Volume 35, Issue 01, 2022 ISSN 1096-9411 (print) / 2769-822X (online)

Dental Anthropology

A Publication of the Dental Anthropology Association

Dental Anthropology

Volume 35, Issue 01, 2022

Dental Anthropology is the Official Publication of the Dental Anthropology Association.

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Published at
University of Nevada, Reno
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A Contextualized Enamel Growth Rate and Thickness Data Set Collected from British Populations Spanning the Past 2,000 Years

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Keywords: enamel thickness, daily secretion rates

ABSTRACT This article represents an open repository of human enamel data collected/reconstructed from seven populations covering a 2,000 year time period in Britain via five temporally distinct periods. In total, data were collected from 285 permanent teeth, including maxillary and mandibular first molars, and maxillary canines and first incisors. Data were gathered through thin histological methods using standard procedures for sectioning human dental material. In regards to enamel growth, data is collected for daily secretion rates (DSRs) for the inner, mid, and outer areas of lateral and cuspal enamel. For enamel thickness average (AET) and relative (RET) enamel thickness, cuspal linear thickness (CT), and lateral linear thickness (LT) was collected. Alongside the data presented, this article also provides clear and transparent explanations for all the methods involved in its production, in order to ensure understanding of the rigorous protocol and consistency associated with the data provided. The novel data is also contextualised with a compilation of equivalent data published in past articles.

The microscopic study of modern human permanent enamel has commonly analysed both enamel thickness (e.g., Macho & Berner, 1993; Reid and Dean, 2006; Suwa & Kono, 2005; Smith et al., 2006a, 2006b; Aris et al., 2020b) and daily secretion rates (DSRs; e.g., Beynon et al., 1991a; Lacruz & Bromage, 2006; Mahoney, 2008; Aris et al., 2020a; 2020b; Aris and Street, 2021). Both enamel thickness and DSRs have multiple component parts required for their reconstruction and analysis. For enamel thickness these include dentine area, enamel cap area, and enamel dentine junction length; and for DSRs include pre-averaged regional secretion rates collected across the enamel cap (e.g., Aris et al., 2020b). The complexity of these features of human enamel has allowed their subsequent analysis to be broad, but to date these have been inconsistent in coverage in terms of tooth type and enamel feature. For example, permanent molars have been widely analysed for their thickness (e.g., Schwartz, 2000; Suwa and Kono, 2005; Smith et al., 2006a, 2006b; Olejniczak, Smith, Feeney, Machiarelli, Mazurier, Bondioli, and Radovčić, 2008; Mahoney, 2010; Aris et al., 2020b) and cuspal DSRs (e.g., Beynon et al., 1991a; Lacruz and Bromage, 2006; Smith et al., 2007; Mahoney, 2008; Aris et al., 2020b). Conversely the study of permanent incisors and canines has seen very limited research for DSRs (FitzGerald, 1998; Reid, Benyon, and Ramirez Rozzi., 1998; Schwartz, Reid, and Dean, 2001; Aris et al., 2020a; Aris and Street, 2021) or for thickness outside of 3D analyses (e.g., Kono, Suwa, and Tanijiri, 2002; Kono and Suwa, 2008; Smith et al., 2012; Buti, LaCabec, Panetta, Tripodi, Salvadori, Hublin, and Benazzi, 2017). The study of lateral molar DSRs has been similarly limited (Beynon et al., 1991a; Lacruz and Bromage, 2006; Aris et al., 2020b).

In addition to the disproportionate use of microscopic enamel features across tooth types, outside of a select few examples, large data sets for perma-

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nent enamel features have not been presented or made openly accessible (e.g., Reid and Dean, 2006; Smith et al., 2006a). Furthermore, in the cases where developmental enamel variables are made available, outside of a few exceptions (e.g., Kono et al., 2002; Grine, 2004; Reid and Dean, 2006; Mahoney, 2010; Le Luyer et al., 2014; Buti et al., 2017), they are most frequently reported for single populations/samples. Moreover, such variables are also typically reported as averages for groups. Where individual-level enamel data has been reported, it has only concerned enamel thickness, and one single human sample (Kono et al., 2002; Skinner et al., 2015; Lockey et al., 2020). These single human samples were also generated as a comparative sample for equivalent hominin/hominoid data analysis, rather than in direct analysis of human enamel growth/morphological patterns. There is therefore a clear need for the further generation of developmental enamel variable data from multiple modern human populations, in order for intra-specific research of human dentition to continue – a topic that has seen a resurgence in recent years (e.g., Le Luyer, Rottier, and Bayle, 2014; Aris et al., 2020a, 2020b; Aris and Street 2021).

Since the pioneering of enamel thickness research involving human samples (e.g., Molnar and Gantt, 1977; Martin, 1983, 1985), a great deal of research has involved 2D sections of teeth. An area where enamel research has developed over time, and also been less restrictive, is within 3D analysis of anterior teeth (e.g., Feeney, Zermeno, Reid, Nakashima, Sano, Bahar, and Smith, 2010; Smith et al., 2012; Buti et al., 2017) and molars (e.g., Kono-Takeuchi, Suwa, Kanazawa, and Tanijiri, 1997; Kono et al., 2002; Smith et al., 2006a; Kono and Suwa, 2008). These 3D-based studies have involved inter-species hominin analyses, as well as also developing the methodological approaches for intra-specific human enamel thickness analysis. Moreover, genetic analyses have also begun to emerge within the ongoing research of human enamel, which have made substantial strides to explaining inter-species enamel thickness differences within the human phylogeny (e.g., Horvath et al., 2014, Ungar and Hlusko, 2016). While possessing a clear utility, these lines of research do not directly or fully address all the issues discussed so far. They do however help show the importance of continued and nuanced research of human enamel. This therefore highlights the utility of providing more open access to relevant enamel thickness data.

Alongside the areas of inequality in research coverage and data availability regarding microscopic features of human enamel, there is a growing trend in intraspecific analyses investigating whether enamel growth and thickness has varied within the human species over relatively short periods of time. To date, these analyses have found significant variations in both enamel thickness and regional DSRs between geographically similar populations differing in context by as little as 400 years (Aris et al., 2020a; 2020b). This varies from older research in the field which frequently has either pooled dental samples for their growth and thickness data, or just used a single sample population, in order to create representative data sets for geographic regions or the entire human species (e.g., Beynon et al., 1991b; Lacruz and Bromage, 2006; Smith et al., 2007; Mahoney, 2008). While not all past research has pooled human populations (e.g., Grine, 2004; Reid and Dean, 2006), the prevalence towards doing so has meant that more recent research looking into whether the pooling of samples from different populations has been forced to create completely new histological sample collections to conduct their analyses. In these more recent analyses the use of comparative data sets from the pooled representative samples are limited in their utility (e.g., Aris et al., 2020b). In addition, while the production of new samples is useful to the field of dental anthropology, its destructive nature should be considered and pre-existing material used where possible and appropriate to help preserve dental remains wherever possible (Aris, 2020).

This article aims to address the above issues by providing a large and freely accessible data set for researchers to use in analysis of both enamel thickness and enamel growth, via DSR measures across multiple tooth types and for multiple (five) modern human populations, further presented alongside a guide for pre-existing equivalent data. The novel data sets will compromise individual-level data for individuals, as well as regional-level enamel measurements. Data of this type to date has not been reported or made available to this degree, with particular limitations existing regarding enamel growth data. The aim is that through this level of accessibility to this detailed a level of data, future research can more easily branch into the less well-covered features of enamel in current literature, and that further intraspecific research on modern humans can be conducted more easily. This will also represent the first data set regarding anterior tooth type enamel thickness accessible in this way. Finally, it is hoped that the open access publication of this data will help expand the analysis of enamel data gathered at the microscopic level to institutions unable to directly support histological and/or micro-CT methods.

Material and Methods

Dental sample

To produce this repository, histological analysis was conducted on 285 permanent teeth collected from seven populations across five temporally distinct periods: Roman (70-400AD), Early Pre-Medieval (500-600AD), Late Pre-Medieval (800-1200AD), Medieval (1000-1600), and modern-day clinical material (extracted within the last 20 years; Table 1). All archaeological samples came from British excavations and modern-day samples compromised teeth extracted from England and Southern Scotland. Sex was estimated where possible from skeletal elements of the archaeological individuals and known for a number of the modern-day samples. Details on known-sex/sex estimations are listed at the individual-level in the data sets, but a summary of the number of male and female individuals identified for each tooth type and population in provided in Table 2.

Table 1. Descriptive information of dental samples for each population and tooth type.

Population	**Date**	**Location**	**Collection Name**	**Number of teeth sampled**		
				Upper incisors	**Upper Canines**	**First Molars**
All combined	70-~2000AD	England and Scotland	N/A	81	69	115
Roman	70-400AD	Cirencester, Gloucester	St James' Place/ Bath Gate	10	11	11
Early Pre-Medieval	500-600AD	Ramsgate, Kent	Ozengell	22	20	20
Late Pre-Medieval	800-1200AD	Newcastle-Upon-Tyne, Northumberland	Black Gate	10	10	21
Medieval	1100-1500AD	Canterbury, Kent	St Gregory's Priory	19	8	43
	1000-1600AD	York, North Yorkshire	Fishergate House	8	8	5
Modern-day	Extracted within the last 20 years	Newcastle-Upon-Tyne and Glasgow	UCL/Kent	12	12	15

Table 2. Descriptive information regarding the number of individuals across populations and tooth types with known-sex/sex estimations.

Population	Number of male individuals			Number of female individuals		
	Upper incisors	Upper canines	First molars	Upper incisors	Upper canines	First molars
Known sex						
Modern-day	5	9	4	7	3	5
Estimated sex						
Early Pre-Medieval	5	4	2	6	7	7
Late Pre-Medieval	1	5	0	1	2	1
Medieval	3	4	1	3	3	0
Roman	2	5	6	3	4	1

Unworn teeth were selected where possible. When worn, only teeth with approximately 80% of their crown height remaining were selected based on criteria outlined by Guatelli-Steinberg and colleagues (2005), and when wear was present no data relating to the cuspal region of the enamel cap was collected (Figure 1). One tooth was taken from each individual during the sampling process, following the guidelines for destructive sampling of human remains guideline outlined by Mays and colleagues (2013) and on request from the institutions which curated the dental material utilised (see acknowledgements). Left teeth were utilised wherever possible, with the right tooth only being used in instances where the left was missing, poorly preserved, or heavily damaged (data files note whether left or right were analysed). Selection preference was also given to individuals presenting an antimere to the tooth being selected for sectioning.

