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Alternative Dental Measurements: Proposals and Relationships With Other Measurements

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ABSTRACT Most archaeological and fossil teeth are heavily worn, and this greatly limits the usefulness of tooth crown diameter measurements, as they are usually defined at the widest points of the crown. There are alternatives, particularly measurements at the cervix of the tooth, where the crown joints the root, and measurements along a diagonal axis in molars, that are much less affected by wear. These would allow a wider range of specimens to be included, e.g., in the study of dental reduction in Upper Palaeolithic and Mesolithic *Homo sapiens*. In addition, they would allow the little-worn teeth of children to be compared directly with well-worn teeth in adults. These alternatives, however, have been little used, and as yet there have not been any studies of the repeatability with which they can be measured, or of the extent to which they are related to the more usual crown diameters. The present study is based on a group of unworn teeth, where direct comparisons could be made between the alternative measurements, which are not much affected by wear, with the usual crown diameters, which are very much affected. In an interobserver-error study of this material, cervical and diagonal measurements could be recorded as reliably as the usual crown diameters. The buccolingual cervical measurement was strongly correlated with the normal bucclingual crown diameter in all teeth, whereas the mesiodistal cervical measurement was highly correlated with the normal mesiodistal crown diameter in incisors and canines, but less so in premolars and molars. The molar diagonal measurements showed high correlations with all other measurements. Crown areas (robustness index) calculated from the usual diameters were strongly correlated with crown areas calculated from cervical measurements, and crown areas calculated from molar diagonals were strongly correlated with both other areas. Despite the long usage of the more usual maximum crown diameters, the alternative dental measurements could be measured just as reliably, could record similar information about tooth crown size, and would be better measures for the worn dentitions seen in archaeological and fossil material. Am J Phys Anthropol 126:413–426, 2005.

Dental measurements are important in anthropology for the study of sexual dimorphism (Bermudez de Castro et al., 1993; Black, 1978; Brace and Ryan, 1980; De Vito and Saunders, 1990; Dean and Beynon, 1991; Ditch and Rose, 1972; Frayer, 1980; Garn et al., 1966, 1967a,b; Greene, 1973; Leutenegger and Cheverud, 1985; Moss, 1978; Rösing, 1983; Wolpoff, 1976; Yamada and Sakai, 1992), the trend toward tooth and jaw size reduction in Late Pleistocene/Early Holocene humans (Brace, 1964; Brace et al., 1987; Calcagno, 1989; Calcagno and Gibson, 1991; Carlson and van Gerven, 1977; Frayer, 1978, 1984; y'Edynak, 1989, 1992), and differences between past human populations (Harris and Rathbun, 1991; Kieser, 1990). Tooth crowns are routinely measured by mesiodistal and buccolingual crown diameters, which were first defined at least a century ago. Their definition was reassessed several times over the years (Kieser, 1990), but the most widely followed is that of Moorrees and Reed (1954). In this definition, the mesiodistal crown diameter is the largest mesial-to-distal dimension, taken parallel to the occlusal surface (Figs. 1, 2). The buccolingual crown diameter is then the greatest distance between the buccal (or labial) and lingual (or palatal) surfaces, perpendicular to the mesiodistal diameter. The system of measurements therefore centers on the axis of the mesiodistal crown diameter, but the line of the axis itself is not closely defined. Goose (1963) suggested that the mesiodistal diameter axis should run between the contact points of the tooth crown with its neighbors, in normal occlusion. In cases of malocclusion, the positions on the crown at which the contact points would have been in normal occlusion are used instead. In teeth such as unworn incisors and canines, the two definitions of mesiodistal crown diameter are in effect the same. The same is not necessarily true, however, of premolars and molars, in which the contact points may not be at the max-

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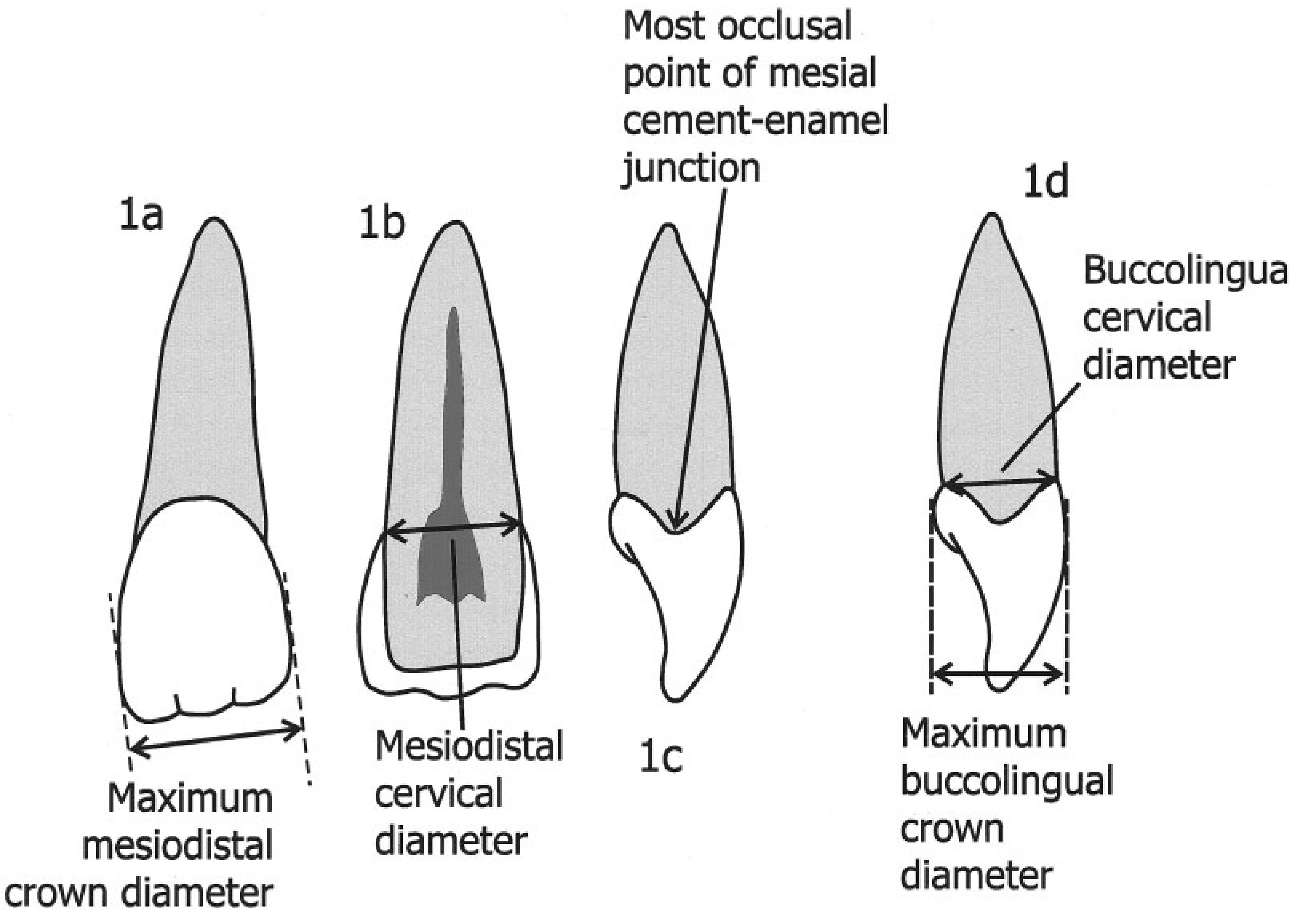

Fig. 1. Crown diameter and cervical diameter measurements in upper incisor. **a:** Labial view. **b:** Mesiodistal section. **c, d:** Mesial view.

imum bulge of the mesial and distal crown sides. Minor occlusal variations can therefore make a measurable difference to the mesiodistal diameter, if the definition of Goose (1963) is followed.

In theory, any change in the axis of the mesiodistal crown diameter would also change the measurement axis of the buccolingual crown diameter, which should be perpendicular to it, but in practice, there is no means by which the angle can be checked. The simplest way to take this measurement in incisors, canines, and premolars, therefore, is to find the maximum diameter from the buccal/labial to lingual crown surfaces by rotating the tooth crown slightly and taking repeated caliper readings. The result may not actually be perpendicular to the mesiodistal diameter, or to the occlusal plane, but as this can only be guessed in an isolated incisor or canine, it is not a realistic aim in any case. Most observers therefore either consciously or unconsciously relax the rules of measurement to some extent.

