Wear of dental materials: Clinical significance and laboratory wear simulation methods — A review

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This review focuses on tribological aspects of teeth during function, the clinical significance of wear, wear of natural teeth and restorative materials and laboratory methods to simulate wear of restorative materials. Ceramic, metal alloy and amalgam show low material wear, whereas resin-based materials demonstrate substantial wear in the long term. The clinical wear shows a high variability with the patient factor accounts for about 50% of the variability. Wear as such seldom compromises the function of the stomatognath system or individual teeth and is in most cases an esthetic problem. Particles that are ingested due to attrition and abrasion wear may pose a health risk to the patient, especially those from composite resin materials. However, systematic clinical studies on that issue are not available. For laboratory research many wear simulation devices and methods have been developed but only few are validated and have a moderate correlation with clinical wear.

Keywords: Wear methods, Composite, Ceramic, Clinical significance, Review

INTRODUCTION

Tribology in the oral cavity: factors and processes

Dental hard tissues (enamel) are subject to wear the very moment when they erupt into the oral cavity or when they get into contact with the antagonist tooth. The same holds true for dental restorations, which are subject to wear processes from the first moment they are inserted into the oral cavity. Different wear mechanisms can be distinguished and they refer to both teeth and restorative materials: When teeth get into contact with each other without a third medium between them, two-body wear, or attrition, is caused1-3. Chewing on food items or brushing teeth with a toothbrush and toothpaste results in three-body wear, or abrasive wear. Buccal and lingual tooth surfaces are mainly exposed to mechanical oral hygiene procedures causing abrasive wear, while the occlusal surfaces are mainly subject to both attrition and abrasive wear. Another phenomenon is described as adhesion wear and occurs when two solid surfaces slide over one another under pressure. The high local pressure causes the surface projections, or asperities, to become plastically deformed and eventually they are joined together. In the process, material may be transferred from one tooth to the artificial surface or enamel of the opposing tooth. Likewise, a similar transfer of material may happen on the proximal surfaces of adjacent teeth. Fatigue wear occurs when large portions of dental hard tissues or restorative material chip off. If this occurs on the cervical part of the tooth, the term abfraction is used.

Saliva is an essential factor that influences wear in the oral cavity. It functions as a lubricant and diminishes wear by reducing friction. Mucopolysaccharides and glycoproteins are the main lubricants in saliva. If acidic substances and high occlusal loads occur together, the wear rate may be accelerated dramatically. Such substances can derive from acidic food items, from gastric acid, or from sources outside the oral cavity, such as factories that emit acidic substances in the air4-5. The acidic attacks that cause loss of tooth substance are summarized as erosive wear, but the term corrosive wear would be more adequate here6.

All these processes occur in the biomechanical stomatognathic system, where the teeth of the upper jaw are fixed to the skull and the teeth of the lower jaw are movable in three directions: to the lateral, front and vertical, which gives them a high degree of movement flexibility. The teeth get into contact with each other during eating and chewing as well as during other processes, such as swallowing, speaking and yawning. Any other tooth contacts are attributed to parafunctional or pathological actions or habits, namely such as bruxism or thegosis7. Bruxism is the technical term for teeth grinding without food and occurs mainly unconsciously at night during short periods of 30 to 60 s an hour8. Patients suffering from bruxism produce high biting forces during the gnashing phases9. The maximum biting forces, however, do not seem to be different from those of non-bruxers10. In some patients, bruxism leads to a hypertrophy of the masticatory muscles (e.g. M. masseter) and to a considerable wear of the teeth, even to the point where dentine becomes exposed. Equally, restorative materials show more wear, fracture or chipping in bruxers. The number of people that show some level of bruxism has significantly increased...
over the last three decades\textsuperscript{11}. Based on several cross-sectional studies, estimates assume that the prevalence of bruxism in the industrialized countries is in the range of 20\%, with physiological stress factors being the most important etiological factor\textsuperscript{12}. Tegosis is the process of sliding teeth into a lateral position and may derive from the evolutionary genetic habit to sharpen teeth. Other actions causing friction and wear on teeth are pipe-smoking as well as chewing on pencils or toothpicks and biting fingernails, etc.

