A Contextualized Enamel Growth Rate and Thickness Data Set Collected from British Populations Spanning the Past 2,000 Years

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**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 Radovčič, 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 Tanijirī, 1997; Kono et al., 2002; Smith et al., 2006a; Kono and Su- wa, 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 analy-
sis 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.

<table>
<thead>
<tr>
<th>Population</th>
<th>Date</th>
<th>Location</th>
<th>Collection Name</th>
<th>Number of teeth sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>All combined</td>
<td>70-~2000AD</td>
<td>England and Scotland</td>
<td>N/A</td>
<td>81</td>
</tr>
<tr>
<td>Roman</td>
<td>70-400AD</td>
<td>Cirencester, Gloucester</td>
<td>St James’ Place/Bath Gate</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ozengell</td>
<td>11</td>
</tr>
<tr>
<td>Early Pre-Medieval</td>
<td>500-600AD</td>
<td>Ramsgate, Kent</td>
<td>Black Gate</td>
<td>22</td>
</tr>
<tr>
<td>Late Pre-Medieval</td>
<td>800-1200AD</td>
<td>Newcastle-Upon-Tyne, Northumberland</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Medieval</td>
<td>1100-1500AD</td>
<td>Canterbury, Kent</td>
<td>St Gregory’s Priory</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>1000-1600AD</td>
<td>York, North Yorkshire</td>
<td>Fishergate House</td>
<td>8</td>
</tr>
<tr>
<td>Modern-day</td>
<td>Extracted within the last 20 years</td>
<td>Newcastle-Upon-Tyne and Glasgow</td>
<td>UCL/Kent</td>
<td>12</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Population</th>
<th>Number of male individuals</th>
<th>Number of female individuals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper incisors</td>
<td>Upper canines</td>
</tr>
<tr>
<td>Known sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern-day</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Estimated sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early Pre-Medieval</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Late Pre-Medieval</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Medieval</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Roman</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>
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 antimer 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 al., 1969). The Pre-Medieval period in Thanet is associated with newly developing urban areas following Roman occupation (McKinley et al., 2015).

![Figure 1](image_url)  
*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.*
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

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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.
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 cusps 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.
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.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Time Period</th>
<th>Tooth Types</th>
<th>N</th>
<th>Data collected</th>
<th>Data level presented at</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Beynon et al., 1991b</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Molars</td>
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<td>X</td>
<td>X</td>
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<td>Lacruz and Bromage, 2006</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Molars</td>
<td>10</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Smith et al., 2007</td>
<td>Various</td>
<td>Various</td>
<td>First molars</td>
<td>21</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Smith et al., 2009</td>
<td>Germany</td>
<td>Modern-day</td>
<td>Third molars</td>
<td>7</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mahoney, 2008</td>
<td>England and Scotland</td>
<td>Bronze-Age</td>
<td>First molars</td>
<td>13</td>
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<td>Schwartz et al., 2001</td>
<td>England and South Africa</td>
<td>Modern-day</td>
<td>Canines</td>
<td>28</td>
<td>X</td>
<td>X</td>
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<tr>
<td><strong>Thickness data</strong></td>
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<td></td>
<td></td>
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<td>Middle Stone Age and Modern-day</td>
<td>Molars</td>
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<td>X</td>
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<td>Olejniczak et al., 2008*</td>
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<td>Various and unknown</td>
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<td>Molars</td>
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<td>Unknown</td>
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<td>Various</td>
<td>12-58</td>
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<td></td>
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<td>Sorenti et al., 2019</td>
<td>Madrid, Spain</td>
<td>20th Century</td>
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<td>Kono, 2004*</td>
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<td>Molars</td>
<td>40-41</td>
<td>X</td>
<td>X</td>
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<td>Second molars</td>
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<td>15-37</td>
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<td>Gantt and Rafter, 1998</td>
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<td>Unknown</td>
<td>Molars</td>
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<td>X</td>
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<td>Mahoney, 2010</td>
<td>England and Scotland</td>
<td>Various</td>
<td>Molars</td>
<td>69</td>
<td>X</td>
<td>X</td>
</tr>
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<td>Suwa and Kono, 2005*</td>
<td>Ohio, USA</td>
<td>800-1100AD</td>
<td>First molars</td>
<td>31-37</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Kono et al., 2002*</td>
<td>Asia</td>
<td>Unknown</td>
<td>First molars</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>Macho and Berner, 1993</td>
<td>Zwentendorf, Austria</td>
<td>1100AD</td>
<td>First molars</td>
<td>21</td>
<td>X</td>
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<tr>
<td>Saunders et al., 2007</td>
<td>Belleville, Canada</td>
<td>1821-1874AD</td>
<td>Canines and premolars</td>
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<td>X</td>
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<tr>
<td>Feeney et al., 2010*</td>
<td>Indonesia</td>
<td>Modern-day</td>
<td>Canines</td>
<td>7-21</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Buti et al., 2017*</td>
<td>Various</td>
<td>Medieval and Clinical</td>
<td>Canines</td>
<td>1-13</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

*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).

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