The buccolingual crown diameter of molars is much more worrying, because it is usually possible to take more than one maximum measurement between their buccal and lingual crown sides. In regularly shaped first and second molars (Fig. 2), there are two bulges on the buccal side and a single bulge on the lingual side. From the definitions above, a buccolingual measurement axis, perpendicular to the mesiodistal axis, should presumably start from this single lingual bulge. If it does, then the other end of the axis falls between the twin bulges of the buccal crown side, and therefore does not record the maximum diameter. The only way to achieve a maximum is to rotate the crown so that the measurement (Fig. 2) is between the lingual bulge and the larger of the two buccal bulges (usually the most mesial), but in that case, the axis is no longer perpendicular to the mesiodistal diameter (Tobias, 1967). This situation is more pronounced for upper molars, which are more asymmetrical. Added to this, for both upper and lower molars, the main bulge of the lingual crown side is at about midcrown height, whereas the buccal bulges are lower down toward the cervix. The maximum measurement is therefore achieved along a line which is not parallel to the occlusal surface (Fig. 2). Molar crown diameters often create a real dilemma, because small rotations of the crown between the caliper jaws can easily cause variations of 1 mm or more. Any attempt to hold the calipers perpendicular to the mesiodistal axis and occlusal plane involves personal judgment, and two observers are likely to produce

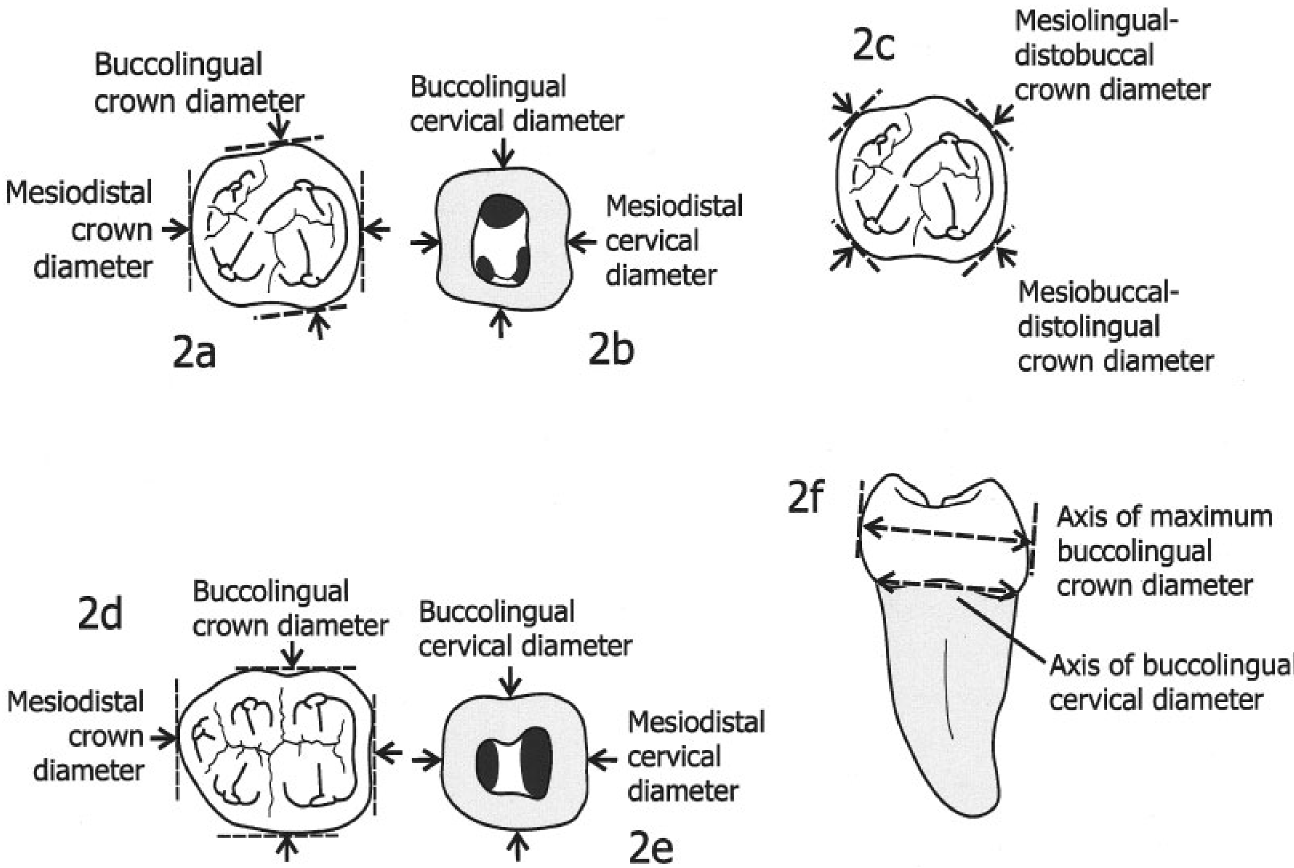

Fig. 2. Crown diameter and cervical diameter measurements in molars. **a, c:** Upper molar occlusal view. **b:** Upper molar transverse section at cervix. **d:** Lower molar occlusal view. **e:** Lower molar transverse section at cervix. **f:** Lower molar mesial view.

different results. It is therefore better to recognize explicitly (Tobias, 1967) that the condition of perpendicularity may need to be relaxed in order to achieve a simple maximum which provides a much more repeatable measurement definition.

When the teeth are held in the jaw, it is difficult to take the mesiodistal crown diameter because the teeth fit tightly against their neighbors, and the caliper points cannot be placed on the maximum convexity of the mesial and distal crown sides. In practice, calipers with needlepoints are used, and in some cases, the teeth can be moved slightly in the jaw to allow a little access for measurement, but it is still rarely possible to push the points far enough in. It is also all too easy to damage a delicate specimen.

Added to these difficulties is the problem of wear. The buccolingual diameter is only affected when most of the crown has been lost through occlusal attrition, but the mesiodistal diameter is strongly affected even at the earliest stages of approximal (interproximal or interstitial) attrition. In an unworn tooth, the measurement landmarks are infinitely small points at the maximum convexity of a curving surface. As approximal attrition advances, it creates two flat wear facets tangential to the curve of the crown side, so that even the smallest amount of wear has a large effect, which is doubled because the measurement is being reduced at both ends. In most studies, teeth that are "too worn to measure" are excluded, but how much is too much when even the smallest amount of attrition can produce a measurable difference? Incisors and canines are much more affected than premolars and molars (Frayer, 1978), but the effects cannot be ignored even there. Dental measurements are taken to the nearest 0.1 mm, and it takes very little wear to make that amount of difference. The problem of wear is at its most difficult with the very worn teeth in jaws from Neolithic, Mesolithic, and Upper and Middle Paleolithic archaeological contexts, and this is unfortunate because it is just this material that is important for studies of dental reduction (see above). In such material, so many specimens have to be left unmeasured that sample size is greatly reduced. Mesiodistal crown diameters, however, are so strongly affected by approximal attrition that it is not valid to compare the less heavily worn dentitions of children with the more heavily worn teeth of adults. This causes problems if dental measurements are to be used to help identify the sex of children (boys and girls are difficult to distinguish in the form of the skeleton). The method relies on establishing baseline groups of adults whose sex is independently known from pelvic or skull morphology, but if their teeth are worn, then no comparison can be made between the baseline group and the less-worn children's teeth. Similarly, if an assemblage of human remains includes both children and adults of varying ages, it is never possible to rule out the effects of wear when comparing it with another assemblage which may have a different age composition. This must, for example, affect the use of mean mesiodistal crown diameter to demonstrate dental reduction.

The aim of the present research, therefore, was to investigate alternative tooth measurements that would be less affected by these problems. The usual crown diameters are arbitrarily chosen maximum dimensions. They are clearly controlled by a complex interaction of genetic and environmental factors (Hillson, 1998), and it is not at all clear that they are necessarily the best record of crown morphology for investigating such phenomena as sexual dimorphism, dental evolution, or the relationships of past populations. There is no reason why other measurements should not be just as good for these purposes, providing they can be recorded reliably. The purpose of the work reported here was:

- to propose such alternatives;
- to examine their relationship with the usual crown diameters in unworn teeth; and
- to test the reliability with which they could be measured and compare it with the usual crown diameters.

