McFarlane, Gina, Floyd, Bruce, Smith, Caitlin and Mahoney, Patrick (2021) ***Estimating original crown height in worn mandibular canines using aspects of dentin morphology.*** **American Journal of Physical Anthropology, 176 (34). pp. 692-702. ISSN 0002-9483.**

Estimating original crown height in worn mandibular canines using aspects of dentin morphology

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ABSTRACT

Objectives

We present a novel method to estimate original crown height (OCH) for worn human mandibular canines using a cubic regression equation based on ratios of worn crown height and exposed dentin. This method may help alleviate issues frequently presented by worn teeth in dental analyses, including those in bioarchaeology.

Materials and Methods

Mandibular canines (*n* = 28) from modern day New Zealand and English populations were selected. Crown height and dentin thickness were ~~are~~ measured on dental thin sections (n = 19) and the resulting ratios (log10) were fitted to a cubic regression curve allowing OCH in worn crowns to be predicted. Variation in the dentin apex position was recorded and effects of angled wear slopes investigated allowing adjusted values to be generated. Our method is trialed for use on intact and sectioned teeth (*n* = 17).

Results

A cubic regression curve best describes the relationship between (log10) ratios and crown height deciles (R^2 = 0.996, df_1=3, df_2 = 336, p <0.001). No significant differences were detected between OCH estimates using our method and digitally recreated cusp outlines of the same crowns (t = 1.024, df = 16, p > 0.05), with a mean absolute error of 0.171 mm and an adjusted coefficient of determination of 0.923.

Conclusion

Our approach offers a quantitative method to estimate the percentage of OCH remaining on worn mandibular canines, and by extension, the original crown height. Our estimates are comparable to ~~with~~ digitally recreated cusps but are less subjective and not limited to crowns with minimal wear.

Keywords

Human canines, crown height, dental wear, dentin morphology, enamel hypoplasia

1 | INTRODUCTION

A broad range of anthropological studies rely on dental analysis as a primary means of investigation, including many within paleoanthropology (e.g., Cunha et al. 2004; Dean and Reid, 2001; Ramirez Rozzi & Bermudez de Castro, 2004; Guatelli-Steinberg, Reid, & Bishop, 2007; Mahoney 2008; Modesto-Mata et al., 2020a) and bioarchaeology (e.g., Amoroso, Garcia, & Cardoso, 2014; Berbesque & Doran, 2008; Cucina & Iscan, 1997; Bocaege & Humphrey, 2016; Littleton, Allen, and McFarlane, 2015; Nava, Frayer, and Bondioli, 2019; Temple, 2016). Worn teeth can be a limiting factor for anthropological studies ~~in many of these analyses~~, particularly when original, or unworn crown height is required. Variation in tooth dimensions has been a focus of investigation for over a hundred years (Kieser, Groeneveld, McKee, & Cameron, 1990), with crown height being the third most common measurement. However, it is also the trait most affected by occlusal wear (Pilloud & Kenyhercz, 2016). The goal of this investigation is to develop a method for estimating the original height of worn mandibular canines based on consistent and scalable characteristics of dentin morphology. Mandibular canines were selected for this trial because, in humans, this tooth type has the longest crown that records enamel formation for over five years (Reid and Dean 2006). This means they are frequently analyzed in terms of lateral enamel formation (e.g., Dean and Reid, 2001; Guatelli-Steinberg et al., 2007; Reid and Ferrell, 2006; McFarlane, Littleton, and Floyd, 2014) and linear enamel hypoplasia, a nonspecific stress defect (e.g., Amoroso et al., 2014; Berbesque & Doran, 2008; Cucina & Iscan, 1997; Goodman and Rose 1990; Guatelli-Steinberg & Lukacs, 1999; Miszkiewicz, 2015).

