Zaatari, 2010). Chewing tough meat that contained some abrasives would require repetitive shearing motions of the jaw, leading to many scratches orientated in the same direction. The consumption of meat in medieval England varied by status amongst adults (above). If childhood status, or age, also determined access to meat, then this might contribute variation to epLsar values amongst the Canterbury children.

Beyond hard and abrasive, and tough foods, there are several other potential microwear formation processes that should be considered when interpreting deciduous enamel textures. First, bite force potential will differ significantly between younger and older children, as the muscles of mastication gain size and strength (Kamegai et al., 2005). As such, more force exerted during chewing would provide more opportunity for hard particles to be driven into enamel as microwear accumulates for the first time. Thus, variation in microwear texture surfaces between children of different ages might relate in part to differences in bite force. Lateral movement of the mandible will also increase with age, as the mandible increases in size. Greater lateral movement, as the mandible moves through the chewing cycle, might produce longer scratches, though this would not necessarily alter an anisotropy value.

‘Teething’, and the use of pacifiers by young children, could contribute microwear that was unrelated to diet. Dental eruption in humans typically commences around the sixth post-natal month as deciduous central incisors emerge through the gum line (Hillson, 2014: his Table 4). The second molar is the last deciduous tooth to erupt, usually towards the start of the third post-natal year (Hillson, 2014: his Table 4). Infants biting on pacifiers might scratch the enamel surface. For example, in medieval England, a child might be given a piece of coral during teething (Hanawalt, 1993:52). This potential source of microwear is more likely in younger infants, and more likely to accumulate on early erupting incisors. Selecting later erupting teeth can reduce the potential for pacifiers to obscure a diet-microwear relationship.

2. Preliminary experimental study

The efficacy of DMTA as an indicator of the physical properties of diet has been demonstrated numerous times using adult permanent teeth (see Section 1.3). Its value, however, has not been demonstrated to the same extent on deciduous teeth. Would a single microwear formation process produce similar microwear texture values for both deciduous and permanent enamel? Or instead, would these two enamel types differ in an unexpected way when exposed to the same formation process. For example, deciduous enamel is more porous and relatively softer than permanent enamel (e.g., Wilson and Beynon, 1989). To investigate microwear formation processes on deciduous relative to permanent enamel we undertook an experimental study before we examined microwear texture surfaces of juveniles from St Gregory's priory and cemetery.

Complexity and anisotropy values were calculated for thirteen deciduous incisors. The deciduous teeth were experimentally abraded, complexity and anisotropy values were re-calculated, and compared to those from before the experiment. We repeated the experiment on six permanent premolars, and compared the results to the deciduous teeth.

2.1. Samples

Thirteen deciduous mandibular incisors were donated by former students to the Indiana Prehistory Laboratory, University of Indianapolis, knowing these teeth would be used in wear experiments. These teeth were included in the experimental study because the labial surface of each tooth showed no signs of gross dental wear. The six permanent maxillary premolars were from an early 20th century cemetery population in Indiana. The premolars were selected because the mesial surface of each tooth was unworn. There was no reason to suspect that the enamel microstructure of the dental samples used in the experimental study would influence microwear formation processes in a way that would differ to the dental samples from Canterbury.

2.2 Experimental procedures

Microwear preparation and analytical procedures are described in section four. Before each tooth was experimentally abraded, a target area was identified, and the complexity and anisotropy of that area was recorded. The same target area was then abraded experimentally and the texture values were recorded again. Thus, we produced “before” and “after” experimental data sets.

One tooth was fixed to a square metal block weighing 1.1 kg using industrial adhesive fixing tape. The tape was folded over the block, and over the tooth cervix and root. Each tooth was positioned so that a relatively flat surface would be scratched. For premolars, that was on the mesial aspect of the tooth. For incisors, it was the labial surface just inferior to the incisal margin. The orientation of rods relative to the enamel surface can influence enamel resistance to abrasion (Rensberger, 2000: his Fig 18.7), but the rod orientation in the target area for both tooth types is similar. The block, with attached tooth, was placed onto a piece of abrasive paper with a 200-grit size (Buehler©) that had been taped to a flat table-top. We chose a grit size of 200 rather than a finer grit size to maximise scratch formation. Only the tooth surface contacted the abrasive paper. The metal block was balanced by hand and pulled across the length of the paper for a distance of 20 centimetres, taking approximately three seconds. A square wooden block was placed next to the abrasive paper and used as a guide to ensure that the distance travelled by the metal block was in a straight line. Each tooth was abraded once. This process produced wear facets that were visible to the naked eye; most were approximately one to two millimetres in diameter.