ALTERNATIVE DENTAL MEASUREMENTS

Diagonal diameters of molars

One possibility for molars is to take diagonal crown diameters (Fig. 2), from mesiobuccal to distolingual and from mesiolingual to distobuccal. This is a simple maximum dimension and the tooth is rotated to give the highest value, so personal judgment is not required when the measurement is taken. There are difficulties because the occlusal outline of the crown is not a regular rectangle, and the degree of rounding at the corners is variable. One major advantage is that these diagonal axes do not include the contact points of the crown, and are therefore not affected by approximal attrition until the facets become large enough to include them. The relationship between such diagonals and the more usual crown diameters is unknown. It is also possible to take similar diagonal diameters at the cervix of the molars, with the caliper points at the cement-enamel junction.

Cervical diameters

Another possibility is to take measurements at the base of the crown, along the cement-enamel junction of the cervix. This idea has almost as long a history as traditional crown diameters (Azouley and Regnault, 1893; Colby, 1996; Falk and Corruccini, 1982; Goose, 1963), but has not often been employed. Where it has been used, measurements have been taken parallel to the more usual crown diameters. For the buccolingual cervical diameter of the crown, this is simply the greatest distance between the buccal and lingual surfaces of the tooth at the cement-enamel junction. The mesial and distal sides of the crown and root are often concave at the cement-enamel junction, so care is needed for definition of the measuring points in the mesiodistal cervical diameter. Colby (1996) followed the mesiodistal crown diameter of Tobias (1967; see below), and defined the cervical diameter as the distance between two parallel lines, perpendicular to the mesiodistal axis and tangential to the most mesial and most distal parts of the cement-enamel junction. To take the measurement in this way, the sides of the caliper points need to be parallel, and the main difficulty arises when the teeth are held in the jaw. The points must be as small as 1 mm or so in width to pass between the teeth at the cervix. In practice, it is difficult to obtain points that are thin enough to pass right through between the teeth (so that the whole depth of crown side can be taken into account) and stiff enough not to bend when the caliper jaws move together. For this reason, the present study defines the mesiodistal cervical diameter in a different way (below).

The cervical diameters are not affected by wear until most of the crown has been lost, so they have a big advantage for archaeological purposes. This advantage is less important for buccolingual diameters, but is crucial for mesiodistal diameters, especially in anterior teeth. In addition, provided that the problem of caliper points can be solved, there is less difficulty when measuring teeth that are still held in the jaw. The main potential difficulty is heavy supragingival calculus deposits, in teeth where continuous eruption or loss of periodontal tissues has moved the gingival attachment down from the crown onto the root. Such deposits may on occasion cover the cement-enamel junction, and without removing them, it may not be possible to take cervical measurements. However, this is relatively rare in archaeological collections where, even if present, the calculus frequently falls off during the removal of matrix or storage.

METHODS

It was necessary to develop new calipers for the cervical measurements. One requirement was caliper points thin enough to pass between teeth still held in the jaw, but not so pointed that they scratched valuable specimens. After many trials, the best were found to be 2-mm stainless steel rods, machined to a fine taper with a narrow rounded tip, and finely polished (Figs. 3, 4). When tested, it proved impossible to scratch tooth surfaces with these. Initially, these points could be fitted to standard Fowler (Helios) needlepoint calipers, as used in dental anthropology for many years. The other requirement, however, was to take a buccolingual diameter under the main bulge of the cingulum of the crown. This required the points to be held differently, so that they met end-to-end. To start with, a

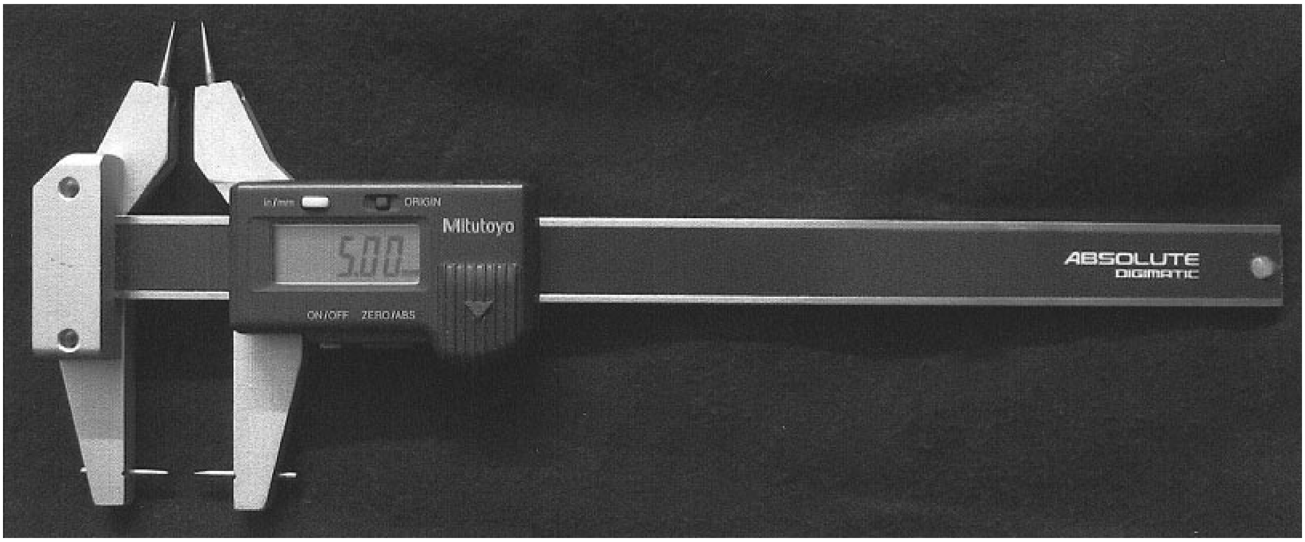

Fig. 3. Caliper for cervical dental measurements used in project. Developed in collaboration with Paleo-Tech, Inc.