In paleoanthropology, the pace of dental development can provide important insight into interspecies variation in the tempo of life history traits (Dean 2006; Smith 1984). When perikymata (incremental ridges on the surface of lateral enamel) are analyzed in terms of their spacing along the crown surface, they directly reflect the pace of imbricational enamel formation (Dean and Reid, 2001; Reid and Ferrell, 2006; McFarlane et al., 2014) and provide a basis for exploring dental developmental differences between hominin species (e.g., Dean and Reid 2001; Guatelli-Steinberg and Reid, 2010; Guatelli-Steinberg et al., 2018; Modesto-Mata et al., 2017, 2020). Despite the loss of occlusal enamel, worn crowns can still provide important information as typically in modern humans, the cervical half of crowns display most variation among individuals in the pace of enamel formation (Reid and Ferrell, 2006; McFarlane et al., 2014). The height of the unworn crown, however, is necessary to ensure deciles (10% increments of crown height commonly used to assess perikymata) are correctly positioned. Otherwise, perikymata counts and their distribution along the crown may not be accurate.

In bioarchaeology, dental wear can limit our ability to effectively estimate the age at which individuals ~~when they~~ developed linear enamel hypoplasia (LEH). These defects record episodes of non-specific physiological stress experienced during infancy and childhood during the period that enamel forms (Goodman and Rose, 1990; Witzel, Kierdorf, Schultz, and Kierdorf, 2008) and as such, offers valuable insights about heath in past populations (e.g., Amoroso et al., 2014; Berbesque & Doran, 2008; Cucina & Iscan, 1997; Goodman and Rose 1990; Geber, 2014; Littleton, 2005; McFarlane, 2018; Miszkiewicz, 2015; Palubeckaitė, Jankauskas, & Boldsen, 2002; Ritzman, Baker, & Schwartz, 2008; Temple, 2012). There are several methods used to estimate the age of an individual when a defect formed, including decile-based age schedules (Reid and Dean 2000; 2006) and regression equations (Goodman, Armelagos, & Rose., 1980; Goodman and Rose, 1990). The accuracy of both techniques depends on a complete crown height

Most erupted tooth crowns have some degree of wear, particularly archaeological specimens (Hillson, FitzGerald, & Flinn, 2005). Analyzing only unworn or minimally worn crowns can limit interpretations due to small sample sizes and introduce bias toward younger individuals who generally have less occlusal wear (Miles, 2001). To resolve these issues, researchers often exclude teeth that have less than 80% of the original crown height remaining and subsequently digitally recreate cuspal profiles to reconstruct the original shape and height (e.g., Dean and Reid, 2001; Saunders, Chan, Kahlon, Kluge, & FitzGerald, 2007; Martin, Guatelli-Steinberg, Sciulli, & Walker, 2008; Guatelli-Steinberg et al., 2007, 2009, 2018; Guatelli-Steinberg and Reid, 2010). This approach can minimize error but depends on the experience of the researcher to produce accurate reconstructions. Recent work, however, addresses the subjectivity concerning molar cusp recreation (Modesto-Mata et al., 2020b). Other solutions include using mean population or sample crown heights (Hodges and Wilkinson, 1990; Song and Goodman, 1999), but this can introduce substantial error at the individual level, as it does not account for individual variation in tooth size.

In a previous trial we found that the dentin profile of a cross section was particularly robust in terms of scalable proportions, unlike enamel thickness that is more variable along the length of the crown (McFarlane, 2013). This means that regardless of overall crown size or height, dentin thickness changes in a predictable manner when measurements are standardized to crown height, as percentages. The aim of this investigation is to assess whether unworn original crown height (OCH) can be estimated from measurable features visible on the surface of worn mandibular canines. We evaluate how consistently dentin morphology co-varies with the progressive loss of height in mandibular canines and assess its usefulness to estimate OCH in worn teeth. If a regression formula can accurately describe ratio changes in these features along the length of a crown, the percentage of OCH remaining on a tooth should be predictable. In addition, we want to assess variation in the position of the dentine horn beneath the cuspal enamel to accurately identify its typical location without needing to section teeth. We also explore the impact that angled occlusal wear surfaces can have on our OCH estimations and suggest adjusted estimations based on the degree of the wear angle (see Supplementary Information). Finally, to check the usefulness of our proposed method, we test the inter-observer error between estimates from two observers and compare these to estimates from digitally recreated cusp outlines of the same crowns using a commonly employed method (Guatelli-Steinberg et al., 2009; Saunders et al., 2007).

