Predictability of clinical wear by laboratory wear methods for the evaluation of dental restorative materials
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Chapter 1

General Introduction
Phenomenology of wear

In the history and evolution of humankind, wear of human teeth was always present and regarded as physiological. The extent of wear was mostly related to nutritional habits, which changed over time. Teeth that were so heavily worn that they did not demonstrate any anatomical tooth morphology were often found in human skulls that date back as early as 160,000 years ago (www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2003/06/12/FOSSIL_TMP&type=sience). The wear was most likely related to the uncooked food, which was eaten at that time and which was very abrasive like roots, plants, cereals etc; additionally the food contained fragments of bone, collagensus material of fish and meat.

From a scientific standpoint, people paid attention to wear and friction mechanisms already in the 18th century, when they examined the teeth of patients as well as the teeth of skulls. John Hunter from Glasgow, Scotland, described in one of the first textbooks in dentistry *The Natural History of Human teeth. Explaining their Structure, Use, Formation, Growth and Diseases* (1771) three modes of tooth wear: abrasion, attrition and erosion [1].

The science of the interaction between materials under action is called “tribology” (from Greek tribo = to rub). Historically, Leonardo da Vinci (1452-1519) was the first to formulate two laws of friction. According to his findings, the frictional resistance was the same for two different objects of the same weight, even if they make contacts over different widths and lengths. He observed that the force required to overcome friction was doubled when the weight was doubled. Similar observations were made by Charles-Augustin de Coulomb (1736-1806). However, it was only in the nineteen-sixties, when increased emphasis was placed on tribological concepts following *The Jost Report* [2], in which vast sums of money were reported to be lost in the UK annually due to the consequences of friction, wear and corrosion (erosion). As a result, several national centres for tribology were set up in the UK and elsewhere. Since then, the term has diffused into the international engineering field and tribology has become a major part of applied sciences, embracing material sciences, physics, chemistry and mechanical engineering. Moreover, international journals like "WEAR", “Journal of Engineering Tribology”, “Journal of Tribology”, “Tribology and interface engineering series” and others were set up to cover phenomena related to the wear of materials.

In 1969 the International Research Group on Wear of Engineering Materials put together a glossary of terms and definitions for the field of tribology. The glossary is included in the “Wear Control Handbook” of the American Society of Mechanical Engineering (ASME) [3]. It contains definitions of 500 general tribological terms in eight languages. In this handbook
wear is defined as the progressive loss of substance from the operating surface of a body, occurring as a result of relative motion at the surface.

There are different forms of wear according to different mechanisms and forms of interaction between materials. However, there is no internationally accepted ISO norm about the different types of wear. A norm by the German Institute of Industrial Norms (DIN No 50320) was withdrawn in 1997 [4]. In this norm, the following mechanisms were defined: adhesion, abrasion, surface fatigue, and tribochemical processes. This classification is based on Burwell [5]. The definitions of these mechanisms have not changed over the years. Adhesion means the formation and separation of interface bonding systems (e.g. cold soldering). Abrasion means material wear due to the scratching or cutting strains of two materials, where one of the surfaces is considerably harder than the other. Surface fatigue is the fatigue and crack formation on surface areas due to tribological strains, leading to gross mechanical failure. By contrast, chemical reactions of the interacting materials or the surrounding medium cause tribochemical processes. As a consequence of tribological interactions, abrasive particles are formed (Figure 1).

Figure 1: Tribological interactions and wear mechanisms according to [6].
Human teeth: their components and physical properties

Human teeth have a unique structure composed of the anisotropic parts: enamel, dento-enamel junction, dentine, cementum, cemento-enamel junction and pulp. As far as dental wear is concerned, only the outer part of enamel and the dentinal part adjacent to enamel have to be taken into account. Dental enamel consists of about 94% inorganic substance, mainly hydroxyapatite and fluorapatite, 2% organic material and 4% water by weight [7]. The high hardness of enamel is attributed to its high mineral content, while its brittleness is attributed to its low tensile strength. The mechanical properties vary with the location on the tooth, local prism orientation and chemical composition [8,9]. Enamel is comprised of long, thin rods arranged in parallel arrays, 2 to 3 µm in diameter, which form a complex and complicated three-dimensional pattern [10]. The organic components of enamel are composed of short peptide fragments, which are breakdown products of amelogenin, the enamel matrix protein [11].