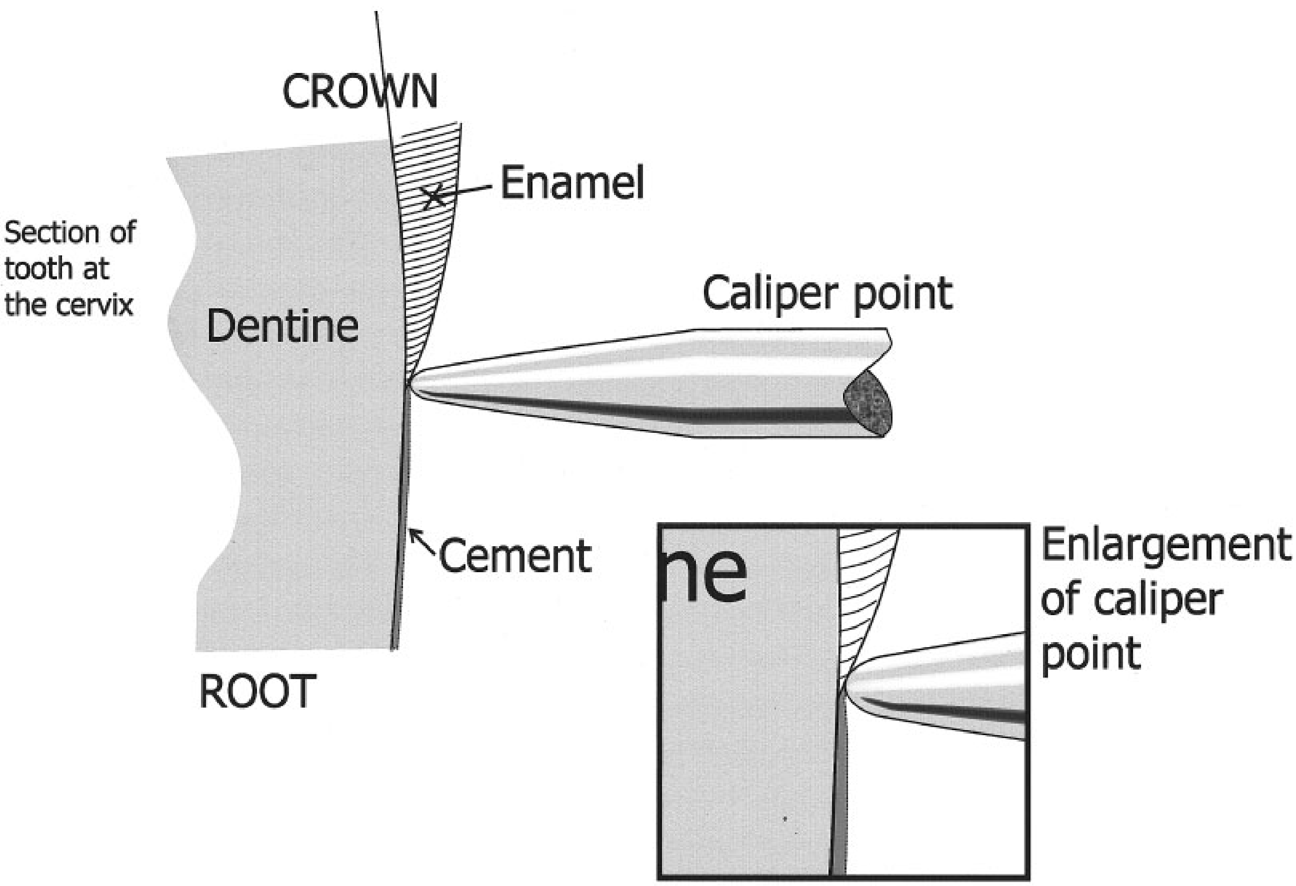

Fig. 4. Placing of caliper point tip for cervical measurements.

6-inch Mitutoyo Digimatic caliper was modified to do this. Finally, the authors collaborated with Jim Kondrat, of Paleo-Tech (http://paleo-tech.com), to design an instrument that would combine both positions of the points (Fig. 3). All calipers had digital displays which read to 0.01 mm, and direct input to the RS232 serial port and PS2 port of a computer, so that measurements could be entered directly into an Access database.

Maximum crown diameters

The method used for the more usual maximum crown diameters followed the description of Tobias (1967), which was found to be easiest to use in practice. In the present study, the teeth were unworn, but wear limits were part of the definition which was intended to be used more generally. The authors only took mesiodistal maximum crown diameters for incisors with stage 3 (of Smith, 1984) or less of occlusal attrition, or for other tooth classes with Smith stage 4 or less. Over these limits, occlusal wear starts to involve the maximum mesial and distal bulges of the crown side, irrespective of approximal wear effects. Buccolingual maximum crown diameters can be taken in teeth with more occlusal wear, and those specimens with up to Smith stage 5 are measured as a rule. If wear is relatively even, so that the maximum bulges of the buccal/labial and lingual/palatal crown sides are both still present, some specimens of Smith stage 6 can be measured. Approximal wear does not have an equivalent scoring method, so it is difficult to define equivalent cutoff points.

Maximum mesiodistal crown diameters. Maximum mesiodistal crown diameter is defined as the distance between two parallel planes, tangential to the most mesial and most distal points of the crown side. This measurement often follows an axis nearly parallel to the occlusal plane and nearly perpendicular to the mesiodistal plane of the tooth (Figs. 1, 2), but the calipers were not deliberately held in this position. The maximum bulge of the mesial and distal crown sides, at which these measurement landmarks lie, corresponds to the contact points in anterior teeth with normal occlusal relationships, but does not necessarily do so for cheek teeth. The actual contact points at which teeth occluded were therefore not taken into account.

Maximum buccolingual crown diameters. Maximum buccolingual crown diameter is defined as the maximum distance between two parallel planes, one tangential to the most lingual/palatal point of the crown side, and the other tangential to a point on the buccal/labial crown side (Figs. 1, 2). For incisors, canines, and premolars, the labial/buccal point is on the single convexity of the crown side. For molars, the maximum measurement was usually found to the most mesial of two or more bulges on the buccal crown side. The axis of the measurement was often not far from perpendicular to the axis of the mesiodistal crown diameter defined above, but this was not used as a defining character for the measurement. For incisors, canines, and premolars, there was little difficulty in taking this measurement. For molars, as noted by Tobias (1967), it is often better to place the jaws of the calipers diagonally across the surface, because the maximum bulge on the buccal crown side is not necessarily directly opposite the maximum bulge on the lingual side. Upper molars, in particular, may be difficult to measure.

Cervical diameters

For all cervical diameters, the tips of the caliper points were placed on the surface of the enamel just occlusal to the cement-enamel junction (Fig. 4). This involved careful placement, first with one tip and then the other, but the edge of the cement layer could usually be felt as the caliper point tips passed over it. A conscious effort needed to be made to move the tips onto the enamel, because they seemed naturally to fall onto the cement surface.

Mesiodistal cervical diameter for incisors and canines. In anterior teeth, the cement-enamel junction has a strong curve to occlusal on the mesial and distal sides (Fig. 1), and this makes a natural measurement landmark at the most occlusal point of the curve. This point can be reached in most teeth still held in the jaw. The mesiodistal cervical diameter was therefore defined as the distance between the most occlusal points of the cement-enamel junction curve on the mesial and distal sides. The mesial curve rises more to occlusal than the distal curve, so the axis of measurement is not strictly parallel to the occlusal plane of the tooth, or the normal definition of the axis for the traditional mesiodistal crown diameter. For isolated teeth, the best caliper points to use were those that met end to end.

Mesiodistal cervical diameter for premolars and molars. The cement-enamel junction on cheek teeth does not have the same strong mesial and distal curve as in the anterior teeth. In the absence of naturally defined landmarks, the measurement point was therefore defined as midway along the cement-enamel junction on the mesial and distal sides of the crown (Fig. 2). Normally, there is a broad concavity at this point, so that the measurement falls to a minimum.

Buccolingual cervical diameter for incisors, canines, and premolars. In these teeth, the cement-enamel junction makes a single curve apically and outwards to labial/buccal and lingual/palatal. This means that the buccolingual cervical diameter can be defined simply as the maximum measurement at the cement-enamel junction from labial/buccal to lingual/palatal (Fig. 1). Once again, these landmarks are not necessarily at equal levels, so the axis of measurement may not be parallel to the occlusal plane or exactly perpendicular to the axis of the mesiodistal diameter.

Buccolingual cervical diameter for molars. The cement-enamel junction does not have a single outward curve on the buccal and lingual sides of molars. This means that the buccolingual cervical diameter could not simply be defined as the maximum measurement: there would be at least two maxima. Instead, the measurement was taken on the cement-enamel junction at points midway along the buccal and lingual/palatal sides. In most upper molars, it was found that this point was the maximum bulge above the single lingual/palatal root, and there was usually a slight depression midway along the buccal side between the two buccal roots. For lower molars, there was usually a slight depression on both the lingual and buccal sides, between roots, at which the measurement was taken. Where there was a large enamel extension, the measurement needed to be taken to one side or the other of this, whichever gave the maximum value.

Diagonal diameters of molars

Mesiobuccal-distolingual crown diameter. This was defined as the maximum distance from the mesiobuccal corner of the crown to the distolingual corner. The corners of the crown are rounded, so the tooth is rotated somewhat like a cam, and multiple measurements are taken, to find the maximum.

Mesiolingual-distobuccal crown diameter. Exactly the same procedure as above was followed for the maximum distance between the mesiolingual and distobuccal corner of the crown.

Mesiobuccal-distolingual cervical diameter. The cervical diagonal was found in the same way as for the mesiobuccal-distolingual crown diameter, but with the caliper points placed at the cement-enamel junction.

Mesiolingual-distobuccal cervical diameter. The cervical diagonal was found in the same way as for the mesiolingual-distobuccal crown diameter, but with the caliper points placed at the cement-enamel junction.