2 | MATERIALS AND METHODS

2.1 | Dental samples

Our sample consists of 28 permanent mandibular canines in total. Nineteen of which were extracted from modern New Zealanders as part of routine dental procedures and collected by Dr. R.M.S. Taylor who donated them to the University of Auckland during the 1970s. This collection is curated by the School of Social Science, University of Auckland. Ethnicity was not available but based on New Zealand Census data (Statistics New Zealand, 2014) the sample is most likely comprised of individuals of British, Māori, Samoan, and Chinese ancestry. These teeth were either unworn or exhibited minimal wear i.e., wear scores of 1 to 2 (Smith, 1984) and were used to produce thin sections. Nine additional teeth from modern British individuals are used to trail our method using intact crowns, which showed minor wear i.e., wear scores of 2 to 3 (Smith, 1984). Ethnicity is unknown and are best considered as multi-ethnic British. The British specimens are part of the UCL-Kent collection curated in the Human Osteology Lab, University of Kent. Ethical approval for histology research on the sample of British teeth was obtained from the UK National Health Service research ethics committee (REC reference: 16/SC/0166; project ID: 203541). All specimens are anonymized with no information regarding age or sex.

2.2 | Sample preparation

Thin sections of 19 mandibular canines were produced using standard histological methods. Teeth were sectioning through the teeth through the labial-lingual plane of the crown (e.g., Reid et al. 1998; Mahoney, 2015). To ensure the correct section line was obtained, the cuspal tip and the most cervical extent of the enamel on the labial and lingual aspects were marked with an indelible pen prior to positioning on the saw. The section line was only referenced to the crown, rather than the whole tooth, as roots can be quite variable in their curvature.

The sections were imaged under (40x) transmitted light microscopy (Leica MDR) and photomontages were created using Inkscape software (Free Software Foundation Inc.). This produced a single complete image of each crown. Most cusps possessed some degree of wear, even if only very minor wear facets. Therefore, to ensure the assessments reflected original unworn crown height as accurately as possible, the original profile of the cusps in section were recreated using a Bézier curve function, which follows the natural extension of the labial and lingual crown surface curves. This procedure recreates the original cusp outline and is based on the method described in Saunders et al. (2007) and later assessed by Guatelli-Steinberg et al. (2009).

2.3 | Determining ratios & dentin apex position.

Dental thin sections were used to calculate the initial ratios of crown height and dentine thickness that underpin the development of our method. Ratios were calculated from measurements of vertical crown height and dentin thickness (crown height/dentine thickness), assessed in series at each 5% of OCH using ImageJ open-source software (version 1.5), see Figure 1. Vertical crown height, as opposed to crown length, is used to ensure heights are comparable to those measured on intact crowns and so ensure that our regression formula is applicable for use on intact teeth.

To identify where the apex of the dentin horn is typically located as a percentage of OCH, measurements were taken from the most cuspal extent to the apex of the horn (Figure 1).

{Figure 1}

2.4 | Computation of the cubic regression curve.

Once ratios were calculated, several parametric curves were fit. A cubic regression (Equation 1) provided the best fit judging from the percentage of variance accounted for and distribution of residuals. All statistical tests were conducted using IBM SPSS (version 20) and an alpha level of 0.05 used to judge statistical significance.

EQUATION 1: $Y = \alpha + \beta_1 (\text{ratio}) + \beta_2 (\text{ratio}^2) + \beta_3 (\text{ratio}^3)$

Where Y is an estimate of the percentage of original crown height (OCH%) that remains of the worn crown and β_1, β_2, and β_3 are the slopes associated with the log10 transformed ratios of worn crown height and exposed dentin. OCH in millimeters can be calculated by dividing worn crown height (mm) by the percentage crown remaining (OCH%) represented as a decimal fraction.

