available at www.sciencedirect.com

journal homepage: www.intl.elsevierhealth.com/journals/dema

Intra-oral restorative materials wear: Rethinking the current approaches: How to measure wear

*Ralph DeLong**

Department of Restorative Sciences, University of Minnesota School of Dentistry, Minneapolis, MN, USA

ARTICLE INFO

Keywords:
Wear
Dental materials
3D imaging
Scanning
Volume
Depth
Area
Contact area
Occlusal contact

ABSTRACT

Objective. To determine what wear parameter(s) have clinical relevance and what factors are important for accurate measurement of these parameters in vivo and in vitro.

Method. Describe biomechanical factors affecting mastication and the mechanics of wear. Investigate how they impact the wear of teeth and restorative materials. Based on this information, define the advantages and disadvantages of using volume, depth, and area parameters to quantify wear. Describe direct and indirect methods of measuring wear and point out advantages and disadvantages of each.

Results. The preferred parameter for quantifying wear is volume. It is independent of occlusal factors and is a measure of work done. If material and environmental factors remain constant, volume loss is linear with time. Depth and area have limited clinical value because of their dependence on occlusal factors; plus, they are not linear with time. When measuring wear the material of interest and the opposing material must be considered; especially if the opposing material is enamel. Wear is best measured by comparing sequential 3D images. Measuring systems should be calibrated with their error reported using sigma values rather means and standard deviations. The quality of the alignment of the sequential images should be included in the error analysis. Cost and availability of 3D imaging systems has severely limited their use in clinical studies.

Significance. Wear is an important consequence of occlusal interactions. If not controlled, wear could lead to poor masticatory function with a concomitant reduction in quality of life and possible deterioration of systemic health.

1. Introduction

Wear is an important consequence of occlusal interactions. If not controlled, wear could lead to poor masticatory function with a concomitant reduction in quality of life and possible deterioration of systemic health [1,2]. Restorative materials play an important part in wear, and differ significantly with respects to wear. Materials may be worn by enamel or they may cause aggressive wear of enamel. Obviously, material wear characteristics are best determined through clinical trials; however, such trials are expensive and time consuming. This limits preliminary testing of potential restorative materials to in vitro evaluation. To be of value, wear simulation must produce clinically relevant results. Validation of wear simulation requires wear measurement parameters that are clinically meaningful, measurable in both the clinic and the laboratory, and accurate. Therefore, when considering how to measure wear, two questions must be answered: (1) what wear parameter(s) have clinical relevance, and (2) what factors are important for accurate measurement of these parameters?

* Present address: Minnesota Dental Research Center for Biomaterials and Biomechanics, 16-212 Moos Health Sciences Tower, 515 Delaware St. SE, Minneapolis, MN 55455, USA. Tel.: +1 612 625 1409; fax: +1 612 626 1484.
E-mail address: delon002@umn.edu.

0109-5641/$ – see front matter © 2006 Academy of Dental Materials. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.dental.2006.02.003

Before these questions can be answered, it is important to understand the biomechanics of mastication.

2. Biomechanical factors

Wear simply defined is a loss of anatomic contour. Pindborg classified the loss of hard tissue as caries, erosion, attrition, or abrasion [3]. Simulations of wear normally focus on the last two classifications because these are biomechanical in nature. Attrition is caused by two-body interactions and includes fracture related to traumatic forces or fatigue. Abrasion is the result of three-body interactions. Both methods of wear occur in the mouth during mastication and other normal daily functions.

The chewing cycle can be divided into three phases: preparatory, crushing, and gliding [4] (Fig. 1). During the preparatory phase, the jaw is positioned for contact with the food bolus. It starts with the jaw opening movement and continues through the closing movement until the teeth contact the food bolus. Normally, no occlusal forces are involved during this phase (sticky foods represent an exception). The crushing phase follows the preparatory phase and represents a three-body interaction of the teeth with the food bolus. It starts when the teeth first contact the food bolus and continues until there is tooth-to-tooth contact or until the jaw begins to open (start of the preparatory phase). At initial contact, the force is distributed through the food bolus. The magnitude of the force experienced by the teeth depends on the stiffness of the food bolus. As the bolus is compressed, the force of mastication is distributed over the surface of the food bolus in contact with the maxillary and mandibular teeth. As the contact surface increases, the force per unit area decreases. The gliding phase, which does not always occur during mastication, starts with tooth-to-tooth contact (complete penetration of the food bolus, if present) and continues until the jaw begins to open (start of the preparatory phase). At contact, the force of mastication is concentrated in the area of occlusal contact. Because of the tooth-to-tooth contact and the presence of the food bolus, both two- and three-body wear mechanisms are occurring.

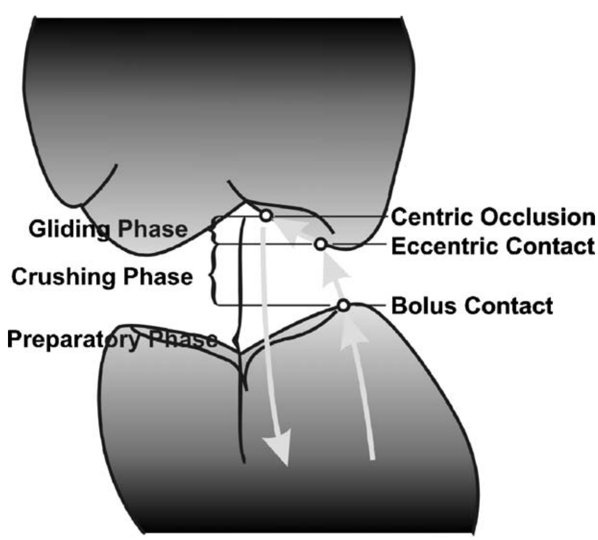

Fig. 1 – Three phases of the chewing cycle. The preparatory phase starts when the lower jaw opens and continues until the upper and lower teeth contact the food bolus. The crushing phase starts at the end of the preparatory phase and continues until there is tooth-to-tooth contact or the jaw once again starts to open. The gliding phase exists while the teeth are in contact, and does not always occur during the chewing cycle.