Statistical methods

The relationships between different measurements were investigated through scatterplots and correlations. In addition to consideration of cervical measures vs. their maximum crown diameter equivalents, diagonals were compared with mesiodistal and buccolingual diameters. Many studies multiply mesiodistal and buccolingual diameters together, to give an approximate occlusal crown area (often called the "robustness index"). In the present study, maximum diameters were multiplied together to produce a "maximum crown area," cervical diameters were similarly multiplied to produce a "cervical crown area," and diagonals were similarly multiplied to produce a "diagonal crown area" (Table 4).

There is some discussion (Kieser, 1990) about the best method for expressing reliability of measurements:

1. "*Coefficients of reliability*" are correlations between sets of measurements repeated on the same specimens. The main difficulty is that the correlation is affected by the variability of measurements in the group of specimens under study, as well as the relationship between two sets of these measurements. Thus, where the overall variability is high relative to the difference between sets of measurements, so will the correlation be high. This was the case with the present study, so they were not used.
2. *Student's* t*-test* was used to investigate systematic differences between observers. The null hypothesis is that there is no difference between the means of different observers for the same measurement, taken on the same teeth.
3. The *method error statistic* was calculated (Kieser, 1990) as:

$$S = \sqrt{\sum_{i=1-n} \frac{(X_i^1 - X_i^2)^2}{2n}}$$

where X^1 is the measurement taken by observer 1, X^2 is the same measurement repeated by observer 2, and n is the number of teeth. In effect, it is a type of mean difference between observers, not taking account of systematically smaller or larger values.

4. In practice, the simple approach of Bland and Altman (Altman and Bland, 1983; Bland and Altman, 1986; Kieser, 1990; Kieser and Groeneveld, 1991; Kieser et al., 1990) was found to be most useful. In a comparison between two sets of measurements taken by different observers, the mean of the pair of measurements taken on each specimen is plotted against the actual two measurement values (Fig. 5). Such plots make it possible to see quickly if there is any systematic difference between observers, or whether the size of error changes over the measurement range. As a concise guide, the repeatability with which a measurement can be taken is expressed as the mean difference between observers, together with its standard error (Table 1). Repeatability can then be defined in terms of the 95% confidence interval around the mean difference.

MATERIALS

The main aim of the project was to investigate the relationship between the usual crown diameters and the alternatives proposed here. The usual maximum crown diameters (especially the mesiodistal) are so strongly affected by wear that they cannot be compared directly with the cervical diameters in worn teeth. It was therefore necessary to find a group of teeth that were unworn. A small assemblage of mostly unerupted and completely unworn permanent teeth was found in material from the East Smithfield site in London, a large Black Death mass-burial cemetery dating to AD 1348–1349. These partially developed teeth had already been removed from the jaws of young individuals for a project involving dental development, and were thus available for the present study. The unworn, isolated teeth also had the advantage of creating ideal, and equal, conditions for taking all the different measurements (including the more usual maximum

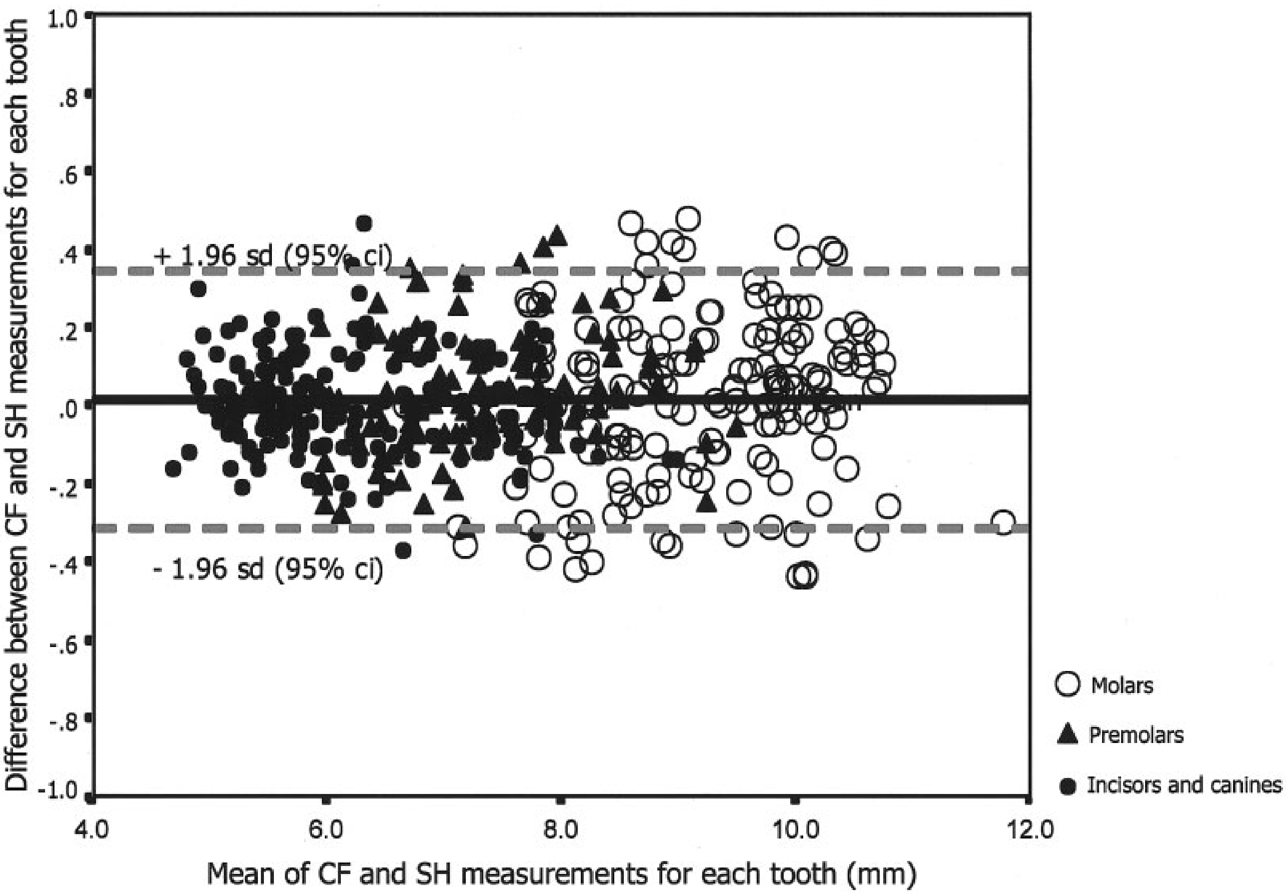

Fig. 5. Example of Bland-Altman plot for cervical buccolingual diameter interobserver error. For each tooth measured by two observers (C.F. and S.H.), mean of two independent measures is plotted along horizontal axis, vs. difference (S.H. measure subtracted from C.F.) up vertical axis. Incisors/canines, premolars, and molars are denoted by different symbols. Thick black line is mean difference for all tooth types, and dashed lines mark 95% confidence intervals calculated as 1.96 times the standard error of difference.

crown diameters) and comparing the reliability of the different approaches.

The collection of teeth was independently measured by two observers (S.H. and C.F.) using the same (Paleo-Tech) type of calipers, using the definitions of measurements given here, over a period of 2 weeks. Both left and right antimeres were measured where they were present. The Access database input table was arranged so that the measurements of left and right teeth could be compared immediately. If there was a difference of more than 0.2 mm, the measurement was repeated for both teeth. In some cases, there was a genuine difference between antimeres, but this approach did allow an instant check to be made and caught a number of errors which might otherwise have been missed. A total of 2,559 tooth antimere pairs was measured by both observers. Where different measurements were plotted against one another and correlated, the mean of the two observers' measurements was used as the value.