2.5 | Applying the method to intact crowns.

Although our regression formula is developed using thin sectioned crowns, in practice it ~~will~~ can be applied to intact teeth. Here, we outline our approach to measuring intact crowns.

If no measurable loss of height has occurred (i.e., score 1, Smith 1984), total crown height can be measured directly. If some loss of crown height has occurred but dentin is not exposed, the percentage of height lost is based on the proximity of the dentin apex assessed by its visibility beneath the enamel, see Results section Figure 4.

When wear has progressed past the apex and dentin is exposed, worn crown height and dentin thickness are measured and the cubic regression formula is applied to establish the remaining percentage of original crown height (OCH%). Exposed dentin is measured using fine nosed digital calipers under a magnifying lamp as it is crucial that assessments are as accurate as possible. Dentin thickness is measured across the dentin at the crown midline from the most labial to the most lingual extent, taking care that only exposed dentin is measured within the surrounding enamel margin. Worn crown height is assessed as vertical crown height measured strictly along the midline from the most apical extent of the crown at the cementoenamel junction to the most cuspal extent. To ensure that vertical height is measured accurately, it is important that the calipers are parallel to the long axis of the tooth. We found this easiest to measure with the tooth positioned in a measuring cradle.

The worn crown height and dentin measurements are converted to ratios (crown height / dentin thickness), log transformed (log10), and applied to the cubic regression equation. If the occlusal wear is approximately horizontal, the resulting value will be the percentage of original crown height that remains on the tooth. If the wear surface is markedly sloped, i.e., equal to or greater than 10^{o}, the angle is measured using a protractor on the crown side that best represents the wear slope at the midline. Once the angle is known, the appropriate adjusted OCH can be determined, see Section 2.6.

2.6 | The effect of angled wear surfaces.

A sloping wear surface can cause a greater amount of dentin to be exposed than is expected by the equation at a given height, but Table 1 corrects for this based on the approximate angle degree. The technique used to produce the adjusted OCH% estimates is available as Supplementary Information.

This additional step is only required for crowns with angled wear slopes to maintain equivalence between dentin measured superiorly (as with intact teeth) and horizontally (as used in the regression equation). Once the unadjusted estimate of OCH% has been calculated and the angle measured, the corrected estimate can be identified in Table 1. Angles less than 10^{o} have only a negligible effect. Values that fall between those listed are first rounded to the nearest 10^{o} ,20^{o}, or 30^{o}. Next, the unadjusted OCH % is located in the column under the appropriate angle and the corresponding value in the adjusted OCH% is identified. For example, a crown that is estimated to have an unadjusted value of 59% remaining with a ~20^{o} wear angle will have an adjusted OCH% of 65, meaning 65% of the original crown height remains. For unadjusted OCH values that are intermediate to those listed on Table 1, an intermediate adjusted OCH is also assumed. Thus, for a crown with a wear angle of 20^{o} and an unadjusted OCH of 80% (intermediate to 77 % and 83%), the final adjusted OCH% is estimated to be 83% complete as this falls approximately midway between the adjusted corresponding values of 80% and 85%.

{Table 1}

Once the remaining percentage of crown height is established, it is used to calculate the original height in millimeters by dividing worn crown height (mm) by the percentage crown remaining (OCH%) represented as a decimal fraction. For example, for a crown that is estimated to have 60% remaining of its original height, and has a worn height of 6.52 mm, will have an original height estimate of 10.86 mm.

2.7 | Accuracy testing

We used two different approaches to test how well our cubic regression formula could predict OCH: one using nine intact crowns and the other using eight images of artificially worn crowns. Eight images of four sectioned crowns were artificially worn by one of the authors (CM), which involved masking a portion of each image to replicate wear. The 'worn' images were then independently assessed by two observers (PM and GM) to produce to sets of OCH estimates.