Active forces are produced by the muscles of mastication. During occlusal contacts, such as those that exist in the gliding phase, the active muscle forces may be resolved into reactive forces perpendicular and tangential to the occlusal surfaces of the teeth. These forces guide the movement of the lower jaw relative to the upper jaw, and are responsible for the wear of the interacting materials.

The general wear equation [5,6] can be written in the following form [7]:

$$\text{wear} \equiv \text{volume loss} = k \times \frac{F \times d}{P_h} \quad (1)$$

where k is a constant that depends on the wear mechanism, F the occlusal force, d the total sliding distance, and P_h is the hardness pressure. The occlusal force is defined as the resolved component of the active muscle force that is perpendicular to the surface at the contact.

An assumption of the wear equation is that there is an interaction between the two surfaces at their interface. Microscopically, the surfaces contact only at the tips of asperities, thus the actual contact area is very small; and the force per unit area of contact is very high. This high pressure can cause a "bonding" of the two surfaces. One surface can be moved relative to the other only by shearing these bonds. Based on this concept, it can be shown that the coefficient of friction can be approximated by [8]:

$$\text{coefficient of friction } (\mu) = \frac{F_S}{F} = \frac{\tau_b}{P_h} \quad (2)$$

where F_S is the tangential force and τ_b is the shear strength. Substituting for hardness pressure in Eq. (1) gives:

$$\text{wear} = k \times \frac{F \times d \times \mu}{T_b} \quad (3)$$

Three fundamentally important concepts in this equation are: (1) if there is no movement ($d = 0$); or (2) if there is no force ($F = 0$); or if there is no friction ($\mu = 0$), then there is no wear.

All three phases of the chewing cycle have movement; however, only the crushing and gliding phases have force and friction. Coefficients of friction were measured between enamel and enamel, amalgam, composite, and porcelain using the University of Minnesota Artificial Oral Environment [9,10] (Table 1). The artificial mouth was programmed to perform bruxing with a lateral excursion of 1 mm and an occlusal force of 13.4 N. Deionized water at 37 °C provided the lubrication.

It can be shown from simple principles, that enamel against enamel can produce significant wear. The combined median contact area for the first molar and first and second premolars is 2 mm^2 (interquartile range 1–4 mm^2) [11]. The shear strength of enamel, as tested by the punch method, is

Table 1 – Coefficients of friction for materials opposed by enamel

Material	Coefficient of friction (S.D.)
Amalgam	0.2 (0.05)
Composite	0.5 (0.1)
Porcelain	0.6 (0.1)
Enamel (unmatched pairs)	0.4 (0.3)

90 MPa [12]. An occlusal force of 100 N with a coefficient of friction of 0.4 produces a shear force of 40 N at the junction between the opposing enamel surfaces. Dividing this by the occlusal contact area of 2 mm^2 gives a shear stress of 20 MPa, which is significantly less than the reported shear strength of enamel. This argument implies that there should be very little enamel wear, or that wear is a fatigue process. At the microscopic level, the contact area can be orders of magnitude less than the macroscopically observed area of 2.0 mm^2 [13]. A decrease of one order of magnitude in the contact area would increase the shear stress beyond that of enamel, and thus lead to enamel wear.

A second mechanism for wear is fatigue, where repeated contacts at the asperities eventually cause the material to fracture. Friction occurs from surfaces riding up and over the asperities. In abrasive wear, the harder material "plows" through the softer material. Although the mechanisms are different, their wear equations are similar to that of adhesive wear [6].

Mastication is a three-body phenomenon. The modern diet is considered to act as a lubricant [added 14]; thus during mastication, the coefficient of friction is lower than that for enamel-to-enamel. The combination of reduced friction and reduced force (the occlusal force is distributed over a larger area) implies that three-body wear is less than two-body wear, see Eq. (3).

Early generation composites were very susceptible to three-body wear. These restorations showed excessive wear across the entire restoration, even in regions where there were no occlusal contacts [15]. This led to the concept of contact and contact-free wear [16]. Contact-free wear (three-body wear) occurs mainly in the valleys created by the primary anatomy of the tooth (Fig. 2) where food flows during the crushing and gliding phases of mastication. Contact wear (two-body wear) occurs in the contact regions of the gliding phase of mastication.

Wearing of teeth has significant clinical consequences both esthetically and functionally. As teeth wear, they continue to erupt, which led to the concept of "wearing into occlusion". If wear continues unabated, the enamel will eventually be breached. Once breached, both the enamel and exposed dentin wear at accelerated rates. Excessive wear on multiple teeth can have disastrous consequences (Fig. 3).

A third form of wear occurs on the cervical regions of teeth. Historically, cervical wear has been referred to as "toothbrush abrasion"; however, today the term non-carious cervical lesion is used because evidence suggests that excessive occlusal wear may be a significant factor in the etiology of these lesions [17–19]. In a clinical case study that followed cervical abrasions in a single individual for a period of 14 years, a high correlation, $r = 0.99$, was found between the volume of material lost on the occlusal surfaces and the growth of cervical lesions [19] (Fig. 4). Current consensus is that these non-carious cervical lesions are multifactorial [20].

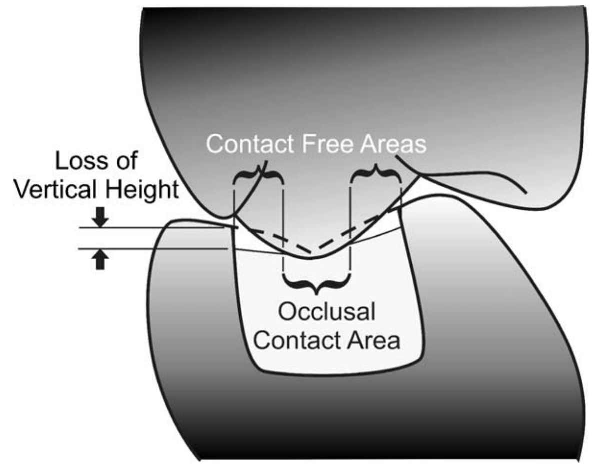

Fig. 2 – Contact and contact-free areas. The occlusal contact area is the region where opposing materials contact. It represents the region where two-body wear can occur. Contact-free areas are regions where only three-body wear occurs. The loss in vertical height is measured using the distance from the cavosurface margin of the preparation to the restoration.