RESULTS

Table 1 shows the results of the preliminary interobserver study, for separate teeth. Numbers of third molars are lower than for the other teeth, because the individuals were relatively young, and in fact no lower third molars were sufficiently developed. Student's *t*-test provides a comparison between mean values of measurements taken by the two observers. None of the results is significant at the 5% level, providing little evidence of systematic differences. In addition, the mean difference figures take into account whether or not one observer gave consistently higher or lower measurements than the other, and thus vary from negative to positive. Most of them are between -0.1 and $+0.1$ mm, and they are not consistently positive or negative in a way that would imply a strong methodological difference between the two observers. Mean differences smaller than -0.1 and greater than $+0.1$ mm are only present in maximum diagonal measurements of molars (particularly the mesiolingual-distobuccal crown diameter), and in the upper third molars, which showed a strong variation in form and often offered difficulties in applying any of the measurement definitions. The mean absolute difference and its standard error are the error statistics resulting from the Bland-Altman approach, for which an example plot is shown in Figure 5. The mean absolute difference does not take into account whether or not

TABLE 1. Interobserver error statistics[1]

		n	t ($p > 0.05$ for all tests)	Mean difference	Standard error of difference	Mean absolute difference	Standard error of absolute difference	Technical (method) error
Upper first incisor	Cerv BL	23	0.054	0.005	0.084	0.125	0.018	0.107
	Cerv MD	26	0.403	0.052	0.129	0.145	0.022	0.128
	Max BL	22	0.877	0.076	0.086	0.069	0.014	0.066
	Max MD	31	−0.270	−0.035	0.130	0.047	0.010	0.050
Upper second incisor	Cerv BL	32	0.345	0.029	0.084	0.106	0.013	0.090
	Cerv MD	34	0.502	0.046	0.092	0.136	0.017	0.119
	Max BL	26	−0.357	−0.032	0.089	0.063	0.012	0.061
	Max MD	36	−0.340	−0.031	0.091	0.067	0.009	0.061
Upper canine	Cerv BL	30	0.418	0.061	0.145	0.100	0.011	0.082
	Cerv MD	31	0.376	0.038	0.102	0.115	0.013	0.096
	Max BL	25	−0.001	0.000	0.148	0.073	0.013	0.068
	Max MD	33	−0.514	−0.044	0.086	0.058	0.011	0.059
Upper third premolar	Cerv BL	26	0.320	0.057	0.179	0.155	0.024	0.139
	Cerv MD	27	0.511	0.038	0.074	0.144	0.020	0.125
	Max BL	26	0.486	0.076	0.157	0.044	0.008	0.041
	Max MD	30	−0.113	−0.011	0.095	0.040	0.006	0.037
Upper fourth premolar	Cerv BL	29	0.248	0.045	0.183	0.099	0.017	0.094
	Cerv MD	32	0.087	0.007	0.083	0.138	0.021	0.127
	Max BL	26	0.072	0.013	0.184	0.059	0.013	0.062
	Max MD	32	−0.329	−0.037	0.111	0.054	0.012	0.061
Upper first molar	Cerv BL	54	0.764	0.065	0.086	0.160	0.016	0.139
	Cerv MD	55	−0.129	−0.010	0.077	0.148	0.018	0.141
	Max BL	55	−0.639	−0.068	0.107	0.148	0.020	0.146
	Max MD	55	−0.769	−0.070	0.092	0.135	0.021	0.144
	Cer Diag A	52	0.341	0.047	0.138	0.133	0.015	0.120
	Cer Diag B	51	0.397	0.049	0.123	0.128	0.015	0.118
	Max Diag A	55	−0.319	−0.037	0.116	0.093	0.012	0.092
	Max Diag B	53	−1.095	−0.118	0.108	0.122	0.013	0.110
Upper second molar	Cerv BL	24	0.130	0.017	0.133	0.156	0.028	0.145
	Cerv MD	26	1.058	0.125	0.118	0.211	0.030	0.184
	Max BL	27	−0.423	−0.081	0.193	0.178	0.030	0.166
	Max MD	27	−0.626	−0.101	0.162	0.143	0.023	0.132
	Cer Diag A	24	−0.181	−0.037	0.201	0.104	0.021	0.102
	Cer Diag B	23	0.380	0.074	0.194	0.182	0.032	0.166
	Max Diag A	25	−0.546	−0.118	0.216	0.167	0.032	0.161
	Max Diag B	23	−1.690	−0.301	0.178	0.149	0.029	0.142
Upper third molar	Cerv BL	3	−0.485	−0.742	1.528	0.047	0.026	0.042
	Cerv MD	4	−0.124	−0.055	0.443	0.190	0.065	0.156
	Max BL	4	0.538	0.541	1.006	0.310	0.169	0.302
	Max MD	4	0.244	0.177	0.726	0.263	0.077	0.208
	Cer Diag A	3	−0.719	−0.521	0.724	0.267	0.100	0.214
	Cer Diag B	3	−0.509	−0.525	1.032	0.077	0.013	0.056
	Max Diag A	4	−0.007	−0.008	1.083	0.207	0.092	0.185
	Max Diag B	2	−1.315	−1.425	1.084	0.195	0.185	0.190
Lower first incisor	Cerv BL	41	0.038	0.003	0.071	0.076	0.010	0.071
	Cerv MD	44	−0.284	−0.013	0.047	0.121	0.013	0.103
	Max BL	39	−0.355	−0.020	0.055	0.042	0.006	0.038
	Max MD	46	−0.674	−0.041	0.060	0.051	0.007	0.049
Lower second incisor	Cerv BL	36	0.646	0.044	0.068	0.073	0.015	0.081
	Cerv MD	44	−0.555	−0.039	0.070	0.124	0.015	0.111
	Max BL	34	−0.507	−0.032	0.064	0.057	0.007	0.050
	Max MD	47	−0.132	−0.010	0.077	0.056	0.011	0.566
Lower canine	Cerv BL	35	−0.653	−0.077	0.118	0.104	0.014	0.094
	Cerv MD	37	−1.106	−0.101	0.091	0.120	0.015	0.107
	Max BL	33	−0.865	−0.097	0.112	0.100	0.014	0.090
	Max MD	41	−0.092	−0.007	0.073	0.060	0.011	0.064
Lower third premolar	Cerv BL	30	−0.428	−0.041	0.097	0.118	0.016	0.105
	Cerv MD	31	−0.362	−0.026	0.071	0.154	0.023	0.139
	Max BL	27	−1.294	−0.119	0.092	0.159	0.024	0.141
	Max MD	33	−0.114	−0.009	0.076	0.065	0.019	0.089
Lower fourth premolar	Cerv BL	23	0.168	0.020	0.121	0.127	0.022	0.116
	Cerv MD	24	−0.444	−0.034	0.076	0.118	0.015	0.097
	Max BL	24	−1.447	−0.166	0.115	0.135	0.015	0.108
	Max MD	27	−0.377	−0.032	0.084	0.038	0.009	0.948
Lower first molar	Cerv BL	57	−0.376	−0.032	0.086	0.194	0.017	0.164
	Cerv MD	59	−0.178	−0.014	0.081	0.173	0.018	0.158
	Max BL	61	−2.031	−0.192	0.094	0.212	0.021	0.191
	Max MD	60	0.159	0.015	0.093	0.072	0.010	0.076
	Cer Diag A	55	0.444	0.046	0.104	0.114	0.012	0.102
	Cer Diag B	50	0.817	0.074	0.090	0.104	0.012	0.094
	Max Diag A	59	−0.722	−0.072	0.099	0.120	0.016	0.122
	Max Diag B	56	−1.075	−0.105	0.098	0.129	0.017	0.126
Lower second molar	Cerv BL	20	−0.284	−0.056	0.196	0.202	0.029	0.168
	Cerv MD	22	0.287	0.038	0.132	0.201	0.030	0.172
	Max BL	23	−0.477	−0.077	0.162	0.115	0.024	0.113
	Max MD	23	−0.162	−0.023	0.145	0.036	0.009	0.038
	Cer Diag A	21	0.271	0.046	0.171	0.217	0.031	0.182
	Cer Diag B	19	0.456	0.084	0.184	0.204	0.030	0.169
	Max Diag A	23	−0.642	−0.104	0.163	0.163	0.026	0.144
	Max Diag B	22	−0.387	−0.071	0.183	0.189	0.030	0.166

Cerv BL, cervical buccolingual diameter; Cerv MD, cervical mesiodistal diameter; Max BL, maximum buccolingual diameter; Max MD, maximum mesiodistal diameter; Cer Diag A, mesiobuccal-distolingual cervical diameter; Cer Diag B, mesiolingual-distobuccal cervical diameter; Max Diag A, mesiobuccal-distolingual crown diameter; Max Diag B, mesiolingual-distobuccal crown diameter. Definitions of statistics are given in text.