The biomechanical process of mastication is very complex and is controlled by trigger zones in the brain stem and involves multiple feedback mechanisms, some of which are located in the periodontal ligament\textsuperscript{13}. Mastication reduces the food bolus to a few cubic millimeters, which facilitates swallowing and digestion. The profile of the force curve corresponds to the positive half of a sine curve and is therefore also called haversine wave form\textsuperscript{14}. The masticatory force depends on the texture of the food as well as on the location where the chewing occurs in the oral cavity. Higher pressure and higher forces are exerted in the posterior region and when grinding hard foodstuffs. However, biting forces vary substantially between different individuals and they decreases with age, with young adults having the highest forces. The magnitude of the biting force is in the range of 10 to 20 N in the initial biting phase and increases to the range of 100 to 140 N in the molars and 25 to 45 N in the incisors at the end of the chewing cycle\textsuperscript{15}. The entire cycle lasts for about 0.8 s whilst the mean duration of occlusion is only about 0.4 to 0.6 s\textsuperscript{13,15}. The sliding distance is less than 1 mm with a speed of 0.25 to 0.5 mm/s\textsuperscript{16}.

Direct antagonist tooth contact totals 15 to 20 min per day, depending on the eating frequencies and habits and does not include the tooth contact during swallowing, which, however, is only of a lower magnitude. The mean chewing frequency is about 1.6 Hz (range 0.9–2.1 Hz) with about 300 strokes per meal\textsuperscript{17}. If we assume that 3 meals are eaten per day, an individual carries out approximately 330,000 chewing cycles per year. However, no systematic studies in large patient samples have yet been carried out on the frequency of chewing cycles. According to the literature, Europeans chew about 400 kg of solid food on average per year\textsuperscript{18}.

CLINICAL IMPORTANCE OF WEAR OF TEETH AND RESTORATIVE MATERIALS

Wear of teeth is physiological and increases with age with males showing significantly more wear than females\textsuperscript{19}. A systematic review revealed that the prevalence of severe tooth wear in patients does not increase on a linear scale from about 3\% at the age of 20 to about 8\% at the age of 40 and to about 17\% at the age of 70\textsuperscript{20}. It seems, though, that the prevalence of tooth wear in the different age groups has increased over the last four decades\textsuperscript{21}. However, there is no consensus on the correct tooth wear index or on the correct method to evaluate tooth wear clinically\textsuperscript{22}.

Wear of natural or restored teeth can have mainly three consequences: (1) esthetic effects that compromise the appearance of the natural and restored teeth, (2) in case of severe wear, irritation of the pulp with clinical signs of hypersensitivity or pulpitis or even opening of the pulp, and (3) functional effects that alter the relationship between the tooth and antagonist and/or tooth and adjacent tooth by promoting phenomena like elongation of antagonists, movement of teeth or reduction of vertical height with possible consequences to the temporomandibular joint (TMJ). A clinical study in the UK on 290 patients that were referred to a dental clinic because of severe tooth wear revealed that esthetic concerns were the most prevalent complaint (59\%), followed by tooth hypersensitivity (40\%)\textsuperscript{23}. Patients who had lost molar tooth support showed significantly more severe wear in the premolar and anterior region. Furthermore, severe tooth wear was more than two times more prevalent in males than in females\textsuperscript{23}. According to a clinical study on 1007 individuals in southeast England, the percentage of excessive wear in natural teeth varied between 3\% and 9\% of all tooth surfaces according to different age groups\textsuperscript{24}.