Evaluating the wear of restorative materials requires that both the material of interest and the opposing material be considered. Clinically, it is the combined wear that is important; especially if the opposing material is enamel. For example, in an in vitro study done using the University of Minnesota artificial oral environment, significant differences were found in the ranking of material wear depending on whether the material alone or the combined wear of the material and enamel were considered. Enamel wear was measured when it opposed enamel, amalgam, and porcelain (Fig. 5). If only the material was considered, then enamel wore more than porcelain, which wore more than amalgam. Combining material wear with the opposing enamel wear found that the enamel–porcelain combination wore more than the enamel–enamel combination and that both wore significantly more than the enamel–amalgam combination.

Fig. 3 – Excessive wear. The lost of posterior stops led to excessive wear of the maxillary anterior teeth.

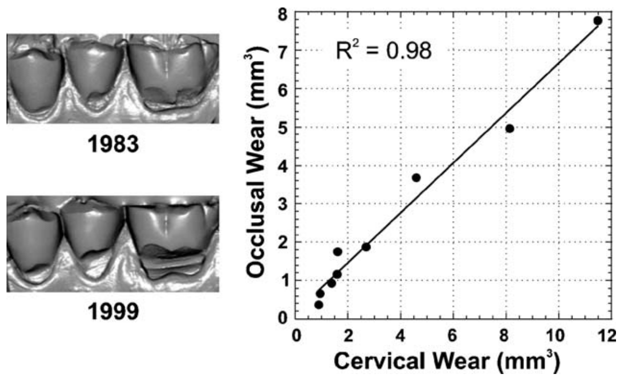

Fig. 4 – Correlation between volume loss in non-carious cervical regions vs. the corresponding occlusal volume loss over a 14-year (1983–1997) time span for a single individual [19].

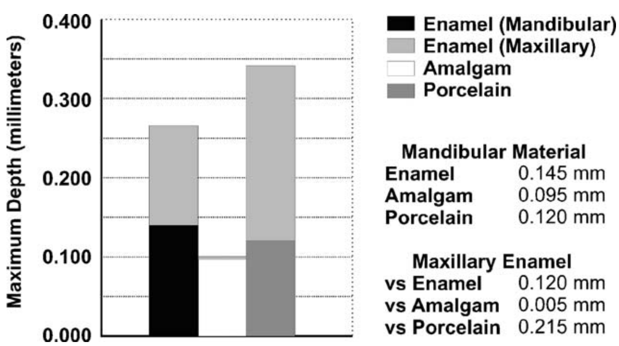

Fig. 5 – The wear of enamel opposed by enamel, amalgam, and porcelain in the University of Minnesota artificial oral environment. The artificial mouth was programmed to perform chewing with a lateral excursion of 0.6 mm and an occlusal force of 13.4 N for 500,000 chewing cycles. Deionized water at 37 °C provided the lubrication. Maximum depth is the largest vertical difference between "before" and "after" 3D images in the wear region.

Because of its reproducible chewing pattern, simulation provides a method for investigating mechanisms of wear. In simulated occlusal wear where the force, gliding path, and number of chewing cycles are held constant, variation in enamel wear rate is related to the coefficient of friction and type of wear mechanism, see Eq. (3). The coefficient of friction for enamel against amalgam is at least a factor of two less than that for enamel against enamel or porcelain (Table 1). Enamel against amalgam demonstrated an adhesive type of wear [7], which is less aggressive (smaller k) than the abrasive wear found with enamel against either enamel or porcelain [21]. Lower friction and adhesive versus abrasive wear can explain the lower enamel–amalgam combination wear rate.

3. Wear parameters

Interest is in parameters that have clinical relevance and that can be measured both in vivo and in vitro using the same, or comparable, methods. An obvious choice is volume because

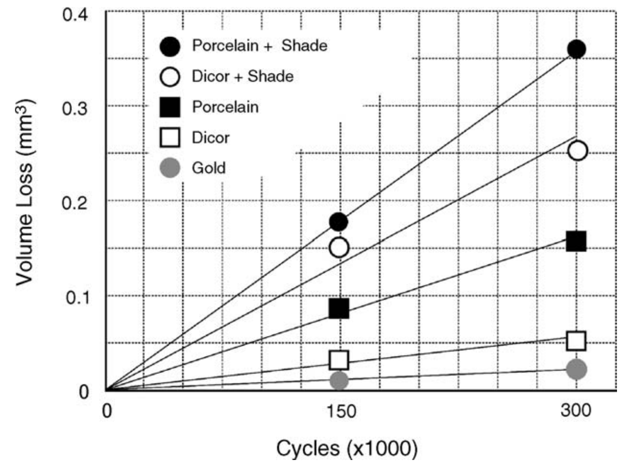

Fig. 6 – The linear relationship of volume loss with time tested in the artificial oral environment where chewing parameters are controlled and are constant with time [22]. Enamel was the antagonist. The lines represent the best linear fits forced through the origin.

wear is defined as the volume of material removed. Volume has two important clinical properties that can be demonstrated through the wear equation. Assume that the chewing parameters (occlusal force, number of chewing cycles, gliding path distance, etc.) remain relatively constant with time. As will be shown, this is a reasonable approximation. Also, assume that the opposing materials do not change over the measure time interval, then the shear strength, τ_b, is a constant. With these assumptions and substituting Eq. (2) into Eq. (3) for the coefficient of friction, the wear equation can be written as:

$$\text{volume loss} = k \times \frac{F_S \times d}{\tau_b}$$

Force times distance is work; thus, volume loss is a measure of the work done, which implies that volume loss is a material property and is independent of occlusal factors. Total gliding distance, d, is calculated as:

$$d = \frac{\text{chewing cycles}}{\text{unit time}} \times \text{gliding path} \times \text{time}$$

Substituting for d in the wear equation, and assuming that the chewing cycles per unit time and the length of the gliding path are relatively constant over time implies that the volume loss is approximately proportional to time.