Ancestry was unknown for all individuals across all populations from which samples were taken. In the case of the archaeological collections this was due to individual records not existing for any of the individuals of any of the populations studied. For the modern-day individuals, due to GDPR data laws (specifically those limiting the storage and dissemination of special data relating to an individual's personal identity) the only information available was the biological sex and town/city location from which the individual had the tooth sampled extracted.

Roman samples

The Roman samples were from two similarly located sites in Cirencester: St James' Place and Bath Gate cemeteries (Figure 2). Both sites dated between 70-400AD (see Table 1), presented archaeological material consistent with Roman-British populations, and are thought to have been small urban populations with access to marine resources from the River Severn (McWhirr et al., 1982).

Early Pre-Medieval samples

The Early Pre-Medieval samples came from a site in Thanet, Ozengell Grange (see Figure 2), dated to 500-600AD (see Table 1). The population is thought to have been small and coastal, with regular access to marine resources from the North Sea and/or the English Channel (Millard et at al., 1969). The Pre-Medieval period in Thanet is associated with newly developing urban areas following Roman occupation (McKinley et al., 2015).

Figure 1. Cross sections displaying examples of worn and unworn teeth analysed. The left cross section, a Medieval upper first incisor, displays no occlusal wear. The right cross section, a Roman upper first incisor, displays occlusal wear and thus no data requiring the cuspal region was collected from it.

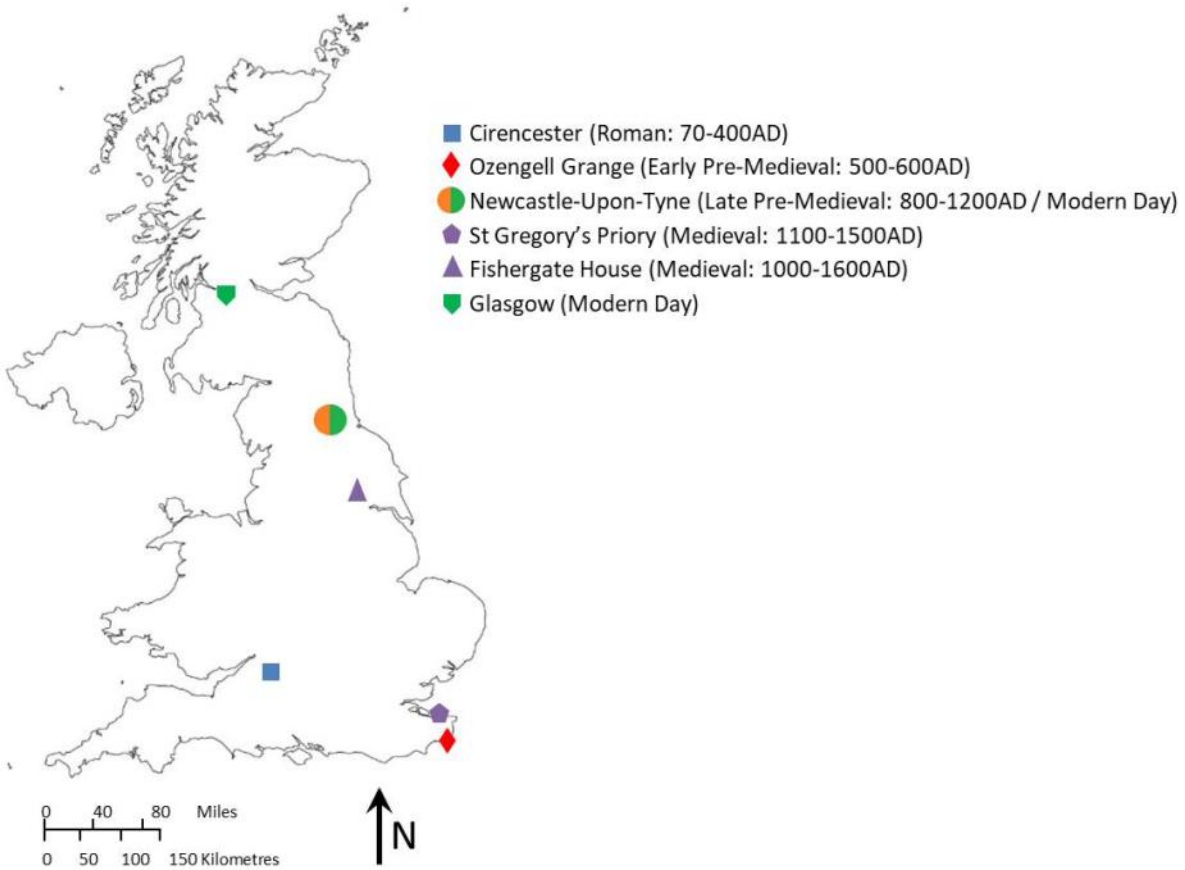

Figure 2. Map of the United-Kingdom and Northern Ireland displaying the geographic location where the archaeological samples were excavated/modern-day samples were extracted. Shapes denote the samples geographic origin, colour the time period they associated with (multi coloured shapes thereby meaning individuals from more than one time period originated from the same location): Roman = Blue, Early Pre-Medieval = Red, Late Pre-Medieval = Orange, Medieval = Purple, Modern-day = Green. Similar guides to these populations' context can be found in articles by Aris and colleagues (2020a, 2020b).

Late Pre-Medieval samples

The Late Pre-Medieval sample came from the Black Gate Cemetery site in Newcastle-Upon-Tyne (see Figure 2), dated to 800-1200AD (see Table 1). This was a large urban population with access to marine resources through proximity to the River Tyne (Swales, 2012).

Medieval samples

The Medieval samples come from two sites: St Gregory's Priory, Canterbury, and Fishergate House, York (see Figure 2). The sites were dated between 1100-1500AD (Hicks and Hicks, 2001) and 1000-1600AD (Holst, 2001) respectively (see Table 1). Both are documented to have been large urban populations (Hicks and Hicks, 2001; Holst, 2001).

Modern-day samples

The modern-day samples came from the UCL/Kent collection, a repository of teeth collected from dental surgeries in northern England (Newcastle-Upon-Tyne) and southern Scotland (Glasgow) (see Figure 2). Ethical approval for histology research on this collection of teeth was obtained from the United Kingdom National Health Service research ethics committee (REC reference: 16/SC/0166; project ID: 203541).

Sample Preparation

Before any tooth was sectioned as a part of producing the data set, resin casts were produced for each incisor, canine and molar using standard methods (Aris, 2020). Producing casts in this way allows for the reproduction of the surface morphology of dental crown, thus allowing for future researchers to analyse features not within the data such, such as crown morphology, microwear, and enamel surface features including perikymata and linear enamel hypoplasia.

Thin sections were produced using standard histological procedures (e.g., Mahoney, 2008; Aris, 2020). All teeth were first embedded in an epoxy resin and hardener mixture (Buehler®) in order to minimise the possibility of teeth fracturing during the sectioning process. Embedded samples were then cut at low speeds using a diamond-edged wafering blade (Buehler® IsoMet 1000 Precision Cutter) through the apex of crown cusps at a longitudinal angle. Samples were then mounted on glass microscope slides and subsequently lapped using grinding pads (Buehler®) until around 120μm thick. Ground samples were then polished using 0.3μm aluminium oxide powder to remove any evidence of lapping. Polished samples were then placed within an ultrasonic bath for a two-minute period in order to remove any micro-debris before being dehydrated using 90% and 100% ethanol-based solutions (Fisher scientific®). Dehydrated sections were finally cleared using Histoclear® and mounted with a glass cover slip using a mounting medium (DPX®). All sections were examined using polarised light microscopy (Olympus BX53 Upright Microscope). Analysis and image capture was conducted using micro imaging software (cellSens).

Due to the requirements for cuts to be made precisely through the cusp and dentine horn apex in order for enamel growth and thickness data collected to be reliable (Aris et al., 2020b), lines were marked on the tooth to help guide the initial cutting of the teeth for each tooth type (Figure 3). Whether this method was successful was assessed by observing the shape of the dentine horn of each cross section – a sharp point (with a V-shaped appearance; Smith et al., 2006a) at the apex denotes and precise cut; a curved/rounded apex a misaligned oblique cut (Reid and Guatelli-Steinberg, 2017). Where oblique cuts were noted the associated sections were not used for data collection (Figure 4).

Measurements Taken

Daily secretion rates

Daily secretion rates were reconstructed using standard methods for the inner, mid, and outer regions of the lateral and cuspal enamel areas of each tooth (e.g., Beynon et al., 1991a; Mahoney, 2008; Schwartz et al., 2001). Regions were determined by dividing the length of the associated

Figure 3. Diagram of how marks were made on upper first incisors, upper canines, and first molars (left to right respectively) before cutting to create a line through the cusp apex and dentine horn. The dashed red line displays the line created by the marks made at the blue crosses. Note the lack of blue cross on the unaligned root apex of the upper canine. The teeth displayed all came from the Fishergate House Medieval collection

Figure 4. Cross sections displaying aligned and misaligned cuts, both observed through the shape of the dentine horn (highlighted with dashed red lines). The left cross section, a Medieval upper first incisor, displays an aligned cut with sharp pointed, V-shaped, dentine horn apex. The right cross section, a Roman first molar, displays a misaligned cut with a rounded dentine horn.

enamel area into three equal parts along the length of enamel prisms. Cuspal enamel regions were determined within the appositional enamel of each tooth, and DSRs were taken from the mesial cusps of molar teeth. Lateral enamel regions were determined within the area of imbricational enamel equidistant between the dentine horn and the dental cervix. Lateral DSRs were taken from the buccal-mesial cusps of molar teeth, and from the labial enamel of canine and incisor teeth.

For each region an initial measurement was made for the length of five adjacent cross striations following the long axis of an appropriate enamel prism. This measurement was then divided by five to give a mean daily rate of secretion (μm/day). This process was repeated five times to give a grand mean and standard deviation for each region of each tooth. Cross striation measurements were all taken at between 20x and 40x magnification. Figure 5 illustrates how cuspal and lateral regions were split and how cross striations were counted along enamel prisms.

Enamel thickness

For each tooth, four 2D measures of enamel thickness were calculated: cuspal thickness (CT), lateral thickness (LT), relative enamel thickness (RET), and average enamel thickness (AET). Each was measured and calculated using a composite image produced by stitching together 20x magnified images using cellSens digital software.