We tested the null hypothesis that there would be no difference between the complexity and anisotropy post-experimental abrasion values from deciduous enamel, when compared to permanent enamel, using a Mann Whitney U test.

2.3 Experimental results

Table 1 shows the experimentally induced microwear texture values. Mean Asfc increased by 5.25 for deciduous teeth, and by 4.64 for permanent teeth, from before to after the experimental abrasion. Mean anisotropy increased by 0.0053 for deciduous teeth, and by 0.0062 for permanent teeth, from before to afterwards. The post-experimental complexity and abrasion values did not differ significantly when compared between deciduous and permanent teeth (p= 0.844, p=0.116, respectively). Therefore, the null hypothesis was retained.

Table 1
Mean experimentally induced microwear texture values.

	Deciduous (n)			Permanent (n)		
	Before	After	Increase	Before	After	Increase
Complexity Asfc	1. 30 (13)	6.55 (13)	5.25	1.69 (6)	6.33 (6)	4.64
Anisotropy epLsar	0.0031 (13)	0.0084 (13)	0.0053	0.0012 (5)	0.0074 (5)	0.0062

2.4 Discussion of experimental results

The experimentally created wear was statistically indistinguishable when compared between deciduous and permanent teeth, indicating that microwear forms in a similar way when these two enamel types are subjected to the same force applied in the same direction. However, there were slight differences in the mean values from the two enamel types. Deciduous enamel accumulated a slightly more complex surface with fewer similarly orientated scratches during the course of the experiment, relative to permanent enamel. We observed that incisor enamel surfaces touching the abrasive paper were more curved compared to premolars. So, these slight differences in the degree to which the microwear values changed could be an artefact of this experiment, as force would have been applied to a smaller area on the incisors compared to the premolars. Future studies can explore this in more detail, to determine if facet size plays a key role in microwear formation. Overall, it is clear that deciduous and permanent enamel produce similar microwear texture surfaces when subjected to the same force applied in the same direction.

2.5 Limitations of experimental study

Results from the experimental study underscore the efficacy of the DMTA variables employed here. However, other DMTA variables commonly used in studies of dietary inference were not examined. Scale of maximum complexity, textural fill volume, and heterogeneity are yet to be analysed. Moreover, our study only included experimental wear generated in a single direction with a single force. It may be possible that a threshold exists whereby extreme force, or the direction of a force, can distinguish between adult and deciduous microwear texture surfaces.

3. Study samples

3.1. St Gregory Priory and Cemetery

The archaeological site is located about 300 meters north of present day Canterbury Cathedral just outside the medieval city wall (Fig. 1). It was in use from the mid-11th to early 16th century, and was excavated between 1988-1991 (Hicks and Hicks, 2001: 1-146). The priory was founded by the Archbishop of Canterbury, Lanfranc, in AD 1084 (Sparks, 2001: 371). Originally it was served by priests, and subsequently by Augustine cannons, who cared for the sick at nearby St John's hospital and provided free burial for the poor in the cemetery (Brent, 1897; Duncombe, 1785; Somner, 1703; Sparks, 2001: 371).

All skeletons were previously excavated (Anderson and Andrews, 2001: 338-370). A total of 91 burials were recovered from inside and around the priory, which included a male with a chalice and a gold-embroidered monastic-like garment suggesting this was a burial location for clergy (Anderson and Andrews, 2001). However, the presence of children and adult females within the priory indicates that this was not a 'closed' monastic community. Instead, these were members of wealthier families (Hicks and Hicks, 2001), who paid for the prestigious burial location, which was a popular way of displaying socio-economic status for wealthy lay people in this period (Daniell, 1997: 96-97).