The relationship of volume with time was tested in the artificial oral environment where the chewing parameters are controlled and are constant with time [22]. Wear of gold, Dicor (a glass ceramic; Corning Glass Works, Corning, NY), Ceramco II body porcelain (Ceramco Inc., Johnson & Johnson Co., East Windsor, NJ), Dicor + shade, and porcelain + shade was measured using enamel as an antagonist. The chewing parameters of the artificial mouth were a maximum occlusal force of 13.4 N, a lateral excursion of 0.6 mm, contact time of 0.2 s, and a chewing rate of 4 Hz. Deionized water was continuously circulated at 37 °C. Volume loss was measured after 150,000 and 300,000 cycles. All materials showed a linear relation to time except Dicor + shade (Fig. 6). This can be explained by the large

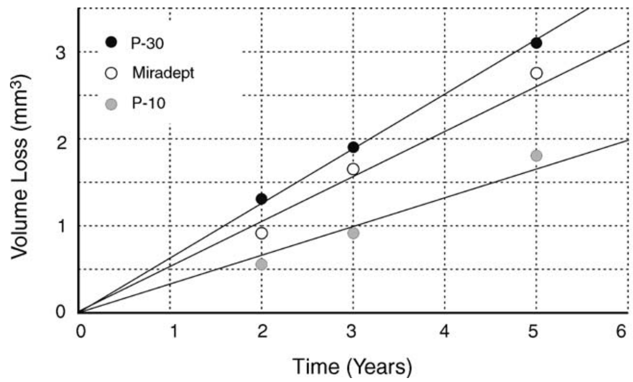

Fig. 7 – The linear relationship of volume loss with time for three posterior composites tested clinically over a 5-year time period [23]. The lines represent the best linear fit to the data forced through zero.

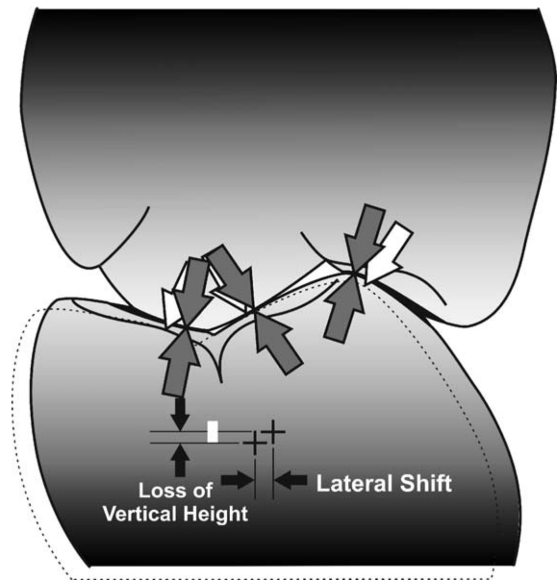

Fig. 8 – In this hypothetical simulation of wear, the dotted line represents the position of the mandibular tooth prior to wear. After wear, the position of the centric contacts has moved from their original positions (white arrows) to the positions represented by the gray arrows. The wear resulted in lateral and vertical shifts of the mandibular tooth relative to the maxillary tooth. The white bar represents the combined loss in vertical height if measured independently on the maxillary and mandibular teeth, which is larger than the clinical loss in vertical height.

difference in material properties between the shade and Dicor materials. Dicor wore significantly less that the shade material, which is essentially a ceramic. The initial wear rate was similar to that of the porcelain + shade material; however, once the shade material was breached, the wear rate decreased. The linearity of volume loss with time was also tested clinically [23]. Again, over a 5-year period, the volume loss was linear with time (Fig. 7). This linear relationship supports the assumption that the occlusal parameters are relatively constant with time.

Volume is a function of the depth and area of the wear region, thus area and depth are potential parameters for measuring clinical wear. Disadvantages of these two parameters are that they represent indirect wear measures, depend on occlusal factors, and vary with time. Consider a hypothetical case of before and after wear on opposing teeth (Fig. 8). Assume the opposing teeth remain in contact as they wear. Under these conditions, three dynamic changes occur in the occlusal parameters: the centric contacts move, the orientation of the teeth to each other changes, and the areas of contact increase. Of particular interest is the movement of the mandibular tooth relative to the maxillary tooth because of its clinical significance. As the teeth wear, the mandibular tooth moves both vertically and laterally. The net effect is the loss of vertical height between the upper and lower jaws; however, this loss is less than the combined measured vertical depths of the wear regions.

A second consequence of change in orientation of opposing teeth during wear is that the regions where the teeth contact change. It is possible that wear will cease in one location and move to a second location. In effect, the wear starts all over. This raises the problem of how to combine the two wear regions. With volume this is not a problem because they are additive; however, with depth and area it can be difficult, if not impossible. If wear regions overlap, it is not possible to get accurate measures of the wear areas because the most recent wear region will destroy some of the area of the earlier wear regions. It can also affect the depth measurement. An example of the dynamic quality of wear is demonstrated in the in situ 2-year wear of a maxillary canine [24]. The baseline image (Fig. 9) shows several wear facets that occurred prior to the capture of the baseline surface. The large wear region is composed of three wear facets on the facial, palatal, and distal surfaces near the incisal edge. From this image, it is not possible to know which area wore first or if they occurred at the same time. The impression is that the wear facets represent regions of active wear; however, when the surface captured 2

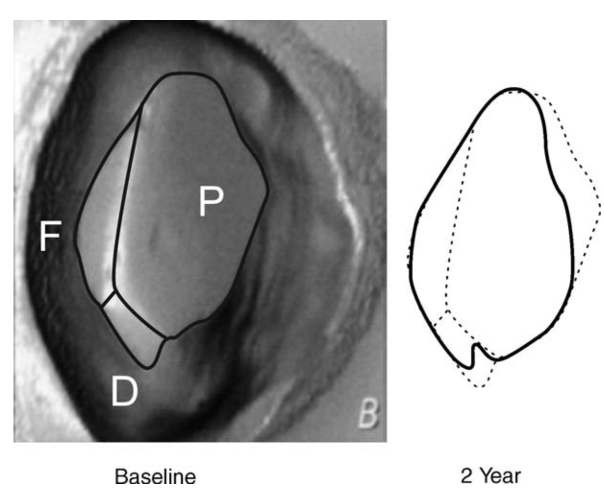

Fig. 9 – The dynamic quality of wear demonstrated in the 2-year wear of a maxillary canine [24]. The baseline image shows three wear facets (black outlines): facial (F), palatal (P), and distal (D). The active wear region after 2 years (solid line) is compared to the baseline wear facets (dashed line).

years later is subtracted from the baseline surface it is seen that active wear occurred on all of the facial and distal wear facets and on only part of the large palatal wear facet. This emphasizes that the area of a wear facet does not always represent active wear. Also, as the facial and distal wear facets grew, they remove some of the original wear area associated with the palatal wear facet. In summary, the area of a wear region is an indirect measure of wear that depends on occlusal factors.