To check how well our method can estimate OCH in practice, nine intact crowns were ~~also~~ assessed independently by the observers (PM and GM) using the procedure for intact teeth. Once intact assessments were complete, the crowns are half sectioned along the midline and the cut surface imaged so the cuspal outline could be digitally recreated and original height measured. Each cusp was digitally recreated independently by PM and GM (using the procedure outlined in section 2.2) and the two versions overlaid to check for discrepancies. Where slight deviations occurred, the two cuspal outlines were merged at the midpoints to create an averaged version. The degree of error between our proposed method, using the mean values of the two observers, and crown height estimates (based on digital recreations of the cusp outlines) was also assessed. Both inter-method and inter-observer error was assessed in terms of technical error of measurement, mean absolute error (MAE), Student's paired *t* test, and adjusted coefficient of determination (adjusted R^2). Technical error of measurement is a measure of precision between repeated measurements that determines the proportion of the total standard deviation attributable to measurement error (Ulijaszek & Kerr, 1999). Absolute mean error reflects the magnitude of absolute (unsigned) differences between the two sets of values. Student's paired *t* test is used to confirm whether the two sets of paired values differ significantly from each other, while adjusted coefficient of determination reports the percentage of values that lie within the expected linear relationship between the two data sets while taking into account the size of the data set and the number of divergent data points.

3 | RESULTS

3.1 | Ratios

Descriptive statistics for ratios of crown height and dentin thickness calculated at each 5% increment of crown height are shown in Table 2. Ratios become progressively smaller along the crown towards the cementoenamel junction as dentin thickness becomes increasingly wider. This shift is evident in the distribution of median ratio values from 90% to 5% of original crown height (see Figure 2). The greater range of values in each half decile segment from 90% to 80% of OCH reflects variation in the position of the dentin apex. Ratios greater than 45 at 90% OCH only occur when the apex was located at this level and signifies that the dentin horn has not actually lost height.

{Table 2}

{Figure 2}

3.2 | Curve fit

Using the percentage of OCH remaining as the dependent variable, we found the best curve fit was provided by a cubic regression curve of log10-transformed ratios, see Equation 2.

EQUATION 2: Y = 41.245; β_1 = 46.208, β_2 = 2.792, β_3 = -8.216

where Y equals the percentage of original crown height that remains on a worn crown (OCH%) and β_1, β_2, β_3 represent the slopes of the log-10 transformed ratio, its squared value and its cubic value, respectively.

This model demonstrated a very good fit across the range of data and the predicted curve (R^2 = 0.996, F = 27761.74, p <0.001, df_1=3, df_2 = 336, see Figure 3, upper), with residuals being small and mostly randomly distributed above and below zero with only limited evidence of autocorrelation at the extremes (Figure 3, lower).

{Figure 3}

3.3 | Dentin apex position

In the 19 mandibular canines evaluated, the apices of the dentin horn are located between approximately 95% and 90% of OCH, with most at approximately 93% OCH beneath the unworn cusp (Figure 4). Some apices, however, are situated very close to these limits - two were positioned at 95% and two at 90.0%. We also note that crowns with slight wear but neither a pinprick of dentin exposed nor the apex visible as a darker region under the occlusal enamel were typically between 95% and 97% complete.

{Figure 4}

3.4 | Trial

Nine intact and eight artificially worn crowns were independently assessed by two recorders (PM and GM). The percentage of original crown height remaining on each cusp was calculated using our described method and adjusted for wear angles, when necessary, using Table 1. The percentage of crown remaining was then used to calculate the original height of each crown in millimeters. Resulting OCHs (mm) are compared to the heights of the digitally recreated cusps of each crown (Table 3).

{Table 3}

3.5 | Error assessments

First, inter-observer error was assessed between the two observers (PM and GM), then comparisons were made between the digitally recreated crowns and our method using the mean values of the two observers. Composite images showing OCH estimates by the two observers together with the height of the recreated cusps are available in Supplementary Images.