The cemetery was established just before the priory (Sparks, 1988: 31), and a total of 1342 skeletons were recovered during excavation. Historical textual records indicate that the cemetery served poorer families from local parishes, people who could not afford burial fees, and patients from nearby St. John's hospital (Brent, 1879; Somner, 1703). It was in constant use until a few years after the priory was dissolved in the 16th century (Sparks, 1988: 32, 2001: 376).

4. Materials and methods

4.1 Sample selection

Microwear values were produced for deciduous maxillary first and second molars from 44 juvenile skeletons aged one to eight years. These skeletons were selected because they retained the skeletal elements needed to estimate age-at-death. We focused upon maxillary molars because they have thicker enamel (Mahoney, 2013), that (usually) has relatively less gross wear compared to their mandibular isomeres. This was important as dentin microwear was not a focus of the present study. The molars selected were also suitable for cleaning and casting for microwear. Microwear values were subdivided into age groups, which were created from skeletal age-at-death (see below) and the timing of dental eruption (Table 2).

Two juvenile skeletons from the priory dated to the earliest Lanfranc period (11th century). The microwear Asfc and epLsar values for these individuals were within the range of microwear values for juveniles from the priory which dated to the 14th-16th centuries. Following this, microwear values were treated as one time period for subsequent analyses. The cemetery burials were not sub-divided by century during excavation.

Table 2
Deciduous microwear samples

n	Age in yrs	Tooth type[1]
7	1-2	Udm1
16	2.1-4	Udm1, Udm2
14	4.1-6	Udm1, Udm2
7	6.1-8	Udm1, Udm2

[1] Udm1 = maxillary first molar. Udm2 = maxillary second molar

4.2 Preparation and microwear texture data

All teeth were prepared in the Human Osteology Research Lab, University of Kent, using standard methods (e.g., Mahoney, 2006; Nystrom et al., 2004; Schmidt, 2001). The occlusal surface of each tooth was cleaned using 95% ethanol and cotton wool. Impressions of phase II facets were taken using a rubber-based addition-curing silicone (Colténe-Whaledent Lightbody President Jet®). The first impression was discarded and a second impression was taken and used to create the cast. The dental impression was set into dental putty (Colténe-Whaledent, President Putty®). An epoxy resin and hardner (Buehler EpoxiCure®) was poured into the impression to produce a cast of the occlusal surface.

Microwear texture data were produced in the Indiana Prehistory Lab, University of Indianapolis. Resin dental casts were examined using a Sensofar® White Light Confocal Profiler at a magnification of 100x. The microscope collected data from four contiguous areas totalling 276 x 204μm^2. After digitally stitching the original four areas together, the final study area was 242 x181μm^2. Data came from Phase II wear facets (usually facet 9). Data cloud manipulation was undertaken using Sensoscan® software, where the data were levelled and non-microwear entities (primarily any remaining dirt) were removed. Analysis of the data cloud required the use of Sfrax® and Toothfrax®, which are scale-sensitive fractal analysis programs customized for dental microwear texture analysis. Microwear variables Asfc and epLsar were recorded as scale-dependent relative values (Scott et al., 2006).

4.3. Estimating age-at-death

For the one child aged 1 year, we estimated age-at-death using enamel formation times (Mahoney, 2011). For the rest of the children we used a combination of enamel formation times (Moorrees et al., 1963a,b), timing of dental eruption (Schour and Massler, 1941; Al-

Qahtani et al., 2010), long bone length (Hoppa, 1992; Scheuer et. al., 1980), and fusion of cervical vertebra (Scheuer and Black, 2000).

4 .4. Statistical analyses

The distribution of each microwear variable for each childhood age group (1-2, 2.1-4, 4.1-6, 6.1-8yrs) was checked with a one sample Kolmogorov–Smirnov test and did not differ significantly from a normal curve. However, sample sizes were unequal. Thus, microwear was compared between the four age groups using a non-parametric Kruskal-Wallis test. Multiple post-hoc pair-wise comparisons of the age groups were undertaken using a Tamhane-2 test. Microwear was compared between the two status groups using a Mann Whitney U test.