Dentine, on the other hand, is a biological compound, which consists of about 70% inorganic material, 18% organic matrix and 12% water by weight [12]. The dentinal tubules run through the entire dentinal substance and are surrounded by highly mineralized dentine material. The biological interface between dentine and enamel exhibits a high fracture toughness, thus making it possible to dissipate stresses and prevent crack propagation [9]. The underlying more resilient dentine supports the integrity of the enamel. Dentine demonstrates a considerably higher fracture toughness than the overlaying enamel, which is much harder than dentine. The physical and mechanical properties (mean values) of enamel and dentine are listed in Table 1. The values should only be regarded as rough guidelines, as the table is compiled from different studies and textbooks and the study design of the experiments that provided the data might have differed from one study to the other. The table also contains data (mean values) on contemporary composite resin materials. It can be seen that the physical properties of composite resins match very well those of enamel or dentine, except for fracture toughness and Young’s modulus, which is much higher in dentine and enamel respectively. However, there are differences with regard to the composition of composites. Microfilled composites have a low friction, but also a low modulus of elasticity and fracture toughness. By contrast, hybrid composites exhibit a higher friction but also a higher fracture toughness.
Tribology in the oral cavity: factors and processes

Dental hard tissues (enamel, dentine) 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 a dental restoration, which is subject to wear processes from the first moment it is inserted into the oral cavity. Different wear mechanisms can be distinguished and they refer to both enamel and artificial restorative materials. In the case of intracoronal restorations, such as direct fillings or inlays, both artificial and biological substrates are subject to wear in the same tooth. When teeth get into contact without a food bolus or anything in between them, this is called two-body or attrition wear (from Latin *attritio* = rubbing against) [23]. When we chew on food items or brush our teeth with a toothbrush and toothpaste, three-body or abrasive wear (from Latin *abrasio* = wear or *abradere* = to scratch off) is caused. Buccal and lingual tooth surfaces are mainly exposed to mechanical oral hygiene procedures causing abrasive wear, while the occlusal surfaces are subject to both attrition and abrasive wear, which occur almost simultaneously or in short subsequent episodes. Another phenomenon is described as adhesion wear (from Latin *adhaesio* = adherence) and occurs when two solid surfaces slide over one another under pressure. Surface projections or asperities are plastically deformed and eventually joined together by the high local pressure. In the process, material may be transferred from the artificial material on one tooth to the artificial material on the opposing tooth or to the tooth enamel. Likewise, a similar transfer of material may happen on the proximal surfaces of
neighbouring or 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.
All these mechanical interactions between two materials, which result in a net loss of
material (fatigue wear/abfraction) can be further described by friction that leads to
microploughing, microcutting, microcracking, and microfatigue [24].
Another essential influencing factor in the oral cavity is saliva, which functions as a
lubricant and diminishes wear by reducing the friction. Saliva is produced by three
glandulae, namely the Glandula parotis, the Glandula submaxilibraris and the Glandulae
linguales. Saliva contains mainly water and only 0.5% dissolved substances.
Mucopolysaccharides and glycoproteins mainly act as the lubricant in saliva. All solid
tissues and mucosal membranes in the oral cavity are covered by a layer of absorbed
salivary proteins, the so-called acquired pellicle, which forms instantly after e.g. cleaning
procedures. Saliva is also essential to prepare food to swallow it. Besides the lubricant
function, saliva contains buffer systems that neutralize both acids from the food bolus and
products from bacterial activities. In addition to the mechanical interactions, chemically
active substances can also attack dental hard tissues and restorative materials. When
acidic substances interact with high occlusal loads, the wear rate may be dramatically
accelerated, as an in vitro study has shown [25]. These substances can derive from acidic
food items, like soft drinks, fruit, juices, vinegar, etc, from the gastric reflux, like in the case
of patients suffering from bulimia or anorexia nervosa, or from sources outside the oral
cavity, like factories that emit acidic substances in the air [26]. The acidic attacks that
cause loss of tooth substance are summarized as erosive wear (from Latin erodere =
“gnawing off”), although the term corrosive wear (from Latin corrodere = “gnawing away”) would be more adequate [27]. In a report of a workshop on the mechanisms,
manifestations and measurements of wear, only the following four types were described:
adhesive wear, abrasive wear, fatigue wear and corrosive wear [23].
All these processes occur in the biomechanical stomatognathic system with the teeth of
the upper jaw being fixed to the skull, while the teeth of the lower jaw are movable in three
directions: to the lateral, front and vertical thus giving the jaw a high degree of movement
flexibility. The teeth get into contact during the conscious activity of chewing food items
and as a side effect during other processes, such as swallowing, speaking and yawning.
Tooth contacts other than these are attributed to parafunctional or pathological actions or
habits, namely bruxism and thegosis [28]. Bruxism is the technical term for teeth grinding
without food and occurs mainly unconsciously and predominantly at night during short
periods of 30 to 60 seconds each hour [29]. Patients suffering from bruxism exert high biting forces during the gnashing phases [30]. Maximal biting forces, however, do not seem to be different compared to non-bruxers [31]. In some patients, bruxism leads to the hypertrophy of masticatory muscles (eg *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 [32]. 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 [33]. Thegosis is the process of sliding teeth into a lateral position that may derive from the evolutionary genetic habit to sharpen teeth. Other actions that cause friction and wear on teeth are pipe-smoking as well as the chewing on pencils, tooth picks, finger nails etc.