Depth is not a good parameter for comparing wear because its magnitude depends on where the depth is measured and the direction from which it is measured. Depth was used historically because of its link to vertical dimension and because early composite wore so rapidly that the cavosurface margin of the preparation was quickly exposed, and thus could be used as a reference. The amount of wear was measured from the cavosurface margin to the surface of the material [25]. The assumption was that the majority of the material was lost due to three-body, contact-free wear and that the wear was relatively uniform across the material. Most new generation composites show little wear, thus this method has limited value.

Occlusal contact areas, which are the areas where teeth actually contact, are different from wear region areas. The occlusal contact area is similar between opposing materials, and is always less than or equal to the area of the corresponding wear region. Opposing wear regions are significantly different because one material is sliding against the other and subsequently has a smaller wear region. Occlusal contact areas identify where force is applied, and represent a point-in-time location of occlusal contacts. Although contact areas change during the chewing cycle, it is important to identify where they occur because they indicate if the material of interest is experiencing two-body wear and they enable estimating how the chewing force is distributed.

4. Methods of measuring wear

Probably the most universally used method of measuring wear is the non-parametric test devised for the United States Public Health Service (USPHS) [26]. Three well-defined categories are used to assess wear: “alpha”, “bravo”, and “Charlie”. An “alpha” score means there is no wear; “bravo” means visible wear; however, it is still clinically acceptable; and “Charlie” means excessive wear and the restoration must be replaced. The advantages of the USPHS method are that it is readily available and does not require special equipment. The disadvantages are that it is subjective and takes a long time to get significant results [27].

A second popular method for measuring clinical wear is the Leinfelder et al. method [25]. Replicas of the restoration are compared to calibrated standard casts that have increasing wear in approximately 0.1 mm steps. Wear is measured at the periphery of the restoration. One assumption is that wear, measured as a loss in vertical dimension, is relatively uniform across the surface of the restoration. Inter-evaluator error is about 0.05 mm [28]. Advantages of this method are that it is fast and inexpensive; however, it tends to underestimate wear [23].

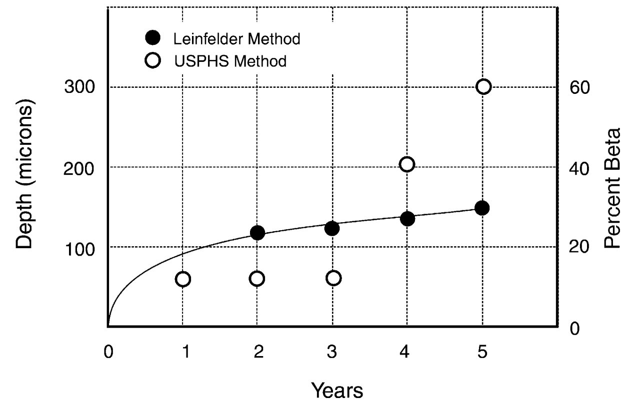

Fig. 10 – The wear of a posterior composite measured using the USPHS and the Leinfelder et al. methods.

Fig. 10 shows the wear of a posterior composite measured using the USPHS and the Leinfelder et al. methods [25]. The USPHS method showed a significant change in the performance of the material between the third and forth years of the study. The Leinfelder et al. method indicated that the majority of the wear occurred during the first 2 years followed by lower wear for the next 3 years. Based on these results, the Leinfelder et al. method took 2 years to reach the same conclusion that the USPHS method found in 4 years. This represents a significant savings in the cost of running a clinic trial.

Without a doubt, the best method for measuring wear is by comparing sequential 3D images of the materials of interest. Three-dimensional images are captured using various scanning methods such as contact profilers, non-contact white light or laser scanners, or micro-or cone CT scanners. Sequential 3D images are aligned to each other by maximizing the overlap of common, unaltered surface topology of the images (a process called surface registration). The aligned surfaces are then subtracted to reveal changes with time.

Three-dimensional scanning is the preferred method for measuring wear because it is quantitative, accurate, provides storable 3D databases that can be compared to other 3D databases, and it is applicable to both the clinic and the laboratory [29]. Disadvantages include the need for specialized hardware and software and cost. These have proven to be significant disadvantages because 3D scanning technology has been available since the mid 1980s; however, few clinical studies have used this technology to measure wear. With the cost of scanners dropping and with the number of scanning services becoming increasing, more clinical studies may use the technology in the future.

Before progressing, it is important to understand the difference between accuracy and precision. Accuracy is how well the measured value represents the “truth”. Precision is the repeatability of the measurement system; the spread of the measured values. It is possible to have a very precise system but with poor accuracy (Fig. 11). This means that the system has a bias. Bias can be determined and corrected through calibration of the measuring device. It is also possible to have a very accurate system with poor precision. In this case, accuracy is determined by the mean of multiple measurements. Ideally, the measuring system is both accurate and precise.

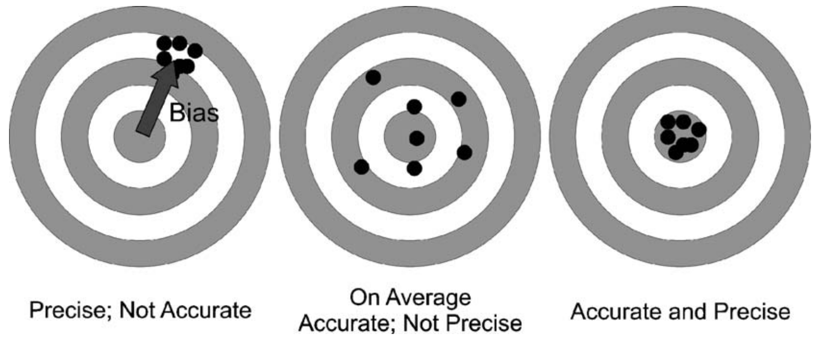

Fig. 11 – Accuracy vs. Precision. Accuracy is how well a measure value represents the "truth". Precision is the repeatability of the measurement system. A measurement system can be very precise but have poor accuracy, which implies that the system has a bias. A system can be very accurate on average, but have poor precision. The ideal measuring system is both accurate and precise.