5. Results

Microwear descriptive statistics are summarized in Table 3. Figure 2 illustrates microwear texture surfaces. A Kruskal-Wallis test revealed that the complexity of microwear surfaces differed significantly between the four childhood age groups (H=9.037, *p*=0.029), but anisotropy did not (H=6.572, *p*=0.087). Post-hoc tests of pair-wise mean differences using the T2 statistic indicates that children aged 4.1-6 years of age had a significantly lower mean complexity value compared to younger (aged 2.1-4yrs; *p*=0.017) or older children (6.1-8yrs; *p*=0.011). Microwear did not differ significantly between higher and lower status children within the age group 2.1-4yrs, or within the age group 4.1-6 yrs.

Table 3
Deciduous microwear mean values

			Asfc		epLsar	
		n	mean	sd	mean	sd
Group	Age					
a	1-2	7	1.81	0.57	0.0039	0.0019
b	2.1-4	16	2.14	0.61	0.0029	0.0016
c	4.1-6	14	1.63	0.43	0.0033	0.0014
d	6.1-8	7	2.25	0.41	0.0019	0.0010
e	1-8	44	1.95	0.57	0.0030	0.0016
Group	Status[1]					
b	lower	12	2.09	0.58	0.0028	0.0017
b	higher	4	2.28	0.80	0.0036	0.0007
c	lower	9	1.74	0.54	0.0030	0.0015
c	higher	5	1.53	0.31	0.0040	0.0007

[1] Lower = cemetery; higher = priory.

6. Discussion

6.1. Weaning amongst one to two year olds.

Microwear was present on molars from seven children in this age group (Table 3). The presence of microwear suggests that mixed-feeding, at least, had commenced. On average, their molar surfaces had a low Asfc and higher epLsar value, which is usually associated with the consumption of tougher foods amongst extant primates (section 1.3). Therefore, at first glance, there appears to be discrepancy between the microwear and the type of diet consumed by the youngest children, as textual accounts indicate that a soft and limited range of foods, such as pap or panda (Orme, 2003:71) would have been consumed. However, a high epLsar can also be indicator of jaw movements during chewing (Ungar et al., 2010). On average, the one to year olds had the most anisotropic texture surfaces compared to all other childhood groups. Thus, the orientation of their microwear was the most organized, reflecting the fewest changes in jaw direction during chewing. This makes sense, when viewed alongside the limited range of foods consumed by this age group. The low mean complexity value for the youngest children, relative to the 2.1-4yr olds, more likely represents the consumption of soft foods (Scott et al., 2012). Flour in pap or panda, contaminated during the milling process is one potential source of the abrasive particles that caused microwear for this age group.

The youngest infant with microwear was aged 1 year, which implies that mixed-feeding might have commenced slightly earlier for some children in Canterbury, compared to children from the contemporary Fishergate House cemetery in the north of England where breast milk continued to be a significant part of the diet until age 18 months (Burt, 2013, 2015). However, there is no change in microwear throughout the course of the year, which might have indicated a transition from mixed-feeding to fully weaned. Instead, a child aged 1.25 years had a similar complexity value compared to another aged 1.75 years (Asfc= 1.71 and 1.69 respectively). This may simply reflect a gradual change in feeding practices that is not detectable from microwear. Alternatively, breast-feeding might have been completely removed from the infant diet at or around the start of the second year after birth. If this was the case for the Canterbury children then their weaning age would lie within the lower end of the age-range recommended for weaning in texts from the period (Fildes, 1995: 115). It would also lie within the lowermost end of the weaning age-range indicated by isotopic studies at contemporary Wharram Percy in the north of England, where breast-feeding ceased between one to two years of age (Mays et al., 2002).

6.2. Variation in diet with age

Dental microwear texture analysis results suggest that the physical properties of diet for children in medieval Canterbury varied from one age group to the next.