Wear particles derived from restorative materials may have a biological and/or toxicological effect if swallowed or inhaled. Components that can be released from amalgams during the masticatory process include copper, zinc and mercury. Based on clinical wear rates of amalgam fillings, the average amount of dissolved zinc and copper was found to be small even over a long period of time\textsuperscript{25}. Likewise, the amount of mercury released due to abrasion seems to be relatively irrelevant clinically—as measured in bruxist patients\textsuperscript{26}. Wear of noble gold-based dental alloys and ceramic materials is low and these materials are regarded as being relatively inert, even if some particles may be swallowed\textsuperscript{27,28}. However, alloys that contain nickel, chromium and beryllium are considered to have a higher allergic and mutagenic potential. With resin-based composites, there are some concerns that, in addition to the leaching of (co)monomers, micro- and nano-sized filler particles may be worn, swallowed or inhaled and then be accumulated in the tissues. These accumulations may be linked to diseases of the liver, kidney, lung and intestine\textsuperscript{29-31}. The particle size of the dust grains created during grinding and polishing of resin composite fillings with diamond burs and rubber instrument is —depending on the material—in the micrometer and submicrometer range (between <100 nm and >15 µm), as shown in an in vivo study, where 75\% of the particles were smaller than 2.5 µm (Fig. 1)\textsuperscript{32}. An efficient suction system, water spray and protecting masks should be used during grinding and polishing to prevent, or at least to reduce, the inhalation of nano- and microsized composite dust. However, the ingestion of the particles that are caused by wear cannot be avoided.

Studies with radionucleated 14C- (co)monomers demonstrated high intestinal absorption\textsuperscript{33-35}. Once released, (co)monomers can diffuse into the pulp chamber or they can be absorbed through the lungs by inhalation.
In this way, they reach the systemic circulation\textsuperscript{[36,37]}, where they are further metabolized\textsuperscript{[38,39]}. Studies have shown that cellular or liver microsomal degradation of (co)monomers leads to the formation of the epoxy compound 2,3-epoxymethacrylic acid\textsuperscript{[38-52]}. Composite dust has a very wide size variation ranging from a couple of nanometers to more than 15 µm. The large dust particles typically consisted of filler particles embedded in resin, but very frequently single nano-filler particles could be observed (arrows)\textsuperscript{[20]. (Courtesy Van Landuyt and by Dental Materials)}

Wear behavior of natural teeth and dental restorative materials

Dental enamel is highly resistant to wear with a mean annual vertical enamel loss rate of about 20–30 µm in posterior teeth\textsuperscript{[33-60]}. The wear rate of enamel is higher during the first two years after coming into contact with the opposing teeth (running-in phase) and decreases thereafter. Furthermore, the surface hardness of enamel and its depth of wear vary with age: lower hardness and higher depth of wear were observed in older patients compared with young or middle aged patients\textsuperscript{[19]}. The wear of enamel mainly results from microfracturing and is characterized by delamination and microploughing. In contrast, the wear of dentine is characterized by ductile chip formation.

Artificial dental materials can be grouped into five different categories: metal alloys, ceramics, amalgams, composites and unfilled polymers. Clinical wear of dental alloys and ceramic materials is low. A concern was raised that the antagonist teeth may become excessively abraded by ceramic materials that show a high strength, E-modulus and/or surface hardness\textsuperscript{[86]}. However, this concern has been proven to be unfounded in clinical trials with these materials\textsuperscript{[67,68]}.

Resin composites show a particular wear pattern because many characteristics associated with their composition directly affect their wear resistance. Composites consist of filler particles dispersed in a brittle polymer. The fillers consist of glass particles such as silicon oxide (quartz), barium aluminium silicate or fillers that are manufactured from the matrix polymer by grinding the matrix to small-sized/miniscule/nanoscale particles, commonly referred to as pre-polymer fillers. The polymers are produced from various monomers, such as bisphenol-A-glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethyleneglycol dimethacrylate (TEGDMA) and other monomers. They are polymerized with initiators that are sensitive to visible light\textsuperscript{[69]}. Ideally, the loading force is completely transferred from the matrix to the filler particles. The physical properties such as flexural strength, fracture toughness, Vickers hardness, modulus of elasticity, curing depth, etc. are defined by the components used in the composition of the material\textsuperscript{[89]}. The physical properties in turn, may influence the wear of the composite. In direct contact between resin composite and antagonist, the wear pattern is mostly a combination of attrition/abrasive wear and microfatigue. The friction coefficient and the surface roughness are determining factors for the wear rate of composites. Thus, the size and volume of the fillers affect the wear rate. A low modulus of elasticity leads to larger contact areas and consequently to lower pressure.

Large filler particles, on the other hand, are associated with high friction coefficients and lead to high...
internal shear stress in the polymer matrix. The latter in particular occurred in the early composites of the eighties. These composites contained large fillers and showed excessive wear in the posterior region, which was clinically visible as loss of contour.