RET is a dimensionless index and free-scale derivative of the average enamel thickness (AET) which encompasses the entire 2D surface area of an enamel cross section. AET (mm) is calculated by dividing the surface area by the length of the EDJ (enamel dentine junction) (Martin, 1983). RET is then calculated by dividing the associated AET by the square root of the dentine surface area of the surrounding EDJ and bi-cervical diameter (e.g., Smith et al., 2006a; Olenjniczak et al., 2008; Figure 6).

Cuspal thickness was taken from the buccal-mesial cups of the molars and primary cusp of the incisors and canines. Lateral thickness was also

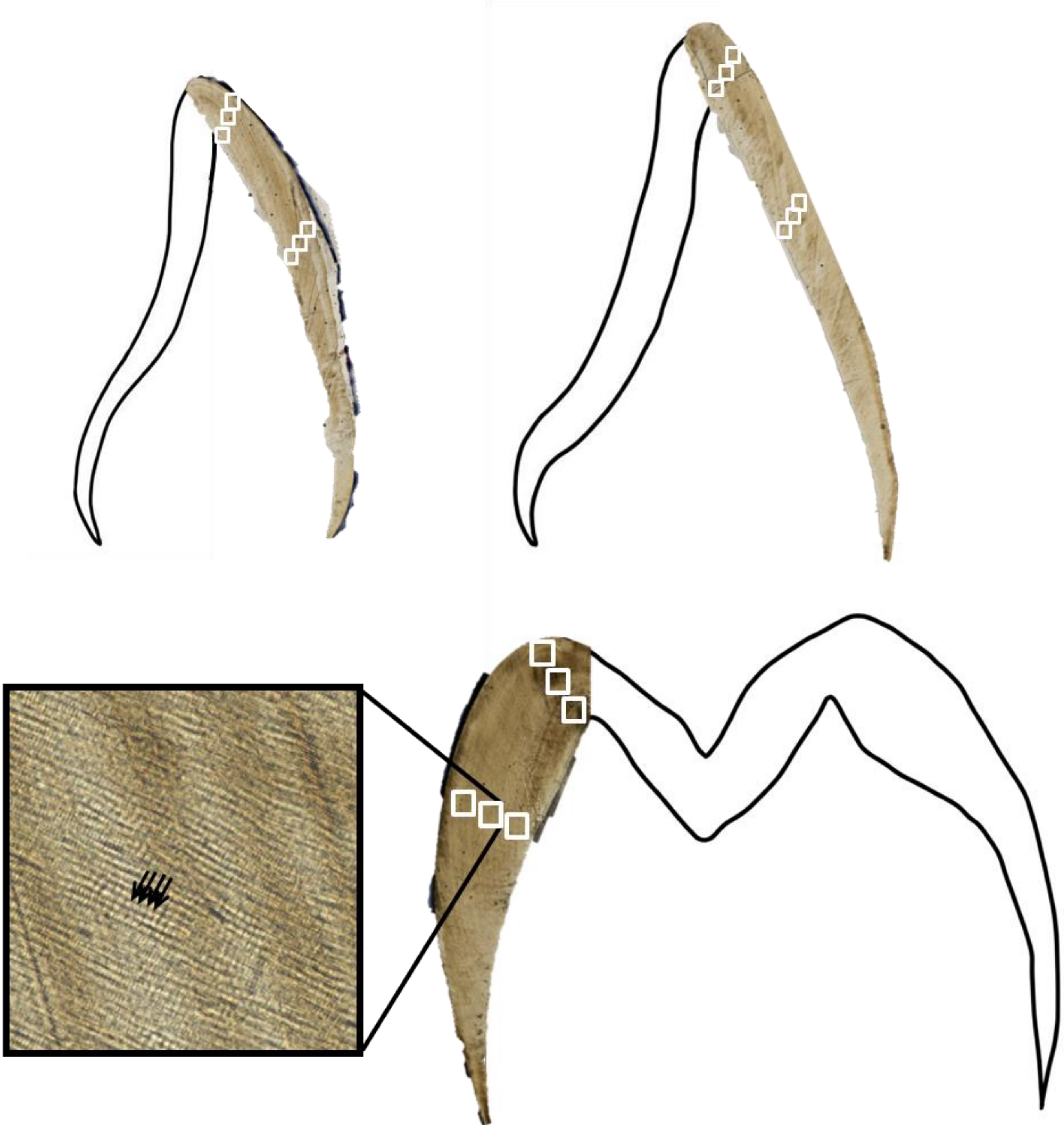

Figure 5. Diagrams of incisor (top left), canine (top right), and molar (bottom) cross sections with inner, mid, and outer regions for cuspal and lateral enamel regions isolated for DSR analysis. White squares show these enamel regions. The black square shows a 40x magnified superimposition of the mid lateral molar enamel. Black arrows indicate individual cross striations.

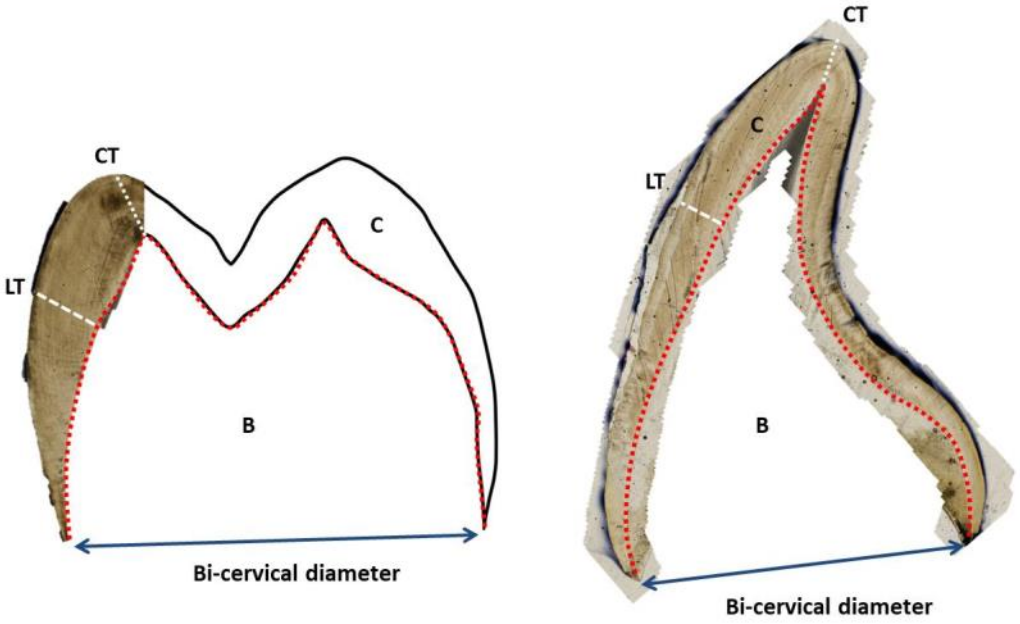

Figure 6. Cross-sectional images and reconstructions of 2D enamel thickness measures taken for molars (left) and canines and incisors (right). **C**. the enamel cap area and **B**. the dentine encompassed by the enamel and bi-cervical diameter (double-headed arrow). The area of **C**. was divided by the length of the EDJ (marked by dotted red line) to give the average enamel thickness (AET) in mm. The AET is divided by the square root of the area of **B** and multiplied by 100 to give the relative enamel thickness (RET) (e.g. Martin, 1983), which is a dimensionless index. The dotted white lines (CT) illustrate the cuspal enamel thickness measurements (e.g. Beynon and Wood, 1986). The dashed white lines (LT) illustrate lateral enamel thickness measurements (e.g. Grine and Martin, 1988). Similar guides to taking these measures can also be found in an article by Aris and colleagues (2020b).

taken from the mesial cusps of the molars, and from the labial region of incisor and canine enamel. Cuspal thickness (mm) was calculated by measuring the distance between the apex of the dentine horn and the cusp tip. Lateral thickness (mm) was calculated by measuring the maximum length between the EDJ and the enamel surface along a line perpendicular to the EDJ. The location of this line determined within the area of the tooth between the dental cervix and the first Retzius line to form in contact with the outer enamel surface (see dotted lines of Figure 1). These two linear measurements have been presented in past studies under different abbreviations (Beynon and Wood, 1986; Grine, 2005; Hlusko et al., 2004; Mahoney, 2010; Schwartz, 2000a, 2000b).

Pre-existing data

Equivalent data to that which is provided in this article, regarding enamel secretion rates and thickness, has been routinely published in studies regarding human enamel. A large number of those articles were compiled with details as to the enamel variables analysed and context information of relevant human samples, in order to contextualise the novel data generated for this project. By compiling this data it is easier to identify where the novel data presented here fills temporal and/or geographical gaps in existing data, and thus where gaps also persist. Where the same data has been utilised in multiple published works only one is detailed; preference was given to the original source where possible (Table 3).

Note: Articles using similar data which have been published to date but are not included are those which utilised the data sets provided in this article (Aris et al., 2020a, 2020b; Aris and Street, 2021).

Conclusions

Data utility

The combined data sets presented here represent the largest data repository of its kind in relation to developmental variables of human enamel in both archaeological and modern contexts. Moreover, it holds particular value in being the only such data set available which lists individual-level data for enamel growth and thickness for multiple tooth types and multiple different populations. This will allow for future research to have wider accessibility to comparative data for both intra- and interspecies and population analyses of permanent enamel involving human samples. Moreover, it is

Table 3. Existing published data for enamel DSRs and relevant thickness measures detailed with temporal and geographic contexts, tooth type information, and level at which data is available.