Technical error of measurement (TEM), mean absolute error (MAE), Student's paired t statistic, and the adjusted coefficient of determination were calculated for both sets of comparisons (Table 4). TEM and MAE were slightly lower between the two observers than between the two methods (our proposed method versus digitally recreated cusps). This suggests slightly greater error is present between the two methods than exists between the two methods. The paired *t* test confirms no significant differences were detected between the two sets of height measurements when either observers or methods were compared. The adjusted coefficient of determination, which assumes a linear relationship exists between the two data sets (i.e., R^2), suggests crown height estimates between the two observers vary by 5% (1 - 0.947), while the two methods vary by 8% (1 - 0.923).

{Table 4}

4 | DISCUSSION

Here we present a novel method to estimate OCH for worn mandibular canines. This procedure is effective because it utilizes a consistent and scalable relationship between dentin morphology and crown height. This relationship means that crown height, when standardized as a percentage, can be associated with specific ratios of worn crown height and dentin thickness (Figure 5). The ratios, when Log10 transformed, were found to closely approximate a cubic regression curve such that the percentage of original crown height remaining on a worn crown could be predicted with good accuracy (R^2 = 0.996).

{Figure 5}

Crown height estimates obtained using our method on intact crowns did not differ significantly to estimates based on digitally recreated cusps, which is an accepted technique for estimating the full extent of cusps with minor wear (e.g., Saunders et al., 2007). Specifically, 92% of the variation in crown height estimates obtained using our method is explained by crown heights of the digitally recreated crowns. An advantage of our system is that it relies upon ~~permits~~ a quantitative method to estimate the extent of occlusal wear in crowns that have lost more than 80% of their original height~~, which can be difficult to accurately establish~~.

~~We believe~~ Our method will be useful for analyses that require original height of lower canines, including the correct placement of crown deciles. This means, for example, that the timing of LEH defects and perikymata counts per deciles can be established more accurately in worn crowns. In some situations, this may allow the inclusion of worn teeth that would typically be excluded from analysis, such as those with less than 80% of crown height remaining. ~~to still be analyzed~~. Furthermore, because the method offers a quantitative approach, it should help eliminate a potential source of variation between studies that estimate original crown height. A future direction is to calculate tooth specific regression formulae, so our method can be expanded to all teeth thereby permitting a quantified approach to recording dental wear.

As the mandibular canine is a sexually dimorphic tooth (Fernée, Zakrewski, and Brown, 2021; García-Campos et al., 2018; Saunders et al., 2007; Schwartz & Dean, 2005; Schwartz, Reid, and Dean, 2001), it would be useful to understand if sex might influence our regression formula. Specifically, male canines have more dentin relative to crown size than females, while females tend to have relatively more enamel (García-Campos et al., 2018; Saunders et al., 2007; Schwartz & Dean, 2005; Schwartz, et al., 2001). Although sex was not known for our sample, we did not observe variation in the ratios that would suggest a marked dimorphic response. However, if the depth of the dentine horn beneath the cusp varied by sex, this could explain the slight variation in ratios we noted in the upper deciles. It is also possible that while dentin proportions are sexually dimorphic, dentin morphology may still scale accordingly. The crowns used to produce our regression formula varied in size from 9.66 to 12.34 mm, yet this did not influence their ratio values. Ideally, these aspects should be tested in a dental sample of known sex.

The TEM and MAE associated with inter-observer and inter-method comparisons are within the error ranges reported for standard buccal-lingual and mesial-distal crown measurements.

Although error assessments associated with crown height measurements are not reported, Kieser et al. (1990~~;524~~) report MAE for buccolingual and mesiodistal measurements that range from 0.172 to 0.740, which are higher than our inter-observer MAE (0.094)~~, while~~ . Our inter-method MAE (0.171) is similar to their lowest assessment. Hillson et al. (2005~~:421~~) report mean absolute differences for buccolingual and mesiodistal measurements that encompass our MAE and range from 0.038 to 0.310. Hillson at al. (2005) also report TEMs ranging from 0.037 to 0.566, which again encompass our TEMs for both inter-observer (0.094) and inter-method (0.149).