6.2.1. Two to four years of age.

Children aged two to four display an increased mean complexity of enamel surfaces combined with a lower mean anisotropy, relative to one to two year olds. When this combination of microwear features are compared with the base-line texture surfaces from extant primates (section 1.3), it implies that the Canterbury children in this age group consumed a range of foods that included relatively harder and more abrasive items. These texture surfaces might be expected, as their diet was probably no longer focused upon just soft infant foods like pap and panda. A more varied diet is also suggested by the lowered mean anisotropy value, indicating that jaw movements were more disorganized during chewing. Increased bite force relative to the infants (Kamegai et al., 2005) might be a factor here as well, driving hard particles deeper into the enamel surface leading to a higher complexity value.

6.2.2. Four to six years of age.

There was a significant change in the physical properties of diet amongst children in this age group. The four to six year olds had significantly less texture complexity than either younger (2.1-4yrs) or older (6.1-8yrs) children. The lowered complexity was matched by a higher mean anisotropy value, which approached significance when compared to the less anisotropic enamel from the 6.1-8 year olds. This combination of microwear features, lower Asfc and higher epLsar (section 1.3), implies that the diet of children in medieval Canterbury had altered, and now included tougher foods.

A change in diet between age four to six could relate in part to a period in which childhood routines started to change (Bailey et al., 2008; Hanawalt, 1977: 64). Greater mobility allowed children to accompany adults outside of their home and into the work place, paradoxically leading to more time spent in adult company (Flemming, 2001; Hanawalt 1977, 1988:158). More time in adult company may have given more access to adult dietary staples, such as a meat or vegetable pottage (e.g., Brears, 2008). A greater component of meat in the diet of the Canterbury children might explain the change in microwear (e.g., El-Zaatari, 2010), especially if this was a permanent supplement to early childhood foods.

Support for the idea that children in this age group accessed 'tougher' adult dietary staples, rather than returning to a soft diet similar to the infants, is provided by examining their bite force potential. Children in this age group would have exerted significantly more force during chewing compared to the one to two year olds (Kamegai et al., 2005). If the change in the microwear pattern of the four to six year olds occurred because they re-accessed a soft infant diet, whilst for example caring for a younger sibling (Hanawalt, 1988: 157), then you would expect the enamel of the older children to have a higher complexity value, as abrasive particles from the shared foods would have been driven deeper into their enamel. This idea is not supported by the mean microwear texture values, which show that the older children had a lower, not a higher mean Asfc value, relative to the infants. Neither does 'teething' nor a 'sick-bed' diet seem likely causal agents. All deciduous teeth would have erupted by around the age of 2.5 years, so pacifiers would not have contributed to the microwear of this age group, or to the preceding age group. A sick-bed diet would not necessarily contribute to the microwear of only this age group.

6.2.3. Six to eight years of age.

Children in this age group had the roughest texture surfaces with many pits and scratches of different sizes overlying each other. The scratches were the least orientated compared to all other childhood age groups, leading to the lowest epLsar value. The reduced range of complexity and anisotropy values for this group indicates that fewer children deviated away from the rough and disorganized wear features. If the tougher diet of the preceding age group marks the introduction of 'adult foods', then the increase in food hardness in the eldest children might indicate the addition of hard 'adult' foods. This idea is supported by historical textual accounts. From around the age of seven onwards children were treated increasingly like young adults and were given independent tasks outside of their home (Hanawalt, 1977, 1988: 158; Fleming, 2001: 64), including apprenticeships or employment as household servants (Bailey et al., 2008; Dunlop, 1912). It might be expected therefore, that this change in a child's social network would provide reduced opportunity for a distinct childhood diet as they entered a new environment.

6.3. Childhood status and diet

Mean complexity and anisotropy values for children aged two to four years, or four to six years of age, did not vary consistently with status (Table 3). This finding lends support to the idea that the relationship between status and food consumption for medieval children might be more complex compared to adults (Burt, 2013, 2015; Dawson and Robson Brown, 2013).