DSR data

Source	Location	Time Period	Tooth Types	N	Data collected Cuspal DSRs	Data collected Lateral DSRs	Data level presented at
Beynon et al., 1991b	Unknown	Unknown	Molars	11-15	X	X	Species
Lacruz and Bromage, 2006	Unknown	Unknown	Molars	10	X	X	Species
Smith et al., 2007	Various	Various	First molars	21	X		Species
Smith et al., 2009	Germany	Modern-day	Third molars	7	X		Species
Mahoney, 2008	England and Scotland	Bronze-Age	First molars	13	X		Population
Schwartz et al., 2001	England and South Africa	Modern-day	Canines	28	X	X	Sex

Thickness data

Source	Location	Time Period	Tooth Types	N	RET	CT	LT	Data level presented at
Smith et al., 2006a and b*	Various	Middle Stone Age and Modern-day	Molars	1-55	X			Population
Olejniczak et al., 2008*	Various and unknown	Various and unknown	First molars	1-6	X			Species
Lockey, 2020	Unknown	Unknown	Molars	9-10	X			Individual
Martin, 1983	Unknown	Unknown	Molars	13	X			Species
Skinner et al., 2015	Various	Unknown	Molars	8-15	X			Individual
Smith et al., 2009	Germany	Modern-day	Third molars	8	X			Species
Smith et al., 2008	Various	Various	Various	12-58	X			Species
Sorenti et al., 2019	Madrid, Spain	20th Century	Molars	20-31	X			Sex
Kono, 2004*	Asia	Various	Molars	40-41	X		X	Population
Grine, 1991	Unknown	Unknown	First molars	10	X		X	Species
Grine, 2004	Various	Modern-day	Second molars	1-23	X		X	Population
Reid and Dean, 2006	Various	Various	Various	15-37		X		Population
Gantt and Rafter, 1998	Unknown	Unknown	Molars	3-23		X	X	Species
Mahoney, 2010	England and Scotland	Various	Molars	69		X	X	Population
Suwa and Kono, 2005*	Ohio, USA	800-1100AD	First molars	31-37		X	X	Population
Kono et al., 2002*	Asia	Unknown	First molars	5		X	X	Individual
Macho and Berner, 1993	Zwentendorf, Austria	1100AD	First molars	21			X	Population
Saunders et al., 2007	Belleville, Canada	1821-1874AD	Canines and premolars	72	X			Sex
Feeney et al., 2010*	Indonesia	Modern-day	Canines	7-21	X			Population
Buti et al., 2017*	Various	Medieval and Clinical	Canines	1-13	X			Population

*Some or all data generated within a 3D context hoped that the compilation of similar data available in past research publications here will assist in researchers locating suitable comparative data regarding enamel growth and thickness data in addition to that provided here.

For specific examples of the data's utility, all articles which have utilised any data presented here compromise the work of Aris (2020), Aris and colleagues (2020a, 2020b), and Aris and Street (2021). Throughout these articles, all content here including enamel DSRs, enamel thickness, and methodological approaches, are used in specific research projects.

Data ethics and acknowledgements

Data of the kind presented here is collected via destructive methods, which has a permanent impact on the collections analysed, and thereby their curating institutions. As a result, while this data is publicly available for use in future research, it is strongly recommended that such research acknowledge both the generosity and ethical stringency of the curators acknowledged in this article. Moreover, further care must be taken when utilising the modern-day data from the UCL/Kent collection. Not only should the University of Kent be acknowledged, but it should be detailed that the ethical approval for histological research on this collection of teeth was obtained from the United Kingdom National Health Service research ethics committee. Furthermore, the REC reference: 16/SC/0166; project ID: 203541, should also be noted (as it has been here in section *2.1.5*).

Acknowledgements

Thanks go to the Corinium Museum, Trust for Thanet Archaeology, and the Universities of Durham, Kent, and Sheffield for granting permission to sample the teeth sectioned as a part of developing this repository. Thanks also go to the two anonymous reviewers and editor for their positive feedback and comments which helped greatly improve this article.

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Assessing Error in Human Dental Measurements: A Comparison of Resin Casts, Plaster Casts, and Dental Enamel

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Keywords: methods, dental anthropology, dental casts, measurement error

ABSTRACT Technical advances in 3D morphometrics and other forms of digital analysis allow for detailed measurements of dental metrics yet, consistently, dental anthropologists show a publishing preference for measurements using dental calipers. For many researchers, dental casts are often measured when field seasons or collections-based trips do not allow ample time to measure the original teeth. As such, this study aimed to assess differences among measurements of plaster casts, resin casts, and dental enamel to determine if variables such as material softness or shrinkage could lead to measurement error. Results of a paired t-test demonstrate no statistically significant difference in buccolingual crown measurements from 23 commingled canines and first molars. Likewise, while plaster casts exhibited overall smaller mean (and individual) measurements than enamel and resin, the differences (around 0.04 mm on average) are negligible. We, therefore, conclude that casts can be used in place of original teeth, where needed, and which material type is "best" can be determined by the researcher's preferred medium.

Often circumstances do not allow for the long-term use of skeletal material for research purposes (e.g., repatriation and reburial, length of research visit, etc.). In such cases, ongoing availability of materials, through the production of dental impressions (negative replica of the teeth) and dental casts (lifelike reproductions from impressions) is more practical. However, in order to collect accurate measurement data, differences in error rates between casted dentition and the original teeth must be statistically insignificant so that the results of the study are not impacted. As such it is imperative that a researcher knows whether dental replicas consistently over or underestimate dental dimensions compared to dental enamel, and whether there are significant differences in measurements between casting mediums. Similarly, it is crucial to know whether the tools used to measure replicas impact precision.

The dimensional stability of the materials used to make dental impressions and dental casts has been widely studied. Dental alginates (irreversible hydrocolloid compounds) have long been favored as an impression material in clinical settings for their low cost. This material is not often used by dental anthropologists because it does not have long-term dimensional stability requiring casts to be made within a few hours or a single day (e.g., Sedda, Casarotto, Raustia, and Borracchini, 2008). In skeletally based dentitions there is also a higher chance that teeth will be pulled from the jaw given the density of the material and need for a dental tray to hold the alginate. Within dental anthropology, the use of polyvinyl siloxane replica materials (PVS) has become more common because it is gentler on skeletal dentitions and multiple casts can be made from the same impression as needed, due to long-term dimensional stability (e.g., Chee and

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Donovan, 1992) as long as temperatures do not fluctuate wildly (Kelso, Hulsey, and Driscoll, 2020). Casting material such as gypsum plaster (plaster) are popular when dental morphometrics are the focus, though epoxy resins (resin) have gained popularity among dental anthropologists due to the higher resolution of surface features such as linear enamel hypoplasia and macrowear/ microwear features. A recent study of commonly used resin and plaster materials found that there was no difference in measured size between epoxy resins and dental stone, though the study measured differences using a Scanning Electron Microscope (Junior, Kreve, and Carvalho, 2018).

While dental anthropologists can measure casts using a variety of tools ranging from calipers to 3D scans (e.g., Al-Mulla and Murad, 2010; Bowes, Dear, Close, and Freer, 2017; Keating, Knox, Bibb, and Zhurov, 2008; Kumar, Phillip, Kumar, Rawar, Priya, Kumaran, 2015; Reuschl, Wieland, Stiesch, Wenzel, and Dittmer, 2016), calipers are still widely used across different field and lab settings. In measurements using calipers material surface hardness is a primary concern as the metal tips must be tightly fit to the surface of the replica and have the potential to leave impressions or scratches on soft surfaces. The most commonly used caliper for measuring dental dimensions is the Hillson-Fitzgerald caliper (Hillson, FitzGerald, and Finn, 2005). These calipers are made of a durable metal with thin needle point tips for better fit in interproximal spaces of in-situ dentitions (i.e., teeth implanted in the jaw). Of the three dental surfaces, enamel is the hardest and should be unaffected by the adjustment of the metal calipers. Resin is also a durable material that is unlikely to yield surface stability, but still softer than dental enamel. In contrast, plaster is soft and can be more easily depressed if the calipers are fit too tightly, though visible inspection of a plaster cast can clarify if the surface is damaged (i.e., a small depression would be readily visible).

When previous studies are analyzed to ascertain answers to the questions posed in our study, differences in approach, temporal changes in the quality of impression and casting products, and emergent technologies for measuring dentitions make comparisons problematic. For example, early studies such as Hunter and Priest (1960) measured dental stone casts taken from alginate impressions and enamel (intra-orally in living patients) using a Helios-style caliper (i.e., no needle tips). Later studies such as Pant, Juszczyk, Clark, and Radford (2008) use PVS impressions materials to make plaster casts to compare with both 3D printed resins (measured by a scanning electron microscope) and digital scans (measured using computer software). Further, the conditions in which impressions are taken can have quite an impact. For example, Hollinger, Lorton, Krantz, and Connelly (1984) found “material distortion and shrinkage is unpredictable” (308) in impressions of edentulous individuals and highly impacted by the preparation of the dental tray while Pant et al. (2008) found that temperature differences impacted the “architectural stability” of PVS. Studies such as Kelso et al. (2020) demonstrate additional concerns about the impacts of temperatures on long-term storage of materials.

This study examines the two most common casting materials (epoxy resin and dental stone) measured using the most common field and lab instrument (Hillson-Fitzgerald calipers) to assess differences in buccolingual dimensions. Assuming careful measurements of each replica’s surface (e.g., checking that the calipers did not leave a visible surface indentation) and demonstrated low surface shrinkage rates of the materials measured, we predicted that buccolingual dimensions of both the plaster and resin casts would not be significantly different than the original dental enamel. However, given the softness of plaster casts we predicted that measurements would consistently register as smaller than either resin or plaster.

Materials and Methods

The specimens used in this study were collected from an ossuary located in Chiavari, Italy in the region of Liguria. The ossuary contains the remains of several hundred individuals who were removed from mausoleums and placed in a secondary burial pit as sanctioned by Italian law (DPR n.285/1990). With the exception of a limited number of individuals with identifying materials, the remains deposited in the ossuary are commingled and no contextual information is readily available. Based on cemetery records, the majority of the remains belong to individuals who lived in Chiavari and its hinterland between the late nineteenth and early twentieth century.