What level of accuracy is required to measure clinical wear? A rule of thumb is that the accuracy of a measurement device should be at least one order of magnitude smaller that what is being measured. The ADA specification for composite wear states that a composite cannot lose more than 0.05 mm in height per year. This means that the measurement tool should have an accuracy of 0.005 mm or better. Practically, this is difficult to obtain. For example, companies that provide calibrated measurement services using coordinate measuring machines with accuracies of 0.0001 mm can only certify their measurements to few microns because of operator and environmental factors that influence the final result.

A more practical determination of the minimum acceptable accuracy depends on how sensitive people are to changes in their occlusion. This sensitivity is defined by the absolute threshold — the stimulus amplitude at which a subject detects the stimulus. The logic is that any change in their occlusal surface anatomy below this level will not trigger a neural response; therefore, if the accuracy of the measurement tool is below the absolute threshold, then it should be acceptable. Mean absolute thresholds measured using thin foils of various thicknesses made from different materials ranged between 0.02 and 0.03 mm [30] (Fig. 12). Many subjects could detect foils as thin as 0.010 mm.

Based on the absolute threshold data, a measurement system for quantification of clinical wear should have a minimum accuracy of 0.02 mm, with 0.01 mm being preferred. This is the accuracy for the entire system of which the scanner is only one part. If measurements are done directly in the mouth, then the scanner accuracy is the system accuracy. If measurements are

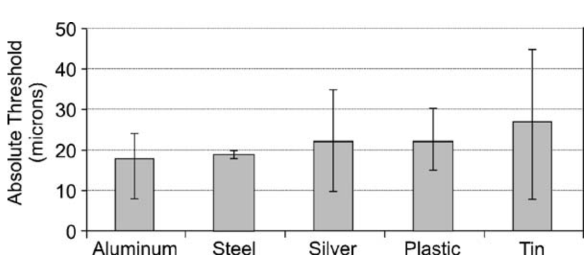

Fig. 12 – Mean absolute threshold for natural teeth measured using thin foils of different materials [30].

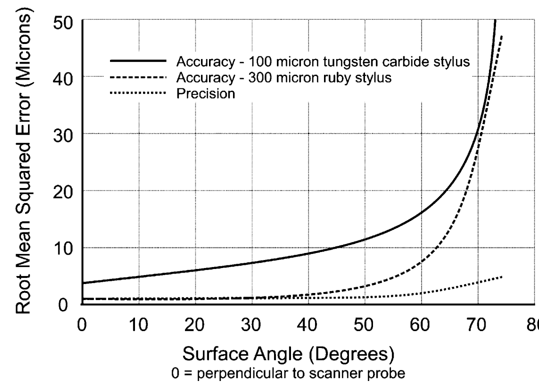

Fig. 13 – Accuracy and precision of a contact profiling system as a function of surface angle. Accuracy depends on the type of stylus. The tungsten carbide stylus has a diameter of 0.1 mm and is round to about 5 μm. The ruby stylus has a diameter of 0.3 mm and is round to 1 μm. Precision was similar for both stylus types.

done using replicas, the indirect measurement method, then accuracy of the impression and replica materials must be combined with the scanner accuracy as part of the overall system accuracy [31].

Up to this point, accuracy has been treated as a single value; however, this is not normally the case. During scanning, a set of 3D points is collected that represents the surface of the object being scanned. The accuracy of each point depends on the shape of the surface and the angle that it makes to the scanner (Fig. 13) [32,33]. The greater the angle the surface makes to the scanner's "line of sight" the less accurate the measurement. One exception to this is the coordinate measuring machines used in calibration services; however, these are point-measuring devices, and are not practical for digitizing surfaces of teeth.

Dependency of accuracy on surface angle can be controlled by scanning the surface multiple times and changing the surface orientation to the scanner each time. The multiple scans are then combined to form a single set of points that defines the entire surface of the object. In addition to reducing the effects of surface angle on accuracy, this method can improve accuracy because multiple points representing the same surface area can be averaged. Also, regions on the surface not visible from one angle (called shadowing) can be seen from a different angle, thus forming a more complete 3D image [31].

Scanners can be categorized as contact and non-contact. Non-contact scanners can be further divided into point, line, area, and volume scanners. Contact profilers for profiling the irregular topology of occlusal surfaces use spherical tipped styli. Resolution is limited by the size of the stylus tip, which typically have diameters 0.1 mm or larger. Advantages of the contact profiling systems are good accuracy with relatively low cost, and they are not affected by differences in surface material properties such as color or transparency. Disadvantages are that they are slow and require rigid surfaces. Non-contact point profiling systems are similar to the contact profilers in the way they digitize surfaces. Their "stylus" is a light source or microscope focused on the surface. Their main advantage over the contact profiler is that they do not contact the surface. Their disadvantage is that they require an opaque, diffuse reflecting surface. Resolution depends on the focus light source, which is typically less than 0.025 mm. Non-contact line laser systems scan the surface using a straight line projected on the surface. A digital camera captures images of the line as it moves across the surface. The known geometry of the system and triangulation enable calculating the surface points. Area scanners are similar to line scanners except that they project a pattern over the surface and use triangulation, moiré fringe patterns, interferometry, phase shifting, or combinations of these to calculate surface points. The main advantage of line and area scanners is that they are significantly faster than point scanners. The trade-off is lower resolution because the line or pattern cannot be focused as sharply as a single point; however, it is typically 0.1 mm or better. Volume scanners are CT based. Their resolution is determined by voxel size, and ranges from a few microns (micro CT) to hundreds of microns. The advantage of volume systems is that shadowing is not a problem. Disadvantages are cost and radiation.