7. Conclusion

This study conducted the first 3D intra-specific dental microwear texture analysis of childhood diet. We searched for evidence of dietary weaning, evaluated variation in the physical properties of diet against age, and compared higher with lower status children. Results indicate that mixed-feeding in Canterbury could commence by the end of a child's first year. After weaning, and until the age of eight, there was no simple trajectory in the physical properties of the foods that were consumed in the weeks before death. Diet contained abrasives for all age groups. Texture surfaces indicated that, on average, the four to six year olds consumed a diet that included tough foods whilst the eldest children consumed the hardest diet. We related these changes in microwear texture surfaces to medieval textual records that refer to lifestyle developments for these age groups. Our study also lends support to the idea that the relationship between socio-economic status and diet for children in medieval England might not be as clear as it is for adults. We conclude that deciduous dental microwear texture analyses hold great potential for revealing very subtle changes to childhood diet in the past.

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Fig.1. Map of United Kingdom showing Medieval Canterbury in AD1703 (after Somner, AD1703). Dental samples were from juvenile skeletons recovered during excavation of St Gregory's priory and cemetery. See Section 3.1.

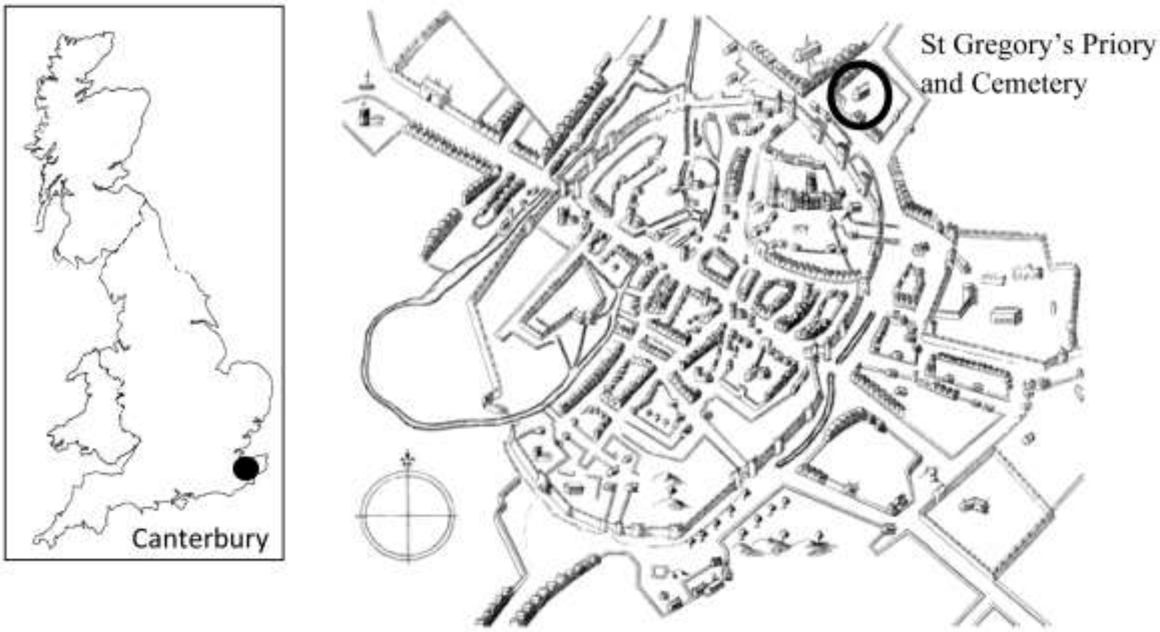

Fig.2. Bivariate box plot (**A**) subdividing each age group in Table 3 into quartiles, with dental microwear texture images showing 3D representations of molar enamel surfaces from two children in the cemetery. Each image represents a field of view measuring 242 x 181μm^2. Changes in colour indicate changes in depth. (**B**) When many pits and scratches are present together, or overlying each other, they produce a ‘rougher’ surface and a higher complexity value. The more complex surface of the 6.1-8 year olds, combined with a relatively low anisotropy value **(C)**, implies that they had a harder diet compared to the 4.1-6 year olds. Their anisotropy value is low because scratches (lower right to upper left corner; lower surface to upper right corner) are not orientated in the same direction.