The composite technology has been continuously optimized since then. While the composites of the late nineties did not show the excessive wear of the early generations anymore, their wear rate was still higher than that of enamel. In a clinical trial on 35 posterior resin restorations, the volumetric loss of the material did not increase substantially during the first 3 years\(^5\). After the third year of clinical service, however, there was a non-linear increase of mean wear until the end of the clinical study (5th year, Fig. 2)\(^5,7\). It can be assumed that the wear of the resin composite restorations will have further increased after the 5th year of clinical service, which indicates that wear in many patients will not be restricted to attrition wear but will extend to include abrasive wear affecting the entire occlusal surface. Yet, the variability was very high and the distribution was uneven amongst the individuals in the above study: the coefficient of variation was between 30% and 80%. Similar levels of variability also occurred in the clinical trials of the Clinical Research Associates (CRA) [now: Technologies in Restorative and Caries (TRAC)]. This institute clinically evaluated many resin materials for both direct and indirect Class II restorations and for indirect crowns and fixed dental prostheses in the 90ties of last century (1990s)\(^6\). In those trials, the restorations were exclusively placed in the posterior regions, mostly in molars. In total, 1484 posterior restorations were placed and wear data of up to three years of clinical service was collected on 25 different resin composite materials as well as on one amalgam material and enamel. The results of that study showed that the mean coefficient of variation of the wear results within one material was 53% which leads to the assumption that 53% of the variability is due to the influence of patient-related factors (Fig. 3)\(^6\). Chewing and biting force, type and frequency of nutrition, parafunction, bruxism, etc. may be patient factors affecting wear. Due to the high variability, the wear results of 17 out of the 26 resin composite materials were in the same statistical subgroup and were statistically not significantly different, if ANOVA with a post-hoc test to adjust for multiple comparisons was applied\(^6\).

The CRA clinical wear data also showed that up to date no composite resin is as wear resistant as amalgam or enamel\(^6\). The good wear resistance of amalgam materials can be explained by the fact that surface tension is partly compensated by plastic deformation. During the wear process, an oxide layer is continuously formed and removed.

Nevertheless, fillings with contemporary resin composite materials do not fail because of wear but mainly because of caries at the restorative margins or material fractures\(^7,8\). Even a 30-year clinical trial involving three resin composites demonstrated that
wear was not the primary cause of failure\textsuperscript{74}. Occlusal wear of resin composite restorations may be detected clinically over time but it does not hamper the long-term survival of the restoration (Fig. 4).

**HOW TO MEASURE WEAR**

Along with many other criteria, wear started to be evaluated as part of the USPHS scoring system which was introduced in early 1970s\textsuperscript{75}. The evaluation, however, is very subjective and wear cannot be accurately assessed. Therefore, researchers modified the criteria according to their needs, which led to many different sets of modified USPHS criteria. Only in the last decade, a group of renowned scientists have further developed the USPHS criteria by systematically structuring them using normative and subjective guidelines. However, this group acknowledges that wear can only be precisely quantified with the help of sophisticated equipment\textsuperscript{76,77}.

Nowadays, mechanical or electro-optical sensors are used to quantify clinical wear. Nonetheless, it is necessary to take physical impressions. The quality of the impression is therefore crucial for accurate measurements. Systems that use optical technology have advantages over mechanical sensors\textsuperscript{78,79}. One optical system in particular has been identified to measure wear with an accuracy of 10 µm both in clinical trials and in vitro\textsuperscript{80}. To avoid fabricating impressions and replicas, some researchers use intraoral scanners for wear measurements. As these scanners, however, are designed for the fabrication of CAD/CAM ceramic or polymer restorations rather than for wear measurements, they, and the software, are generally not as user-friendly as laboratory scanners specifically designed for wear measurements\textsuperscript{81,82}. However, some scanners provide sufficiently accurate results and are comparable to systems that use replicas for wear measurements.