Twenty-three canine and first molar crowns were measured following Hillson et al. (2005). Dental impressions were made using a high-resolution polyvinyl siloxane compound (Affinis), preferred by dental anthropologists because of its dimensional stability. These dentition were selected based on larger samples of preserved teeth and, thus, represent a convenience sample. Casts were made of gypsum plaster (Dentstone) and an epoxy

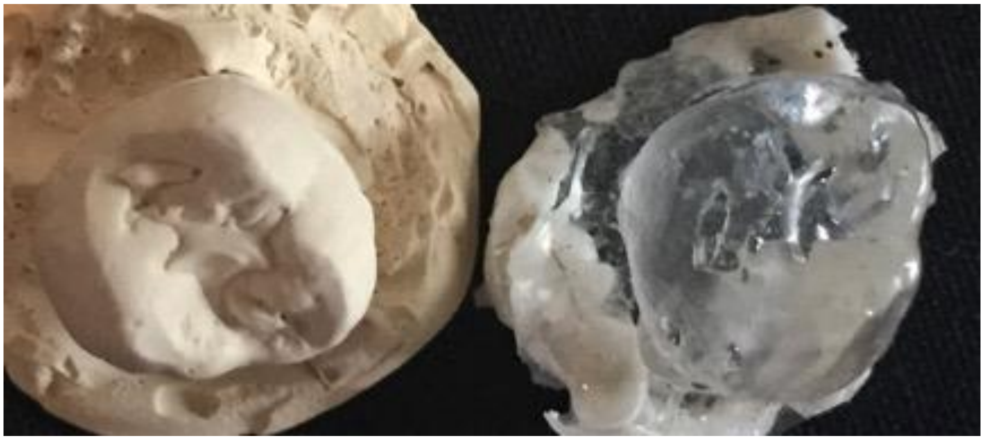

Figure 1: Plaster (left) and resin (right) casts of a first molar.

resin (Epofix) (Figure 1). The company Modern Materials produces Dentstone and reports a 0.11 percent "Expansion" rate of materials. The company Struers produces Epofix and claims a 0.3 percent shrinkage rate. Dental dimensions were recorded by a single researcher to eliminate interobserver error using Paleo-Tech's digital Hillson-Fitzergerald calipers (Hillson et al., 2005), which automatically import measurements into a designated Excel spreadsheet when a button is depressed on the caliper's surface. To reduce intraobserver error, dimensions of each tooth were recorded five times consecutively and reported as an average.

Only buccolingual crown dimensions were measured in this study because this dental measurement is unaffected by mixed samples of isolated teeth (i.e., not in situ) and those still imbedded in the jaw with neighboring teeth (i.e., in situ). Conversely, mesiodistal measurements are more challenging to measure because of tight interproximal spacing between teeth in-situ. Therefore, when trying to measure between interproximal spaces, there is a higher likelihood that resin or epoxy would be impressed by the tips of the calipers (and affect measurement). As the sample comprised both loose teeth and those imbedded in the jaw, this posed an increased chance that significant differences in measurements would reflect differences in applied pressure to the cast surface. Therefore, because this study used a mixed sample, measurements of mesiodistal differences on the tooth surfaces would not have been comparable. Further while comparative analyses between mesiodistal measurements for isolated teeth and in-situ dentitions was possible, overall small samples sizes available in the study did not allow for such a fine scale analysis of the cause of potential measurement variation.

To test the first proposal, that buccolingual crown dimensions would not vary significantly between enamel, resin, and plaster, a paired t-test was used (following Kieser, 1990). A paired t-test examines mean differences between groups of data and is reported as a t-value and associated significance or p-value (in this case with a 95% confidence interval). To test the second proposal, that buccolingual measurements of plaster would be smaller, simple mean differences were compared as well as individual measurements to determine the proportion of cases in which plaster measured as smallest. Though small sample sizes were used in the present study, statistical power would not be improved by a larger sample because the variables are not dependent.

Results and Discussion

Table 1 presents the results of the paired t-test comparing buccolingual measurements on tooth enamel to plaster and resin casts. None of the pairings demonstrated a statistically significant difference in measurement at the 0.05 (95%) confidence interval. These results support our predictions that both types of casts can be used in lieu of the original teeth when conducting odontometric analyses, without significant error in measurement.

Table 2 reports the mean measurements for each material type. Measurements of the enamel were slightly larger on average than either plaster or resin, though plaster casts (as predicted) had the smallest mean of the three. Still, the differences between the overall means were minimal. Enamel measured, on average, 0.035 mm larger than resin and 0.043 mm larger than plaster. In the raw data, there were only three cases (13%) in which one or more of the replicas (plaster or resin) and/or origi-

Table 1. Paired t-test results comparing tooth enamel, plaster casts, and resin casts (indicates statistical significance).*

Material type	N	t	p-value
Enamel-Resin	23	0.8985	0.3787
Enamel-Plaster	23	1.0464	0.3068
Plaster-Resin	23	0.9751	0.3401

Table 2. Mean measurements and proportions (n=23).

Material type	Mean (in mm)	Proportion (in %)
Enamel	10.242	22
Plaster	10.199	52
Resin	10.207	13

nal tooth (enamel) measured exactly the same. Interestingly, individual measurements of plaster casts were lowest in more than half the cases (52%), followed by enamel (22%), and resin (13%). Therefore, while plaster replicas produced some of the smallest measurements they were not exclusively the smallest measurements. Overall, despite measurable differences between individual teeth and in the combined sample, for all intents and purposes these measurements are identical.

The primary limitations of this study are sample size and composition. While the overall collection was estimated at 600 individuals, only a small portion of the collection resides in the U.S. Additionally, differential preservation, significant tooth wear, and other limiting variables in the roughly 60 individuals meant only 23 teeth were able to be measured. Additionally, this sample was one of convenience because it was available and nearby to the university where the study took place; therefore, these teeth may not reflect dental crown variability that could impact measurement. Similarly, as a modern human sample we are unable to conclude that such measurements are similarly accurate for other primate dentition, where there may be higher morphological variability. Finally, as noted in the materials and methods section, only buccolingual crown dimensions were gathered. While it was easy to measure isolated teeth in this setting, we were unable to replicate *in situ* dentition (i.e., teeth seated in the maxilla and/or mandible). Such measurements require a higher level of dexterity to measure because of potentially tight interproximal spacing. As such, there is always the possibility that heavier compression of the calipers on softer cast materials could have resulted in significant differences between measurements.

Given the minor differences between measurements, material choice can be determined by the researcher’s preference because both casting materials provide accurate measurements. The researchers found that plaster casts were generally easier to measure than either enamel or resin casts because resin is translucent and has a smooth surface texture (like dental enamel) while plaster is opaque and slightly textured. Specifically, the texture of plaster makes it less likely that caliper tips slip during measurements. If cost is an issue, resins also tend to be more expensive than dental plasters.

Conclusions

The results of this study provide solid support for the continued use of either plaster or resin dental casts as proxies for original teeth, when needed. Future research might examine different tooth types, different primate and ancestral hominin species, and/or include mesiodistal measurements. The present study excluded incisors and premolars, therefore, additional research on measurement error rates for incisors or premolars could be examined to determine if the results were specific to canines and molars. Additionally, wide variation in tooth morphology and size across primate and ancestral hominin species could produce issues with measurement that should be considered.

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Gaps in Information: What Missing Teeth Mean in Bioarchaeology

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Keywords: Postmortem tooth loss, Dental pathology, Dental disease

ABSTRACT Previous bioarchaeological analysis of postmortem tooth loss (PMTL) has failed to recognize the potential influence of diseased dental tissue on tooth retention after death. Because tooth loss from a traditional taphonomy prospective is treated simply as missing data, demographic studies are potentially influenced by underestimations of disease prevalence. To investigate the association of tooth loss and dental disease, data on the pathological conditions observed in the tissues were collected on a sample of teeth from 771 individuals. By analyzing the evidence of disease in the bone and dental tissues immediately surrounding empty alveolar sockets suggestive of PMTL, trends in the presence of diseased tissue and retention of a tooth emerged. When compared to teeth retained after death, PMTL sockets were 15.3% less likely to retain neighboring teeth and 21.5% less likely to have neighboring teeth that showed no signs of carious or periapical lesions. The results suggest that the traditional explanation of susceptibility to loss due to the exposure and morphology of single-rooted, anterior teeth does not sufficiently explain the causes of PMTL in many cases. Rather, it would be more accurate to consider PMTL, in part, as an advanced symptom of dental disease when interpreting missing teeth in the bioarchaeological record.

Tooth enamel is the densest, most resilient tissue in the human body (Hillson, 1996). As a result, human teeth typically can survive a wide range of environments, making them a rich source of information for bioarchaeologists gathering data on human behavior. Indeed, the importance of the dentition in bioarchaeology relates to the fact that it informs on human evolution, diet, growth and development, migration, identity, and disease (Scott and Turner, 1988; Hillson, 1996). Since the oral cavity has direct contact with both the external and internal environment, examination of oral disease in the dentition enhances our understanding of the differences in foodways between and within cultures. Dental disease provides significant information concerning ancient diet and cultural practices, as well as the influence of diet on pathological conditions of the dentition (Konig, 2000; Moynihan, 2005). Dental disease is sometimes used as a proxy for understanding oral health, but the inconsistency in defining the term *health* has led researchers to move away from the umbrella term that includes unknowable factors (e.g., psychosocial aspects) and instead focus on *dental disease* as indicated by specific conditions (e.g., dental caries; Pilloud and Fancher, 2019).

Although teeth are valuable indicators of disease and life history, as well as a source of demographic and cultural data, several studies highlight the prevalence of sample bias arising from antemortem and postmortem teeth loss (e.g., Lukacs, 1995; Erdal and Duyar, 1999). Loose or missing teeth are extremely common in bioarchaeological samples, and a review of the literature has shown inconsistent methods in dealing with the consequent bias during data collection and analysis. The study of dental pathology is further complicated by the varying preservation rates of the multiple

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This paper was the recipient of the Albert A. Dahlberg prize awarded by the Dental Anthropology Association in 2021.

tissues that make up the dentition. Teeth are enclosed in some of the most fragile bone, the alveolar sockets of the maxilla and mandible. That brittle enclosure is susceptible to much more damage in archaeological contexts than the teeth themselves, and results in significant tooth loss after death.

This article explores the potential influence of missing teeth on the analysis of skeletal samples utilizing a statistical examination of patterns in dental pathology to infer what information may have been lost from teeth missing postmortem. We will focus on patterns found in various samples that exhibit missing teeth to potentially correct the underrepresentation of oral disease prevalence and will propose steps to correct possible biases from data loss.

Taphonomy of Tooth Loss

Tooth loss after death can occur through tissue loss during natural processes of decomposition. The conical shape of roots, especially of anterior teeth, makes teeth susceptible to coming loose from their sockets (Oliveira, Melani, Antunes, Freitas, and Galvão, 2000). The burial environment also affects decomposition of the soft and hard tissues and influences postmortem tooth loss (PMTL). In addition to tissue shrinkage and decomposition during skeletonization, handling of the remains during excavation, examination, transport, and storage can contribute to the dislodging and loss of teeth (Đurić, Rakočević, and Tuller, 2004; Oliveira et al., 2000). A common storage method for crania, for example, is to rest them on their mandibles for stability, which may damage maxillary teeth (Oliveira et al., 2000).