TABLE 2. Correlations between maximum and cervical diameters

Product moment correlation coefficient (number of teeth)[1]	Cervical vs. maximum		Buccolingual vs. mesiodistal	
	Buccolingual diameter	Mesiodistal diameter	Maximum diameter	Cervical diameter
Upper 1st incisor	0.741 (51)	0.744 (66)	0.425 (62)	0.474 (56)
Upper 2nd incisor	0.849 (61)	0.805 (73)	0.185 (66)[2]	0.325 (68)
Upper canine	0.877 (57)	0.570 (64)	0.504 (60)	0.829 (63)
Upper 3rd premolar	0.867 (53)	0.536 (58)	0.893 (58)	0.673 (55)
Upper 4th premolar	0.921 (55)	0.731 (66)	0.858 (60)	0.832 (61)
Upper 1st molar	0.695 (114)	0.575 (115)	0.817 (115)	0.491 (114)
Upper 2nd molar	0.638 (52)	0.620 (57)	0.588 (59)	0.392 (51)
Upper 3rd molar	0.960 (7)	0.920 (8)	0.955 (9)	0.956 (7)
Lower 1st incisor	0.846 (79)	0.502 (94)	0.442 (85)	0.451 (89)
Lower 2nd incisor	0.825 (74)	0.617 (92)	0.276 (82)	0.389 (81)
Lower canine	0.953 (72)	0.391 (81)	0.367 (77)	0.570 (74)
Lower 3rd premolar	0.631 (60)	0.485 (66)	0.411 (61)	0.511 (63)
Lower 4th premolar	0.699 (47)	0.638 (51)	0.782 (50)	0.644 (49)
Lower 1st molar	0.426 (121)	0.613 (122)	0.683 (124)	0.519 (121)
Lower 2nd molar	0.705 (128)	0.767 (50)	0.812 (52)	0.479 (48)

[1] Pearson product-moment correlations are all significant at $P < 0.001$, unless otherwise indicated. [2] Not significant

TABLE 3. Correlations between maximum and cervical mesiobuccal-distolingual diagonal diameters and mesiolingual-distobuccal diagonal diameters

Product moment correlation coefficient (number of teeth)[1]	Cervical vs. maximum diameters		Mesiobuccal-distolingual vs. mesiolingual-distobuccal diameter	
	Mesiobuccal-distolingual diameter	Mesiolingual-distobuccal diameter	Cervical diameter	Maximum diameter
Upper 1st molar	0.835 (112)	0.825 (108)	0.708 (113)	0.816 (108)
Upper 2nd molar	0.844 (52)	0.787 (49)	0.631 (55)	0.761 (51)
Upper 3rd molar	0.977 (7)	0.992 (6)	0.988 (6)	0.956 (7)
Lower 1st molar	0.786 (117)	0.461 (107)	0.859 (120)	0.790 (111)
Lower 2nd molar	0.906 (48)	0.934 (44)	0.924 (50)	0.928 (45)

[1] Pearson product-moment correlations are all significant at $p < 0.001$, unless otherwise indicated.

one observer consistently gave larger measurements than the other, but rather the overall level of difference, and always gives a positive value. In most cases, it does not exceed 0.15 mm. Values in molars, and to some extent premolars, tend to be a little higher than those for incisors and canines. For incisors and canines, the mean absolute difference is slightly larger for cervical diameters than for maximum crown diameters. The standard error of absolute difference is an expression of the spread of measures around the mean difference between observers. For many of the measurements it is 0.02 mm or less, implying a narrow spread, well within the precision to which dental measurements are usually taken. There is not much variation between the different definitions of measurements, although again molars tend to show slightly higher values than incisors and canines, and the highest values are for the upper third molar. The method error statistic is, in effect, another way of calculating the mean difference between the two sets of measurements. Most are around the 0.1 level, either somewhat less or slightly more. In general, molars have higher values than premolars, canines, or incisors. For canines and incisors, the maximum crown diameters have slightly lower values than the cervical diameters, but for the molars, the different measurement definitions yield more similar results.

The correlations (Table 2) between maximum crown diameters and equivalent cervical diameters do not generally show a consistently strong relationship. All correlations are positive. The highest correlations are shown in both mesiodistal and buccolingual diameters of the upper incisors, and buccolingual diameters of the lower incisors, upper and lower canines, and upper premolars. The molar correlations are not high. Similarly, most of the correlations between mesiodistal and buccolingual diameters (Table 2) are low, for both maximum and cervical definitions. Scattered higher correlations occur in the premolar and molar tooth rows, but show little pattern.

For diagonal crown diameters of molars, there are consistently high correlations between the maximum crown and cervical definitions, with the exception of one correlation in the lower first molar (Table 3). In addition, the mesiobuccal-distolingual diagonal is for the most part highly correlated with the distobuccal-distolingual diagonal (Table 3), for both maximum and cervical definitions. The maximum diagonal diameters are also highly (or moderately highly) correlated with the more usual maximum crown diameters (Table 4), and the cervical diagonal diameters are highly correlated with the cervical crown diameters (Table 5).

TABLE 4. Correlations between maximum diagonals and maximum diameters

Product moment correlation coefficient (number of teeth)[1]	Mesiobuccal-distolingual maximum diameter: Versus maximum mesiodistal diameter	Mesiobuccal-distolingual maximum diameter: Versus maximum buccolingual diameter	Mesiolingual-distobuccal maximum diameter: Versus maximum mesiodistal diameter	Mesiolingual-distobuccal maximum diameter: Versus maximum buccolingual diameter
Upper 1st molar	0.777 (115)	0.764 (115)	0.828 (113)	0.793 (113)
Upper 2nd molar	0.632 (57)	0.609 (57)	0.776 (55)	0.831 (55)
Upper 3rd molar	0.957 (8)	0.929 (8)	0.978 (6)	0.996 (6)
Lower 1st molar	0.8 (122)	0.811 (123)	0.939 (119)	0.790 (120)
Lower 2nd molar	0.94 (51)	0.889 (51)	0.933 (50)	0.86 (50)

[1] Pearson product-moment correlations are all significant at $p < 0.001$, unless otherwise indicated.

TABLE 5. Correlations between cervical diagonals and cervical diameters

Product moment correlation coefficient (number of teeth)[1]	Mesiobuccal-distolingual cervical diameter: Versus cervical mesiodistal diameter	Mesiobuccal-distolingual cervical diameter: Versus cervical buccolingual diameter	Mesiolingual-distobuccal cervical diameter: Versus cervical mesiodistal diameter	Mesiolingual-distobuccal cervical diameter: Versus cervical buccolingual diameter
Upper 1st molar	0.709 (112)	0.703 (112)	0.608 (110)	0.751 (113)
Upper 2nd molar	0.541 (51)	0.816 (51)	0.531 (51)	0.804 (50)
Upper 3rd molar	0.998 (7)	0.954 (7)	0.957 (7)	1.0 (7)
Lower 1st molar	0.744 (119)	0.616 (118)	0.715 (112)	0.613 (112)
Lower 2nd molar	0.845 (47)	0.693 (47)	0.820 (45)	0.581 (45)

[1] Pearson product-moment correlations are all significant at $p < 0.001$, unless otherwise indicated.

TABLE 6. Relationships between different forms of crown area (robustness index)[1]

Product moment correlation coefficient (number of teeth)	Cervical area vs. maximum area	Maximum diagonal area vs. maximum crown area	Cervical diagonal area vs. cervical area
Upper 1st incisor	0.866 (50)		
Upper 2nd incisor	0.857 (60)		
Upper canine	0.790 (57)		
Upper 3rd premolar	0.828 (51)		
Upper 4th premolar	0.873 (55)		
Upper 1st molar	0.727 (114)	0.896 (113)	0.839 (108)
Upper 2nd molar	0.686 (51)	0.864 (55)	0.819 (50)
Upper 3rd molar	0.980 (7)	0.990 (6)	0.999 (7)
Lower 1st incisor	0.655 (77)		
Lower 2nd incisor	0.785 (72)		
Lower canine	0.786 (71)		
Lower 3rd premolar	0.617 (59)		
Lower 4th premolar	0.748 (46)		
Lower 1st molar	0.585 (120)	0.936 (119)	0.808 (111)
Lower 2nd molar	0.747 (48)	0.996 (50)	0.854 (44)

[1] Correlations of cervical crown area with maximum crown area, maximum diagonal crown area with maximum crown area, and cervical diagonal crown area with cervical crown area. Pearson product-moment correlations are all significant at $p < 0.001$, unless otherwise indicated. Cervical crown area is calculated as product of mesiodistal cervical diameter and buccolingual cervical diameter. Maximum crown area is calculated as product of maximum mesiodistal crown diameter and maximum buccolingual crown diameter. Maximum diagonal crown area is calculated as product of mesiobuccal-distolingual maximum diameter and mesiolingual-distobuccal maximum diameter. Cervical diagonal crown area is calculated as product of mesiobuccal-distolingual cervical diameter and mesiolingual-distobuccal cervical diameter.