**LABORATORY METHODS TO TEST DENTAL MATERIALS FOR WEAR**

In 2001, the International Organization for Standardization (ISO) published a technical specification on "guidance on testing of wear", describing 8 different test methods of two- and/or three-body contact\textsuperscript{83} (see Table 1). Another ISO technical specification covers the wear caused by toothbrushing\textsuperscript{84}. However, the usefulness of this ISO standard is debatable as contemporary restorative are very resistant to toothbrushing, which has been shown both in vitro\textsuperscript{85,86} and in vivo\textsuperscript{87}. The advantage of these standards is that defined test methods are described which can be performed and reproduced with relatively easily accessible means in laboratories. The specifications for test methods, however, are the greatest common denominator between the representatives of industry, authorities, and universities, who work together in the standardization committees. As a consequence, the ISO standard tests and recommendations are not necessarily scientifically robust and often lack evidence for correlation between test results and clinical phenomena. This fact may also explain why the eight-wear test methods of the ISO standard do not include a description of their advantages and disadvantages. Furthermore, the specification does not mention whether the methods have been validated and whether the devices with which the methods have been performed were qualified for that purpose. If you try to retrieve this information from the original literature, you may notice that hardly any of the methods described in the relevant ISO technical specification followed the guidelines established by FDA and that virtually none of the wear-related components of these simulators had been evaluated.

The different two- and three-body test methods vary with regard to a number of aspects, such as load, number of cycles, frequency of cycles, abrasive medium, type of force actuator, sliding movement, etc. (see Table 1). Qualification and validation, however, are indispensable prerequisites for a test to become a standard laboratory test\textsuperscript{88}. The test equipment must operate within acceptable and reproducible limits and tolerances to generate reproducible results. A systematic review showed that the wear rate results for the same resin composite subjected to the same wear method and using the same wear parameters varied between 30\% and 70\%\textsuperscript{89}.

A device that is used to test dental materials for wear should have the following features:

- Force and force impulses should be reproducible and adjustable in the range of 20 N to 150 N.
- A lateral movement of the stylus should be integrated in the system to be able to test the material for microfatigue.
- Continuous water change should also be integrated to remove abraded particles from the interface between stylus and material.
- All movements should be computer-controlled and adjustable.

A qualified machine should use two axes of movement (vertical and horizontal). At present, three commercially available chewing simulators, the Willytec chewing simulator\textsuperscript{90,91}, the MTS chewing simulator\textsuperscript{14,91} and the Bose ElectroForce 3330 Dental Wear Simulator (www. bose-electroforce.com), fulfil these criteria. For the latter machine, however, no studies on wear have been published, only on fatigue of dental restorations\textsuperscript{92}.

Furthermore, some institutes developed their own systems, such as the OHSU machine\textsuperscript{93}, the Alabama machine\textsuperscript{94}, the Zurich machine\textsuperscript{95}, the Regensburg simulator\textsuperscript{96} and the BIOMAT simulator\textsuperscript{97}. More recently, a complex system with six actuators has been developed at the University of Bristol: the Dento-Munch Robo-Simulator\textsuperscript{98}. This simulator tries to mimic the entire process of movements of the lower jaw by using a Stewart platform.