The postmortem interval, root morphology and number, and excavation methods all influence the rate of PMTL (Tibbett and Carter, 2008). Recent bioarchaeological literature emphasizes the need for careful excavation to ensure the complete recovery of the dentition. Because skulls are often recovered with teeth missing, it is important to maximize tooth recovery through careful excavation methods. Loose teeth that are outside of expected anatomical position may not be recognized during excavation, especially if burial context is not carefully examined (Đurić et al., 2004). The lack of standard excavation methods has affected the way human remains are analyzed in both bioarchaeological and forensic contexts (Evis, Hanson, and Cheetham, 2016; Haglund, 1997). Recent research suggests that a stratigraphic excavation method results in more evidence recovery than an arbitrary level method, especially in small element recovery rates and with fewer bones categorized as unassociated (Evis et al., 2016, Tuller and Đurić, 2006). The recovery of disarticulated material, such as dental remains, is crucial for constructing biological profiles and paleoepidemiology research (Tuller and Đurić, 2006).

Pathology of Tooth Loss

Although PMTL in bioarchaeological contexts is often due to carelessness during excavation, the amount of effective soft tissue holding a tooth in its anatomical position also is an important factor to consider (Đurić et al., 2004). Periodontal disease influences the integrity of the periodontal ligament that helps anchors the cementum to the alveolar bone and the gingiva, and therefore contributes to the potential for teeth to be easily dislodged postmortem (Đurić et al., 2004; Meller, Urzua, Moncada, and von Ohle, 2009).

Oral disease can be introduced through several different pathways and can affect both the soft and hard tissues of the oral cavity. Teeth are at risk for loss through infection of the adjacent tissues or due to trauma to the enamel structure. The three main pathological conditions of interest are dental caries (carious lesions in the tooth), periapical lesions (lytic lesions in the alveolar bone), or occlusal tooth wear (loss of tooth enamel). These pathological conditions threaten the integrity of the tissues involved, therefore compromising the tooth as a unit. The most significant outcome, no matter the pathogenesis, is loss of the overall tooth.

Once a tooth is lost, both the soft tissue and the surrounding alveolar bone begin to heal. Within eight weeks of tooth loss, most of the socket is filled with remodeled bone (Larjava, 2012). This remodeling reaches the alveolar crest within three to four months (Shiroma, Terrado-Naguinlin and Zuerlein, 2019), and continues for around six months, with variation based on the location and presence of neighboring teeth (Larjava, 2012). But the successful healing of a single tooth socket does not spare the rest of the oral cavity from a similar fate. Typically, the interaction of the environment and the tissues of the mouth are not confined to one tooth alone; oral pathological conditions often have multiple causes, and more than one tooth may be affected by the same disease process. As the dental tissues respond and react at different rates, moving beyond an individual tooth and considering the implications of oral pathology creates a better sense of the physical indications of an individual's overall health. From there, population level analysis provides perspective on overall disease prevalence in a past community.

Although rarely recorded beyond an inventory, tooth loss is often included in the larger interpretations of prehistoric dentitions (Costa, 1980; Lukacs, 2007). The loss of data from absent teeth is one of the most prevalent concerns in the bioarchaeology dental disease literature (Cucina and Tiesler, 2003). Potential underestimation of dental caries rates has been acknowledged in calculations of disease prevalence in samples with high rates of missing teeth (Lukacs, 1995; Littleton and Frolich, 1993). Analyzing when tooth loss took place (e.g., antemortem or postmortem), and the underlying factors that led to loss of that tooth, can be difficult to determine. Establishing when tooth loss occurred depends on the remaining alveolar bone and the degree to which it has remodeled.

Antemortem tooth loss (AMTL) of the permanent dentition is associated with advanced stages of dental disease. Antemortem tooth loss has several potential causes: caries, pulpitis, or periodontitis resulting from infection of the tooth and the surrounding tissues, or trauma (Costa, 1980; Hillson, 1996; Indriati and Buikstra, 2001; Larsen, 1995). The bias in data collection that results from AMTL has long been acknowledged, primarily in the context of studying rates of dental caries, but only a few researchers have attempted to correct for this loss in data (Hardwick, 1960; Brothwell, 1963; Powell, 1985; Kelley, Levesque, and Weidl, 1991; Lukacs, 1995; Gagnon and Wiesen, 2013). Most successfully, Lukacs proposed the "Caries Correction Factor," which derives from the prevalence of pulp exposure due to carious lesions versus attrition observed in the sample. By creating a sample- or population-specific equation for calibrating caries rates, the correction factor considers the relationship between carious lesions and AMTL (Lukacs, 1995). This focus on the effects and interpretations of AMTL has led to increased incorporation of tooth loss data in dental inventories and oral disease assessments (Nelson, Lukacs, and Yule, 1999; Cucina and Tiesler, 2003).

Postmortem tooth loss, on the other hand, has been much more ignored in the bioarchaeological literature and often treated as missing data. Although it is commonly acknowledged as a data collection bias, it is rarely addressed outside of the need for careful excavation when exhuming human remains (Tuller et al., 2004).

As discussed below, a tooth lost either antemortem or postmortem is often an indication of the subtle changes in the surrounding tissues, and consequently the disease of the overall oral cavity, rather than solely an unfortunate consequence of taphonomic processes. This study examines samples that exhibit different patterns of PMTL and explores how these patterns influence the underrepresentation of oral disease prevalence and how to correct for this bias.

Materials and Methods

The dentition of 771 individuals was inventoried and each tooth or empty tooth socket was assessed for wear and pathological conditions. The methods follow Bartelink's (2006) modification of the scoring system presented in Buikstra and Ubelaker's (1994) *Standards for Data Collection from Human Skeletal Remains*, to provide consistency between the new data collected and Bartelink's 2004-2012 collection of dental data for the final pooled sample. When the tooth was present for observation, dental caries was then scored by location on the tooth and dental wear was recorded using the Smith (1984) system for anterior teeth and premolars and the Scott (1979) system for molars. When assessing teeth for dental caries, all potential lesions were probed using a dental pick and evaluated using a 10x magnification hand lens. For the context of this research, tooth condition was recorded as either present in occlusion, AMTL, or PMTL. All other cases were excluded. Neighboring tissues in this context were represented by an examination of the teeth immediately mesial and distal to the selected tooth and the alveolar bone that surrounded those teeth. In the case of the third molar, there was no distal tooth, so the second molar was its only neighbor. As dental disease is not often isolated to a single tooth, we hypothesize that the condition of the tooth was affected by the presence of carious lesions in the neighboring teeth and/or by the presence of periapical lesions in the neighboring tissues, given that periapical lesions can weaken the tissues holding a tooth within the alveolar bone.

To be marked as "observable," a tooth must have been present and in the occlusal plane, with greater than 2 mm of vertical enamel surrounding at least 50% crown circumference, eliminating overly worn and loose teeth. Subadults were removed from the original sample to ensure all individuals had permanent dentition. Individuals with tooth loss due to potential congenital absence (judged by examining tooth positions relative to tooth types) were also excluded for ease of comparison.

The pooled data set consisted of 771 adult individuals from Late Holocene (5000-200 BP) archaeological sites in pre-contact California, which was created using the dental inventories and pathology assessments. The sample population was represented by individuals from CA-ALA-307, -309, -

328, and -329, sites located near the shoreline of the San Francisco Bay, the ancestral homelands of the Ohlone tribe, and from CA-SAC-06, -43, -60 and SJO-68, -142, and -154, sites located in the Central Valley, the ancestral homelands of the Plains Miwok tribe. This research used a combination of new data collected for this study and previously collected data from Bartelink's (2006) dissertation research. All dentitions were examined at UC Berkeley's Phoebe A. Hearst Museum of Anthropology, where they are currently curated. Permission to collect data were provided by the museum's curator and NAGPRA committee.

After instances of PMTL with all observable neighboring teeth were isolated, the collection consisted of two groups: (i) a control group, where the primary tooth examined was present and in occlusion, and (ii) an experimental group, where the primary tooth examined was absent postmortem. Teeth were pooled from right and left sides of the mandible and maxilla. Tooth counts of the total sample are presented in Table 1.

Table 1. Research sample size by tooth and condition.

TOOTH	# CONTROL (PRESENT)	# EXPERIMENTAL (PMTL)
M3	930	166
M2	815	20
M1	924	12
P4	854	118
P3	765	78
C	650	74
I2	522	113
I1	476	73

Results

The data analysis first considers whether instances of PMTL were more often associated with surrounding teeth or neighboring tissues that had already experienced AMTL. The presence or absence of the neighboring teeth was compared between each primary tooth that was present and in occlusion, and those recorded as PMTL. After organizing by tooth type (Table 2), the percentage of primary teeth with both neighboring teeth present was lower in every tooth group when the primary tooth being examined was lost postmortem. The smallest difference was a 2.3% decrease in third molars, and the largest difference was a 25.4% decrease in the fourth premolar. The average difference between having all neighboring teeth present between control teeth and PMTL teeth was a 15.3% decrease when all tooth types were considered. The visual representation (Figure 1) shows that the percent difference was especially high for posterior teeth. The average difference between anterior tooth types was a 12.3% decrease. The average in posterior teeth was a 17.1% decrease (20.8% when third molars were excluded).

When third molars were excluded for not meeting the criteria of having two neighboring teeth, instances of having one neighboring tooth present and the other absent were most often seen in the posterior teeth. In this analysis, greater than 20% of PMTL affected second molars, first molars, fourth premolars, and third premolars had one present and one absent neighbor. Although the change in percentage of teeth with two neighbors present was not as great between control and PMTL incisors, all anterior teeth showed a consistent decline in percent of present neighbors in each experimental group. Rather than a similarly high prevalence of the one present and one absent neighbor alternative, as was seen in posterior teeth, all the anterior teeth were more affected by AMTL on both sides.

Dental Caries and Neighboring Tissues

To understand the effects of specific dental pathological conditions on the prevalence of PMTL, an analysis of the neighboring tissues was also conducted to see how carious lesions and periapical lesions are associated with compromised surrounding tissues and overall tooth loss (Table 3). In this analysis, the control tooth was present without evidence of carious lesions, and the experimental tooth was again one in the same position that was lost postmortem.