When applying our ~~the~~ method to intact teeth, we note two points to be aware of that could influence the accuracy of estimates. Firstly, due to the nature of the regression curve, we found ratios greater than 45 only occurred in situations where the dentin apex was exposed but wear had not progressed past that point and we had in fact measured across the exposed apex. This is important to note because such a ratio will yield an incorrect cubic regression product. However, it is simply remedied by assuming 90% of OCH remains for crowns that yield a ratio greater than 45. This considers that if significantly more crown height remained, the dentin apex would not be exposed, while if less remained the ratio would be lower – reflecting the loss of both dentin apex and crown height. Secondly, angled wear surfaces present a potential source of error~~ as~~ due to the increasing width of dentin in a cervical direction. Measurements taken from a superior aspect may tend to overestimate dentin thickness. However, we calculated adjusted OCH estimates based on the general angle of the surface wear to correct for this (see Supplementary Information).

~~This~~ Our method was developed using mandibular canines from modern New Zealanders, so we cannot be certain if dentin morphology might vary in other populations. Although our sample likely includes various population ancestry groups, and we did not observe any marked variation in ratio values that would point to obvious population differences, we cannot exclude the possibility that such differences might exist. ~~It is possible,~~ For example, ~~that~~ some of the variation in ratios noted in the first deciles could reflect population differences, but this needs to be more rigorously tested.

Our approach ~~of~~ using ratios of worn crown height and exposed dentin to estimate the remaining percentage of a worn crown can be applied to other teeth. This would however require a cubic regression equation ~~developed will need to~~ to be developed for each tooth type in addition to the lower canine. This is because variation in morphology exists even between upper and lower teeth of the same tooth type. Thus, our regression formula developed for mandibular canines is unlikely to be accurate for maxillary canines. Future work investigating the relationship between dentin thickness and crown height in other teeth (or cusps in the case of multi-cusped teeth) would allow tooth specific cubic regression curves to be established.

In summary, we present a novel quantitative method to estimate the original crown height of ~~in~~ worn mandibular canines. We ~~This is achieved by~~ utilized a scalable characteristic of dentin morphology to determine the percentage of original crown height ~~that~~ remaining on a worn crown, from which original crown height was ~~can then be~~ calculated. The effect that angled wear slopes might have on OCH estimates were ~~are~~ investigated and suggested adjustments are reported in Supplementary Information. We trialed our method on both intact crowns and artificially worn images of crowns but found crown height values did not differ significantly from those obtained when cusps were digitally recreated. Error values ~~that~~ are within, or lower than, those reported for other dental measurements obtained using calipers. ~~However,~~ Our method provides a quantified approach to estimating original crown height in worn teeth that is not limited to crowns with relatively minor wear.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

Data used in this investigation is available on request from the corresponding author.

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FIGURE LEGENDS

FIGURE 1 Mandibular canine crown in cross-section showing linear assessments of dentin thickness (white lines) and corresponding crown height at 5% increments of original crown height. Dotted line marks recreated cusp outline and black arrowhead points to dentin apex.

FIGURE 2 Box-and-whisker plots for each half decile (5% increments) represent the median, 25, and 75 centile values of estimated ratios along with minimum and maximum values and outliers.

FIGURE 3 Cubic regression curve (Y = 41.245; $\beta 1 = 46.208$, $\beta 2 = 2.792$, $\beta 3 = -8.216$) fit to log10 transformed ratios of worn crown height and dentin thickness (upper) and associated residual values (lower).

FIGURE 4 Location of dentin apices (n = 19) within the cuspal region (85% to 100% of original crown height).

FIGURE 5 Mean ratios of (worn) crown height and dentin thickness associated with specific percentages of crown height.