As all simulators and wear methods follow different approaches because they are based on different operational and methodological concepts, the results cannot be compared, even if efforts are made to use
| Properties     | Method       | ISO TS65 | Simulator (Force actuator) | Stylus       | Medium                  | Movement               | Force  | Number of cycles | Correlation with clinical wear* | References |
|----------------|--------------|----------|----------------------------|--------------|-------------------------|------------------------|--------|------------------|---------------------------------|------------|
| Abrasion three body | OHSU abrasion yes Proto-tec (electromagnetic) | enamel | poppy seeds/PMMA beads | impact +sliding | 20 N | 50,000 | moderate | 93) |
|                 | Alabama generalized yes Alabama (spring) | poly-acetal | PMMA beads | impact +sliding | 75 N | 400,000 | weak | 94, 114) |
|                 | ACTA yes ACTA (spring) | steel | millet | sliding | 15 N | 200,000 | none | 115) |
|                 | OHSU attrition yes Proto-tec (electromagnetic) | enamel | poppy seeds/PMMA beads | impact +sliding | 70 N | 50,000 | moderate | 93) |
|                 | Alabama localized yes Alabama (spring) | poly-acetal | PMMA beads | impact +sliding | 75 N | 400,000 | weak | 94, 114) |
|                 | Ivoclar-Method (pin-on-block) no Willytec (weights driven by engine) Qualified machine | leucite ceramic | water | impact +sliding (short excursion) | 80 N | 120,000 | weak | 89) |
|                 | Munich-Method (pin-on-block) no Willytec (weights driven by engine) Qualified machine | steatite water | Sliding (long excursion) | 50 N | 50,000 | weak | 116) |
| Attrition       | Minnesota yes MTS (Servohydraulic) Qualified machine | tooth water | sliding | 13.35 N | 500,000 | weak | 14, 91) |
| Contact/two body | DIN (pin-on-disc) yes pin-on-disc machine | Al₂O₃ water | sliding | 8–10 MPa | ? | ? | 83) |
|                 | Zurich yes Zurich simulator CoCom (electromagnetic) | enamel water +alcohol +toothbrushing | impact (+sliding) | 49 N | 1,200,000 | weak | 95, 117) |
|                 | Freiburg (pin-on-disc) yes pin-on-disc machine | Al₂O₃ water | sliding | 8 MPa | 40,000 | ? | 118) |
|                 | Newcastle (pin-on-disc) yes pin-on-disc machine | steatite water | sliding | 15 N | 10,000 | ? | 119, 120) |
|                 | BIOMAT no BIOMAT simulator (cam+weight) | cobalt-chrome water | impact +sliding | 20 MPa (225 N) | 4,000 | ? | 97, 121-123) |
|                 | NBS (pin-on-disc) no weight | enamel/stainless steel/sapphire water | rotation-sliding | 10 MPa | 127,500 | ? | 105, 124, 125) |

*Based on 65)
Similar wear parameters. This has been shown in a blind round robin test, in which the test centers did not know which materials they were testing. This test included 9 materials, which were assessed with 6 different methods (ACTA, Alabama, Ivoclar, Munich, OHSU, Zurich). The variability of the test results turned out to be very large between the methods (Fig. 5).

The following factors that influence wear should be controlled and standardized:

- **Surface roughness of specimen**: The surface roughness of the specimens prior to carrying out the wear should be standardized although the influence seems to be small in the long run.

- **Number of specimens**: The scattering of the results expressed by the standard deviation determines the number of specimens required to statistically differentiate between materials. The variability of the test results mainly reflects the quality of the wear testing device. The more robust a device is constructed and the more reliably test parameters, such as force, speed of stylus, etc. can be reproduced, the lower the variability will be.

- **Loading force**: Higher forces in general produce more wear. However, the relationship does not seem to be linear. There might be even a certain cut-off point at which an increase in the loading force does no longer result in an increase in wear.

- **Type of stylus material**: Enamel would be the material of choice due to its physiological relevance. However, it is not possible to standardize the composition of a biological substrate and extracted teeth are in short supply. The pressable leucite-reinforced ceramic IPS Empress was tested as a suitable material for this purpose and generated a similar wear rate as an enamel stylus of the same shape.

- **Size and shape of stylus**: A pointed stylus produces more wear than a ball-shaped stylus as a ball-shaped stylus has a larger contact area between stylus and material thus producing less fatigue stress on the material.

- **Sliding of stylus**: Sliding is an essential component of a wear testing method in order to subject the material to microfatigue.

- **Descent/lifting speed of stylus**: The speed with which the stylus hits the surface of the specimen creates a force impulse, which is different with varying speeds. If weights are used to exert a force, then the force that is generated on the material is the product of the weight and the descent speed ($F=m\times a$, N). Another variable is the time during which the force is exerted i.e. the force impulse is the product of the force and the time the force is applied ($F=F\times t$, Ns).

- **Lubricant**: Lubricants, such as artificial saliva, reduce the wear as they lower the friction coefficient. A constant change of water removes the worn particles from the interaction zone between stylus and material, thus reducing the effect of the worn material, which, otherwise, may act as an abrasive medium.

- **Number of cycles**: The wear increases with increasing number of cycles. Most in vitro wear test methods demonstrate a running-in phase with a steep increase in wear in the initial phase and a flattening of the curve thereafter because of the increase in the area exposed to the wear forces.

- **Abrasive medium**: An intermediate medium may reduce or increase the wear, compared with water. Furthermore, the composition and the type of the abrasive medium affect the wear rate.