A key issue with 3D scanning is that it must be applicable to both the clinic and laboratory. All of the above methods meet this criterion if replica models are used. Direct scanning is preferred over the indirect methods because of the potential for improved accuracy and simplification in the number of steps; however, scanning intra-orally is extremely difficult. Only two methods exist today: the CEREC CAD/CAM system and cone beam CT scanning. The CEREC system requires spraying the teeth with white powder, which will affect the accuracy of the system. Measurement accuracy of Cone beam CT scanners is a few hundred microns [34], thus they are limited in their ability to measure wear on the occlusal surfaces of teeth.

No matter what system is used to measure wear, it is mandatory that the accuracy and the precision of the system be known. One cannot rely on the manufacturer's specifications because these normally refer to ideal conditions, and only refer to the scanner. Effects of impression and replica materials must be included in determining the accuracy of the system. The system should be calibrated using a standard that resembles what is to be scanned. Geometric standards are often used because their dimensions can be accurately measured using coordinate measuring machines. For example, in calibrating a system for scanning dental arches, a standard was made that approximated the human arch [31]. The standard's dimensions were measured to a certified accuracy of 0.005 mm using a coordinate measuring machine. From these dimensions, a computer model was constructed for comparing with impression and stone replicas of the standard (Fig. 14). Results implied that surfaces created by scanning impressions are twice as accurate as those created by scanning stone replicas of the surfaces.

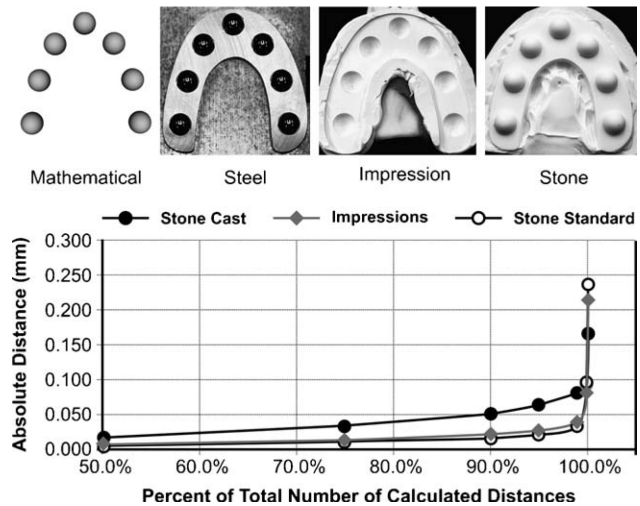

Fig. 14 – Calibration of a scanning system using a mathematical standard. A geometric steel standard was constructed using precision ball bearing arranged in the shape of an arch (steel) and a stone replica of the standard (stone). Centers and radii of the steel and stone standard bearings were measured using a calibration service. Mathematical standards were created using the known centers and radii (mathematical). The stone standard, impressions of the steel standard, and stone casts made from the impressions were compared to the mathematical model of the steel standard. Absolute distances were calculated from each point on the mathematical standard to each of the test surfaces. The absolute values for each comparison were aligned from smallest to largest and plotted against the percent of absolute values below a defined value. Ideally, all absolute values would be the same and the plot would be horizontal. The sharp rise above 99% is a result of outlying points caused by scanning errors.

The method of reporting the accuracy of the scanning system needs to be addressed. Accuracy is typically reported as the mean of multiple measures. The standard deviation is the precision. This works well for reporting values for wear parameters, but tells nothing about the accuracy of reproducing the surfaces or the quality of the registration of the surfaces. Whether one is reporting volume, area, or depth, the value is determined by subtracting two scanned surface images; therefore, it is important to know how well the digitized surface represents the "true" surface. A simple measure is to calculate the shortest distance from each point on the digitized surface to the "true" surface, then average the absolute values of these distances and report the mean as the accuracy plus or minus the standard deviation. Absolute values are used because signed distances on the opposite sides of the surface could partially cancel each other, which would lead to an underestimate of the accuracy. The problem with this method of reporting is that half of the distances are greater than the mean, and could possibly be grouped in the region of wear. Reporting accuracy as the largest distance grossly overestimates the error because of outlying points that occur during scanning (Fig. 14). Outliers are points that result from scanning errors and do not reflect surface topology.

An effective way to report system accuracy is to report the absolute value based on a "sigma" value where sigma is related to the standard deviation. A 1 sigma value is the absolute distance that is equal to or greater than 68% of the measured absolute distances; 2 sigma is greater than 95%; and 3 sigma is greater than 99%. For example, for the stone replica (Fig. 14), 99% of the values are less than 0.08 mm. The corresponding value for the impression is 0.040 mm. This method is similar to confidence intervals in that one has 99% confidence that the error in the digitized surface of the impression is within 0.040 mm of the true value. The error in measuring the depth of a wear facet would then be the square root of two times this or 0.057 mm.

One final point that affects accuracy is the quality of the alignment of surfaces. This is a very important factor, especially for the indirect methods where distortion can occur during the impression step or when creating the replica models. If distortions occur, it is unlikely that they will be identical on both surfaces; therefore, the quality of alignment will be poorer. The quality of alignment can be measured the same way as the accuracy of the surface using absolute distances with the sigma representation. In determining the accuracy of a wear parameter value, the quality of the surface registration must be combined with the accuracy of the surfaces. This is a conservative measure of accuracy because inaccuracies in the surfaces are averaged out to some extent in the surface registration process.

5. Conclusions

The preferred parameter for measuring wear is volume. It is independent of occlusal factors and has clinical value because it is a measure of the work done. If material and environmental factors remain constant, volume loss is linear with time. Depth, which has been used historically because of its association with loss of vertical height, has limited clinical value because of its dependence on occlusal factors. Area also has limited value for a similar reason. Occlusal contact area is clinically important, because it shows how force is distributed across the occlusal table and where teeth are contacting the material. When measuring wear, both the material of interest and the opposing material must be considered; especially if the opposing material is enamel.

Wear is best measured using 3D scanning to compare sequential images of the surface. Measuring systems should be calibrated using a known standard that approximates the surfaces to be measured. Sigma values provide more meaningful measures of scanner accuracy than simple means and standard deviations. Include the quality of the alignment of the "before" and "after" surfaces in the reported error.