When diameters were multiplied to produce crown areas, the maximum crown area showed high correlations with the cervical crown area, and both of these showed high correlations with the diagonal crown area (Table 6).

DISCUSSION

Very few other studies of interobserver error have been carried out for dental measurements. The most appropriate study for comparison is that of Kieser and Groeneveld (1991). Their test was based on dental stone replicas of 35 dentitions, for which the usual maximum crown diameters were measured by the same observer twice on the same day and after an interval of 6 months, and by a different observer also on the same day and after a 6-month interval. They found that mean intra- and interobserver differences were larger for the maximum mesiodistal diameter than for the buccolingual diameter, and that the premolars and molars showed slightly larger mean differences than the incisors and canines. For each tooth class, interobserver differences were larger than intraobserver, and the differences were greater after an interval of 6 months than they were when measurements were repeated the same day. The mean absolute differences of Kieser and

Groeneveld (1991) varied from 0.032–0.298 for their intraobserver study, and 0.129–0.469 for their interobserver study, somewhat larger than those of the present study. This is probably because they were using dental stone replicas of full dentitions, instead of isolated specimens of original teeth. Also, their mesiodistal diameters showed larger measurement errors than their buccolingual diameters, which might well have been due to the difficulty of pressing the caliper points between teeth in the stone casts.

The study of Hunter and Priest (1960) examined interobserver error in mesiodistal diameters measured both in the mouth and in dental stone replicas of the same dentitions. Their mean interobserver differences for intraoral measurements were about the same as those of the present study, but there were also differences (ranging from 0–0.37 mm) between the intraoral measurements and those taken on replicas.

These previously published studies are the basis on which maximum crown diameters are considered to be reliable measurements. All the alternative diameters (maximum, cervical, and diagonal) defined in the present paper can be recorded at least as consistently, and the authors therefore conclude that they are acceptable by the standards normally applied to dental measurements. The results of the present study indicate that molars are slightly more difficult to measure consistently than premolars, canines, and incisors. Molars have less clear landmarks on which to base measurements, and the authors frequently had to make a choice between several possible values, so this is perhaps not surprising. In addition, in the unworn incisors used, cervical measurements were slightly more difficult to take consistently than the traditional maximum crown diameters. With the rounded bulges of unworn contact points, it was a simple matter to rotate the tooth until a maximum mesiodistal diameter was achieved. Similarly, the single bulges of the labial cingulum and lingual tubercle gave little difficulty in obtaining a maximum buccolingual diameter. By contrast, the points had to be placed with a fine tolerance to measure cervical diameters, and this was more difficult on the small incisor teeth.

For some teeth, cervical crown diameters showed consistently strong relationships with their equivalent maximum diameters, but for other teeth, this was not the case. Generally speaking, buccolingual diameters showed strong correlations in all teeth, whereas mesiodistal diameters showed strong correlations in incisors and canines, but lower correlations in premolars and molars. The diagonal measurements of molars were almost all strongly correlated with the mesiodistal and buccolingual diameters, both at the crown maximum and at the cervix. All measurements were strongly correlated with the maximum, the cervical, or the diagonal crown areas, and as might be expected, all these areas were strongly correlated with one another.

In an incisor or canine, the crown flares out above the cervix on the mesial and distal sides, reaching its maximum at the contact points. There is a large vertical distance between the latter and the points on the cement-enamel junction used for cervical measurements. In premolars and molars, the difference is less marked, and it might be expected that there would be a stronger relationship between cervical and maximum diameters in these teeth. The opposite, however, seems to be the case. Still, this relationship is useful because the strong effect of wear on the maximum mesiodistal diameter of incisors and canines makes the cervical mesiodistal diameter a particularly useful measurement in these teeth. By contrast, the measurement points for maximum buccolingual diameters are at the main bulge of the cingulum, a short distance above the cement-enamel junction. It was anticipated that cervical and maximum buccolingual diameters would be quite closely related, and this seems to be the case. They appear to record a similar aspect of crown size.

The sizes of the broad molar crowns seem to be recorded in a similar way by mesiodistal, buccolingual, and diagonal diameters, whether maximum or cervical. Diagonals could therefore be useful measurements in assemblages of worn teeth, where they avoid the approximal attrition facets, and they do not require access to the approximal cervical area, which may be blocked by sediment (particularly in fossil material). Similarly, the product of maximum, cervical, or diagonal diameters for each tooth type seems to yield "crown areas" which are strongly related to one another, and so presumably capture similar information. If a general measure of tooth size is needed, then any of these would be satisfactory. The crown area (robustness index) is often seen as a convenient expression of the size of wearable occlusal surface available in the dentition, although it is clearly a highly simplified and imperfect one. If this is so, the strong relationship between maximum crown area and diagonal crown area would be expected. A strong relationship between maximum and cervical areas would perhaps not be expected, and it might be better to see these areas as a simple summary of overall tooth size.

There is little evidence for a strong relationship between mesiodistal and buccolingual maximum crown diameters, as might be expected from previous studies (Garn et al., 1968). Similarly, the correlations between mesiodistal and buccolingual cervical diameters were mostly moderate to low, with scattered exceptions. By contrast, the diagonal measurements of molars were all highly correlated with one another, and with the maximum and cervical diameters of the crown. As might be expected, the positions of diagonal measurements thus seem to combine elements of both mesiodistal and buccolingual dimensions of the tooth. This makes them potentially very useful summaries of general crown size.

CONCLUSIONS

The usual crown diameter measurements are badly affected by occlusal and approximal tooth wear. Even the slightest approximal wear can reduce the maximum mesiodistal crown diameter by a measurable amount, particularly in incisors and canines. Most archaeological and fossil assemblages of human remains show heavy attrition, and normal crown diameters may in effect record more about wear than they do about the original crown morphology. This paper describes alternative crown measurements, i.e., cervical and diagonal diameters, which are not affected until much later stages of wear. They are, however, not commonly taken, so it is reasonable to ask if they record related aspects of crown morphology, and if they can be measured as reliably as the more usual diameters. The only way to investigate the relationships is to measure completely unworn teeth, so the present study was focused on a group of teeth which were chosen with this in mind. In this group of material, the cervical crown diameters for all teeth, and diagonal diameters for molars, could be recorded as repeatably as the usual maximum diameters. It was concluded that the alternatives provided measurements just as "good" as the more usual approach, in the sense that they could be recorded as reliably. The alternatives were also related in various ways to the more usual maximum diameters. Buccolingual maximum diameters were strongly correlated with buccolingual cervical diameters in all teeth. Mesiodistal diameters showed similarly strong relationships in incisors and canines, but lower in premolars and molars. Molar diagonal measurements (cervical or maximum) of molars were strongly correlated with mesiodistal and buccolingual diameters. All measurements taken were strongly correlated with crown areas (robustness index), whether calculated from maximum diameters, diagonal diameters, or cervical diameters, and these different crown areas were also strongly correlated with one another. In the normally accepted idea of occlusal crown size, it could therefore be concluded that the alternatives record information similar to that in the more usual maximum crown diameters.

The authors conclude that cervical and diagonal alternative measurements of the crown, as described here, can be performed as reliably as the more usual maximum crown diameters. Their relationship with overall crown size seems to be similar to that of maximum crown diameters as well. The alternative measurements are more suitable for the worn teeth that make up the bulk of the archaeological and fossil record, and also open up the possibility of comparing directly the little-worn teeth of children with the more heavily worn teeth of adults. Now that appropriate calipers are available, the alternatives should find wider use alongside the more usual approach. In the future, it may also be possible to use digital imaging systems to measure different aspects of tooth size and shape which are not strongly affected by wear.

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