The wear simulation should follow physical principles. The wear simulation should imitate tribological phenomena that occur in the mouth in a standardized way.

CORRELATION WITH CLINICAL WEAR

A wear method should not only be internally valid, which means that the results for the same material tested at two different points in time are similar. In addition, the wear method should also be externally valid, and correlate with in vivo findings. The raw data on clinical wear of restorative materials was used to correlate the clinical wear results with those of the most frequently cited wear methods. A moderate correlation was found for OHSU (abrasion). Almost no correlation was found for the ACTA method and a weak correlation for the Alabama, Ivoclar, Munich and Zurich methods (see Table 1). The combination of different methods did not improve the correlation.

RATIONALE FOR WEAR SIMULATION

There are no regulatory requirements or international standards with regard to testing dental restorative materials for wear. Therefore, there is no official need to test these materials for wear prior to their market launch. However, if certain claims related to wear, e.g. good wear resistance, are to be made, these claims should be substantiated by adequate laboratory tests. Good wear resistance of polymer materials in particular will not only result in better esthetics but also in a possible lower uptake/ingestion of worn particles and thus result in better biocompatibility.
Most published studies focus on the wear of resin composite materials rather than on the wear of ceramic materials, alloys and polymer materials for denture teeth\(^89\). A systematic review revealed a wide variation with regard to experimental set-ups to test ceramic materials for wear, variability of test results, and the lack of correlation with clinical wear\(^66\). As ceramic materials are very wear resistant and current products do not seem to pose a clinical problem in terms of antagonist enamel wear, there seems to be no urgent need for conducting further comprehensive research and testing on that score. Wear of denture teeth, on the other hand, is still a clinical problem\(^110,111\) but rarely addressed with laboratory research and testing\(^112\).

For resin composite materials, the clinical wear data show that the patient factor contributes to a much higher extent to the variability of wear than the material itself. It is easy to find statistically significant differences in the wear behavior of different materials with standardized tests in the laboratory. But differences between materials in the laboratory which cannot be evaluated in the laboratory by reliable wear testing methods before these materials are released for clinical trials.

Despite the weak correlation between \textit{in vitro} and \textit{in vivo} findings, when new material concepts (systems or technologies) are developed, the wear resistance should be evaluated in the laboratory by reliable wear testing methods before these materials are released for clinical trials.

**SUMMARY**

The clinical significance of increased wear is mainly due to the adverse effect on esthetic appearance and/or functional restrictions. Little is known about the systemic effects of ingested or inhaled worn particles that derive from resin composite restorations, which have a much higher surface-volume-ratio than ceramic materials. There is a need for studies to find out more about the elimination pathways or possible accumulations and the concomitant biological effects of worn particles in the human body.

Wear can efficiently and accurately be measured three-dimensionally with modern laser technology both \textit{in vitro} and \textit{in vivo} restorations. The different laboratory methods to test the wear rate of dental materials follow different concepts and measure different phenomena. Therefore, the results differ from one another. Most of the laboratory methods to test the wear of dental materials are not validated. Low reproducibility and high variability of test results are the consequences. Mimicking the entire masticatory cycle with all possible movements of the lower jaw is not necessarily the best approach. However, a machine that applies a force in only one direction is also inadequate. Instead, the device should have computer-controlled force actuators, bi-axial motion and sufficient water exchange in the test chamber. The device should be simple, robust and efficient and require only low maintenance efforts.

Instead of enamel from extracted teeth, a pressable or machinable ceramic material of low strength can be standardized and is an adequate substitute as stylus material. An indication of a valid wear simulation concept is the fact that the wear of the composites can be explained by the variation in their physical parameters, thus making the method internally valid.

Contemporary composite materials using polymethacrylate technology have less effect on wear than patient-related variability \textit{in vivo}. Clinical wear studies have shown that inter-individual variability is at least 50%, which outweighs the inter-material variability observed in clinical wear trials. However, if materials with new material concepts or properties are to be brought to the market, laboratory wear testing is indispensable.

**CLINICAL RELEVANCE**

Clinical wear of dental materials rarely results in oral pathologies. Only few laboratory wear methods show a moderate correlation to clinical wear.

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