Although all analyses showed that it is rare to have both neighboring teeth affected by the same pathological condition, in the case of carious lesions, there were two cases seen on canine teeth. Both control and experimental groups showed few differences when both neighboring teeth were present. The smallest difference in percent of all neighboring teeth with no caries was 0.8% in second molars, while the greatest difference was only 7.8% in first molars. Neighboring teeth of experimental groups for third premolars, canines, and both incisors all displayed no caries. Consistent with the literature on dental caries, posterior teeth were more affected than anterior teeth.

Most teeth showed a slight decrease in caries prevalence in the surrounding tissues in the experi-

Table 2. Prevalence of all three neighboring tissue categories.

Tooth	Condition	All neighboring teeth present (%)	1 tooth present, 1 tooth AMTL (%)	All neighboring teeth AMTL (%)
M3	Present	93.9	4.9	n/a
	PMTL	91.6	8.4	n/a
M2	Present	92.4	6.1	1.5
	PMTL	75.0	25.0	0.0
M1	Present	94.4	3.4	0.0
	PMTL	75.0	25.0	0.0
P4	Present	96.6	3.3	0.5
	PMTL	71.2	21.2	5.0
P3	Present	97.8	2.2	0.0
	PMTL	76.9	21.8	1.3
C	Present	97.5	1.8	0.6
	PMTL	78.4	9.5	12.2
I2	Present	97.7	2.3	0.0
	PMTL	87.6	7.1	5.3
I1	Present	99.6	0.4	0.0
	PMTL	91.8	4.1	4.1

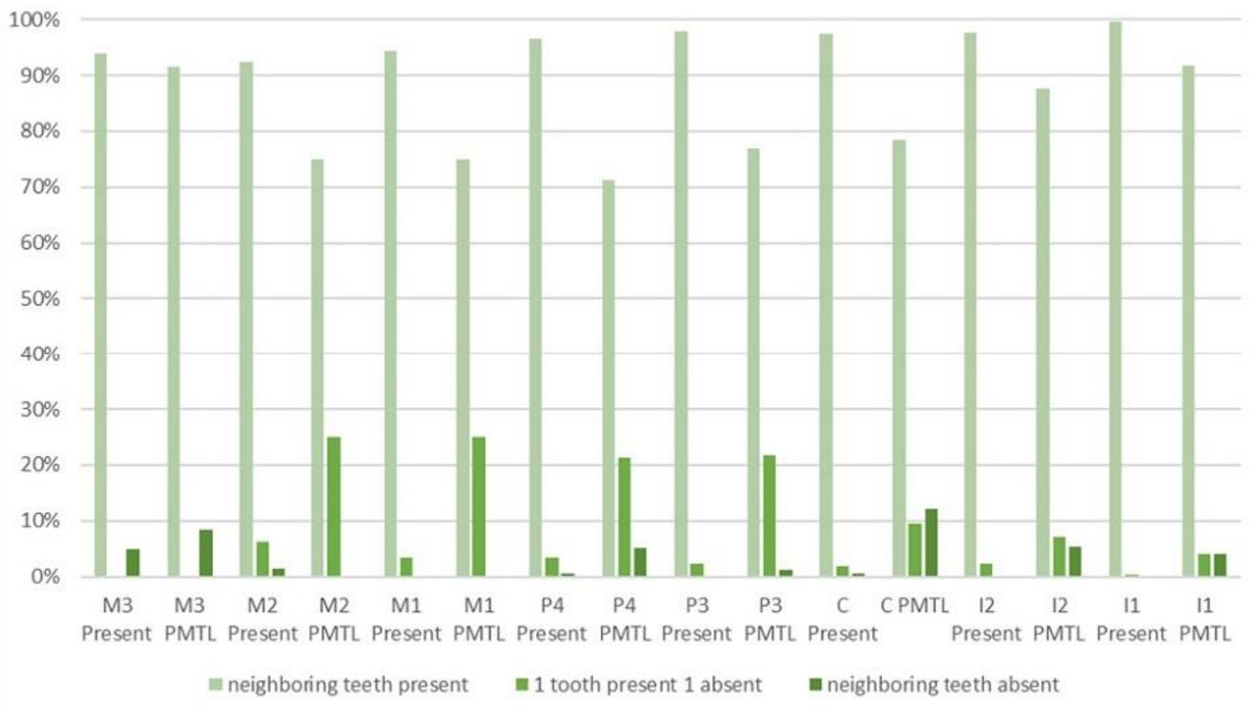

Figure 1. Visual comparison of the prevalence of neighboring tissue categories.

Table 3. Prevalence of all three dental caries inventory categories.

Tooth	Condition	All neighboring teeth no caries (%)	1 neighboring tooth with caries (%)	2 neighboring teeth with caries (%)
M3	Present	95.3	4.7	n/a
	PMTL	98.0	2.0	n/a
M2	Present	92.6	7.4	0.0
	PMTL	93.3	6.7	0.0
M1	Present	96.7	3.3	0.0
	PMTL	88.9	11.1	0.0
P4	Present	97.2	2.8	0.0
	PMTL	96.4	3.6	0.0
P3	Present	98.5	1.5	0.0
	PMTL	100.0	0.0	0.0
C	Present	98.9	0.7	0.3
	PMTL	100.0	0.0	0.0
I2	Present	99.0	1.0	0.0
	PMTL	100.0	0.0	0.0
I1	Present	97.9	2.1	0.0
	PMTL	100.0	0.0	0.0

mental group. Control groups for third molars, second molars, third premolars, canines, and all incisors each had a higher percent of neighbors with carious lesions than their experimental counterparts. When isolated to show teeth that had one neighboring tooth present and one with AMTL, carious lesions were only observed in posterior teeth, consistent with existing literature. Caries rates were again higher in the control group, with a large increase from 80% present second molars with the observable neighbor displaying no caries, to 100% in the neighbors of the PMTL second molars. There was no caries-focused analysis of the difference between present and PMTL teeth with both neighbors absent because, unlike periapical lesions that affect tissue other than on the actual tooth, neighboring teeth necessarily must be present to observe dental caries lesions.

Periapical Lesions and Neighboring Tissues

Following the framework of the caries-focused examination of neighboring teeth, the neighboring tissues (both tooth and alveolar socket) were examined for periapical lesions. Table 4 shows a comparison of the prevalence of periapical lesions when both neighboring teeth were present. The experimental group in every tooth group had more periapical lesions in the neighboring tissues than the control group, except for first molars which had a 1.0% increase in prevalence of no periapical lesions when the primary tooth was recorded as PMTL. The smallest change was a 0.4% decrease in central incisors, and the greatest change was the 18.4% decrease in lateral incisors.

Generally, periapical lesions had a greater influence on non-molar teeth, which was particularly apparent for periapical lesions in teeth with one neighboring tooth present and one lost antemortem. Although there is no particular pattern in the posterior teeth (i.e., minimal differences observed between control and experimental groups), the anterior teeth and fourth premolars show a consistent decrease in unaffected neighboring tissue in the experimental groups (as depicted in Figure 2). The difference between all control and experimental groups shows an average 27% decrease (23.5-33.3%, min-max).

There was not enough data to see a pattern in instances where both neighboring teeth were absent, but the inability to gather enough instances of control data to provide a comparison may be telling. No data showed PMTL with two AMTL neighbors, with a maximum count of nine when divided by tooth number, and with no molars fitting these criteria. With few exceptions, this data set failed to show a present tooth that had two AMTL neighbors. Twelve instances were recorded in second molars, four in fourth premolars, and four in canines. All other teeth had no instances of this tooth loss pattern.

It is possible that some oral pathological conditions may not affect neighboring tissues but are more limited to the individual tooth. Given the expectation that missing neighbors will compromise the maintenance of the primary tooth being analyzed, especially in the case of periapical lesions that affect tissues of the jaw as well as the tooth, it is not surprising that two missing neigh-

Table 4. Prevalence of all three periapical lesion inventory categories.

Tooth	Condition	No PL on all neighboring teeth (%)	1 neighboring tooth with PL (%)	2 neighboring teeth with PL (%)
M3	Present	96.8	3.2	n/a
	PMTL	94.1	5.9	n/a
M2	Present	93.0	7.0	0.0
	PMTL	80.0	20.0	0.0
M1	Present	99.1	0.9	0.0
	PMTL	100.0	0.0	0.0
P4	Present	94.1	5.7	0.2
	PMTL	84.5	14.3	1.2
P3	Present	99.9	0.1	0.0
	PMTL	93.3	5.0	1.7
C	Present	99.1	0.9	0.0
	PMTL	98.3	1.7	0.0
I2	Present	99.2	0.8	0.0
	PMTL	80.8	15.2	4.0
I1	Present	98.9	1.1	0.0
	PMTL	98.5	1.5	0.0

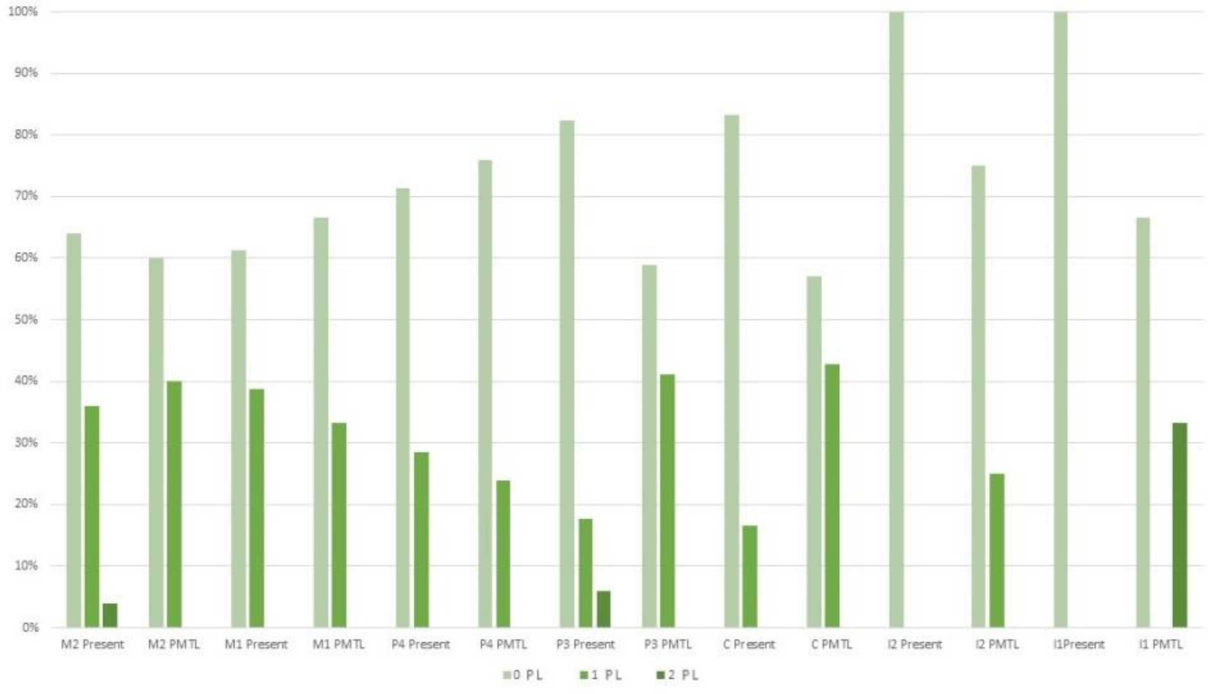

Figure 2. Visual comparison of the prevalence of neighboring tissues exhibiting periapical lesions when one neighboring tooth is present and one is AMTL.

bors make the tissues less likely maintain a tooth. Thus, a large enough control group sample was unavailable for this analysis. This was the only situation where the experimental sample was larger than the control sample.