REFERENCES

[1] Watts MW, Tan EK. Bruxism and cranial–cervical dystonia: is there a relationship? Cranio 1999;17(3):196–201.
[2] Miura H, Miura K, Mizugai H, Arai Y, Umenai T, Isogai E. Chewing ability and quality of life among the elderly residing in a rural community in Japan. J Oral Rehabil 2000;27(8):731–4.
[3] Pindborg JJ. Pathology of the dental hard tissues. Copenhagen: Munksgaard; 1970.
[4] Murphy TR. The timing and mechanism of the human masticatory stroke. Arch Oral Biol 1965;10(6):981–94.
[5] Archard JF. Contact and rubbing of flat surfaces. J Appl Phys 1953;24:981–8.
[6] Rabinowicz E. Friction and wear of materials. New York: John Wiley; 1965. p. 167–179.
[7] DeLong R, Sakaguchi RL, Douglas WH, Pintado MR. The wear of dental amalgam in an artificial mouth: a clinical correlation. Dent Mater 1985;1(6):238–42.
[8] Szeri AZ. In: Larson RW, Dorfman M, editors. Tribology friction, lubrication, and wear. McGraw-Hill Book Company; 1980, ISBN 0-07-062663-4.
[9] Sakaguchi RL. A biophysical analysis of the occlusal wear of dental materials. PhD Thesis, University of Minnesota, 1988.
[10] Douglas WH, Sakaguchi RL, DeLong R. Frictional effects between natural teeth in an artificial mouth. Dent Mater 1985;1(3):115–9.
[11] Owens S, Buschang PH, Throckmorton GS, Palmer L, English J. Masticatory performance and areas of occlusal contact and near contact in subjects with normal occlusion and malocclusion. Am J Orthod Dentofacial Orthopedics 2002;121(6):602–9.
[12] Craig RG, Ward ML, editors. Restorative dental materials. 10th Ed. Mosby-Year Book Inc.; 1997, ISBN 0-8151-1920-8.
[13] Greenwood JA, Williamson JB. Contact of nominally flat surfaces. Proc Royal Soc (London) 1966;A295:300.
[14] Luke DA, Lucas PW. The significance of cusps. J Oral Rehabil 1983;10(3):197–206.
[15] Wilder AD, May KN, Leinfelder KF. Three-year clinical study of UV-cured composite resins in posterior teeth. J Prosthet Dent 1983;50(1):26–30.
[16] Lutz F, Phillips RW, Roulet JF, Setcos JC. In Vivo and in vitro wear of potential posterior composites. J Dent Res 1984;63(6):914–20.
[17] Lee WC, Eakle WS. Stress-induced cervical lesions: review of advances in the past 10 years. J Prosthet Dent 1996;75:487–94.
[18] Bader JD, McClure F, Scurria MS, Shugars DA, Heymann HO. Case-control study of non-carious cervical lesions. Community Dent Oral Epidemiol 1996;2:286–91.
[19] Pintado MR, DeLong R, Ko C-C, Sakaguchi RL, Douglas WH. Correlation of non-carious cervical lesion size and occlusal wear in a single adult over a 14-year time span. J Prosthet Dent 2000;84(4):436–43.
[20] Grippo JO, Simring BA, Schreiner BS. Attrition, abrasion, corrosion and abfraction revisited: a new perspective on tooth surface lesions. J Am Dent Assoc 2004;135(8):1109–18.
[21] DeLong R, Sasik C, Pintado MR, Douglas WH. The wear of enamel when opposed by ceramic systems. Dent Mater 1985;5:266–71.
[22] DeLong R, Pintado MR, Douglas WH. The wear of enamel opposing shaded ceramic restorative materials: an in vitro study. J Prosthet Dent 1992;68:42–8.
[23] Peters MCRB, DeLong R, Pintado MR, Pallesen U, Quist V, Douglas WH. Comparison of two measurement techniques for clinical wear. J Dent 1999;27:479–85.

[24] Pintado MR, Anderson GA, DeLong R, Douglas WH. Variation in tooth wear in young adults over a two-year period. J Prosthet Dent 1997;77:313–20.
[25] Leinfelder KF, Taylor DR, Barkmeier WW, Goldberg AJ. Quantitative wear measurements of posterior composite resins. Dent Mater 1986;2:198–201.
[26] Cvar JF, Ryge G. Criteria for the clinical evaluation of dental restorative materials. USPHS Publication #790-244. San Francisco: US Government Printing Office; 1971; or Ryge G. Clinical performance. In: O'Brien, W.J., Ryge, G. (Eds.), An outline of dental materials and their selection. WB Saunders Company: 1978. p. 366–369.
[27] Taylor DF, Bayne SC, Sturdevant JR, Wilder AD. Comparison of direct and indirect methods for analyzing wear of posterior composite restorations. Dent Mater 1989;5(3):157–60.
[28] Bayne SC, Taylor DF, Rekow ED, Wilder AD, Heymann HO. Confirmation of Leinfelder clinical wear standards. Dent Mater 1994;10(1):11–8.
[29] Perry R, Kugel G, Kunzelmann KH, Flessa HP, Estafan D. Composite restoration wear analysis: conventional methods vs. three-dimensional laser digitizer. J Am Dent Assoc 2000;131(10):1472–7.
[30] Jacobs R, van Steenberghe D. Role of periodontal ligament receptors in the tactile function of teeth: a review. J Periodontal Res 1994;29(3):153–67.
[31] DeLong R, Heinzen M, Hodges JS, Ko CC, Douglas WH. Accuracy of a system for creating 3D computer models of dental arches. J Dent Res 2003;82(6):438–42.
[32] Hewlett ER, Orro ME, Clark GT. Accuracy testing of three-dimensional digitizing systems. Dent Mater 1992;8(1):49–53.
[33] Jovanovski V, Lynch E. Analysis of the morphology of oral structures from 3D co-ordinate data. Monogr Oral Sci 2000;17:73–129.
[34] Kobayashi K, Shimoda S, Nakagawa Y, Yamamoto A. Accuracy in measurement of distance using limited cone-beam computerized tomography. Int J Oral Maxillofac Implants 2004;19(2):228–31.