Affected Neighbors

Because multiple dental conditions can be present in the same individual (even on the same tooth) and would not be accounted for when analysis narrows to focus on a single pathological condition at a time, the scope of analysis was expanded to look at the effects of neighboring tissues affected by either caries or periapical lesions. This included AMTL as an indicator of the final stage of either pathological condition, where the tooth could not be maintained in life.

Figure 3 shows the percentage of neighboring teeth for each tooth position (control) and PMTL, divided by no affected neighbors, one affected neighbor, or both neighbors affected. To be categorized as "affected," a tooth or its surrounding tissue needed to display carious lesions, periapical lesions, be absent antemortem, or any combination of the three conditions. Because third molars only have one neighboring tooth, they again could only be recorded as having one affected neighbor or no affected neighbors.

There is a clear pattern in the visual comparison that PMTL is often surrounded by "affected" or tissues without any indication of disease. In the control groups, the tooth had two unaffected neighbors an average of 92.0% of the time (Table 5). By contrast, the PMTL groups had only an average of only 70.5%. The smallest difference was between the control and PMTL groups for third molars (3.4%), while the largest difference was between the control and PMTL groups for first molars (36.0%).

The PMTL group with the highest percent of two unaffected neighbors was the central incisor. If neighboring tissues do not contribute to its loss in a significant way, then retention of the central incisor is the least influenced by tissue health and tooth loss must be attributed to other, taphonomic factors. This is perhaps the most common taphonomic loss due to the instability of a single location at the anterior of the mouth (exposing it to maximum pressure in burial and collection storage).

The difference in the distribution of one affected neighbor and both neighbors affected also showed an interesting pattern. Non-molar teeth had a much greater percentage of two affected neighbors. The average of non-molar PMTL with two affected neighbors was 9.0% and varied from 6.0 to 12.0%.

Although it is common to see a difference between third molars and the other molars because of the unique single-neighbor quality and differ-

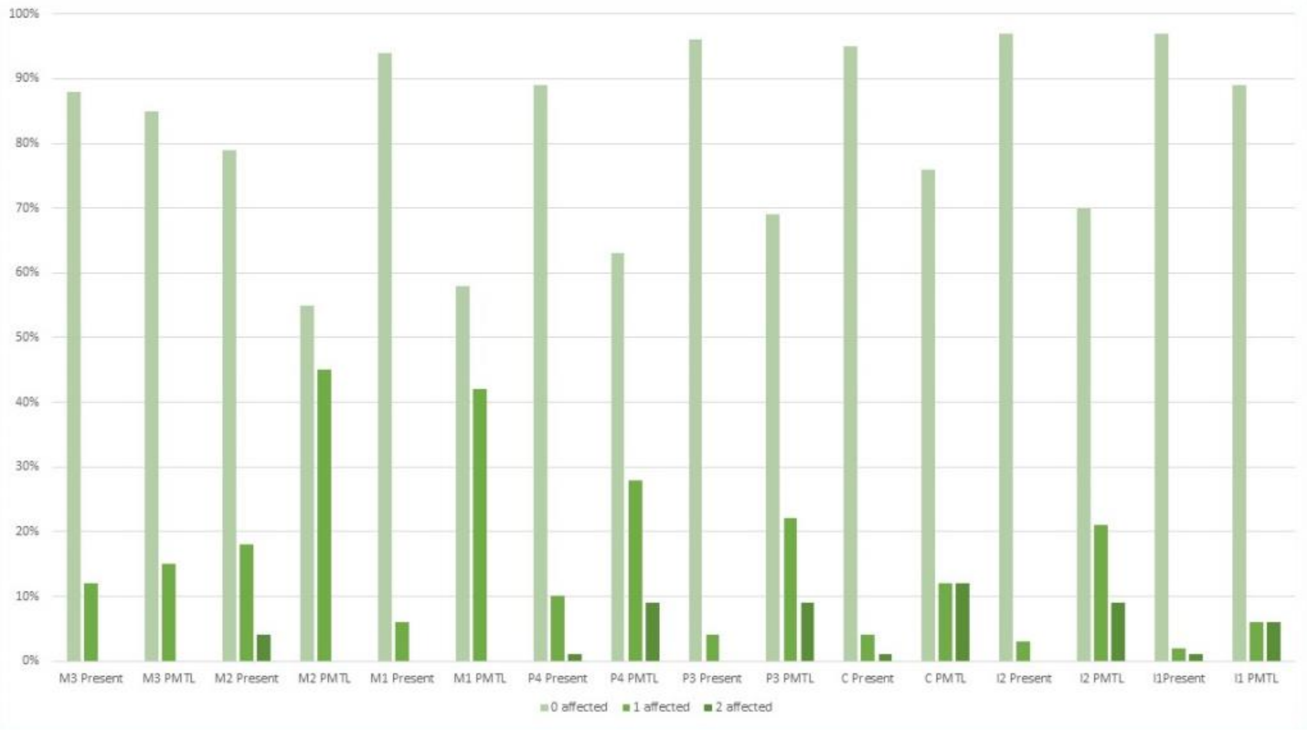

Figure 3. Visual comparison of the prevalence of "affected" neighboring tissues.

Table 5. Prevalence of all three "affected" inventory categories

Tooth	Condition	All neighboring teeth unaffected (%)	1 neighboring tooth affected (%)	2 neighboring teeth affected (%)
M3	Present	88.3	11.7	n/a
	PMTL	84.9	15.1	n/a
M2	Present	78.8	17.7	3.5
	PMTL	55.0	45.0	0.0
M1	Present	94.4	5.6	0.0
	PMTL	55.0	41.7	0.0
P4	Present	88.8	10.1	1.2
	PMTL	62.7	28.0	9.3
P3	Present	96.2	3.5	0.0
	PMTL	69.2	21.8	9.0
C	Present	95.5	3.5	1.0
	PMTL	75.7	12.2	12.2
I2	Present	96.6	3.1	0.3
	PMTL	69.9	21.2	8.8
I1	Present	97.1	2.1	0.8
	PMTL	88.7	5.6	5.6

ences in eruption times, this is one of the only comparisons from this research that showed variation between the second and first molars. They are typically assumed to have similar physical characteristics that make them susceptible to caries, but also are multi-rooted teeth, providing them similar connective stability.

Discussion

The "neighboring tissues" test was designed to determine whether oral pathological conditions influenced PMTL versus solely taphonomic explanations. Patterns between control teeth and PMTL indicate that the integrity of the surrounding tissues affects the retention of a tooth after death. Although there were specific patterns associated with periapical lesions alone, the overall patterns indicated that dental caries does not affect the ability of the tissues to retain a tooth after death. When both neighboring teeth were present, most teeth showed a decrease in carious lesions in the surrounding teeth in the experimental (PMTL) group. This is contrary to the expectation that missing teeth would have more affected neighbors in the presence of any oral pathological condition. However, the experimental group presented more periapical lesions in the neighboring tissues than the control group. Periapical lesions tended to have a greater effect on non-molar teeth. Although there were specific patterns associated with the presence of dental periapical lesions as a solitary pathological condition, dental caries lesions did not affect the ability for the tissues to retain a tooth after death.

To address tissues that have been impacted vs. not impacted by disease, rather than exclude compromising conditions by creating a false categorization that separates dental caries and periapical lesions, the data were lumped into an "affected tissues" test. This clear difference between control and experimental groups supports the research hypothesis that affected tissues are correlated with prevalence of PMTL.

Overall, the analyses conducted indicate that PMTL is often a consequence of pathological conditions rather than solely due to taphonomic damage. Thus, it should be possible to adjust data related to PMTL in the same way AMTL is corrected to generate more reliable caries rates. Using indicators of disease in the surrounding tissues, the presence of a pathological condition in the missing tooth can potentially be inferred, adjusting prevalence rates in a skeletal sample. As with the caries correction factors for AMTL, a sliding scale or population-specific method is needed. This would need to be calculated based on the integrity of the visible tissues and can only be accomplished if PMTL is considered a consequence of pathology, rather than simply the result of postmortem damage to the alveolar bone. More elaborate and precise observations need to be incorporated into the inventory methodology.

Current inventory recommendations only consist of practicing extra care while analyzing the fragile alveolar bone and recording missing teeth as "absent, without alveolar bone remodeling, postmortem tooth loss". There is no current method for recording teeth that are loose and replaced in their crypt, other than recording them as present, which does not distinguish them from teeth that are maintained in the crypt by supporting tissues. A new category should be added to the inventory methods to reflect this difference when inventorying teeth.

If teeth are "absent through postmortem tooth loss" or "present but loose/removable from crypt without force", observations can be made to examine the empty crypt for signs of pathology in the tissue. A closer look during analysis using clues of the surrounding tissue may help indicate the health of the missing teeth, given our improved understanding of how pathological conditions specifically affect tooth retention. Collecting this data will permit a wider range of calculations of dental pathology prevalence for data sets.

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Dental Anthropology

Volume 35, Issue 01, 2022

Data Set

Technical Note

Research Article

Published at:
The University of Nevada, Reno
1664 North Virginia, Reno, Nevada, 89557-0096 U.S.A.