The biomechanical process of mastication is very complex and is regulated by trigger zones in the brain stem and submitted to multiple feedback mechanisms, some of them are located in the periodontal ligament [34]. Mastication reduces the food bolus to a few square millimetres, which facilitates swallowing and digestion. Typically, the masticatory cycle can be divided into four phases [35,36] (Figure 2). First the lower jaw is opened and slides into a lateral position to get into contact with the food bolus. The second phase starts when the teeth get into contact with the food bolus, the anterior teeth bite off a piece of the food and push it to the posterior region. During this phase, biting loads are applied and distributed through the food bolus which gets entrapped between the occluding teeth. In the third phase, the food is compressed and ground while the teeth move laterally and in the fourth phase the teeth move back to their original position. The entire masticatory movement is further complicated because it is completed in two planes: the horizontal (lateral) and frontal planes [37]. In the horizontal plane, the movement line is an arc formed by rotation around the working condylus of the temporo-mandibular joint. When the working condylus is moving to a lateral position, the teeth on the balancing side lose contact in most patients.

The profile of the force curve corresponds to the positive half of a sine curve and is therefore also called haversine wave form [37]. The masticatory force depends on the texture of the food as well as on the location within the oral cavity. Higher forces are exerted in the posterior region and when grinding hard food. However, the biting force varies substantially between different individuals. Lower biting forces were detected in women compared to men as the latter have larger masticatory muscles. Furthermore, the
biting force decreases with age, with young adults having the highest forces. The magnitude of biting force is in the range of 10 to 20 N in the initial biting phase and in the range of 100 to 140 N in the molars and 25 to 45 N in the incisor teeth at the end of the chewing cycle [38]. The entire cycle lasts for about 0.8 seconds whilst the mean duration of occlusion is only about 0.4 to 0.6 seconds [34,38]. The sliding distance is less than 1 mm with a speed of 0.25 to 0.5 mm/sec [39].

The tooth contact periods add up to 15 to 30 minutes per day, depending on the eating frequencies and habits, not including the tooth contact during swallowing, which, however, is only of a lower magnitude. If a mean chewing frequency of about 1.5 Hz and a chewing time of about 20 minutes per day are assumed, an individual carries out 4.87 million chewing cycles per year. According to estimates, human beings chew 18 tons of food on average during their lifetime.

**How to measure clinical wear**

In 1984 Smith and Knight published a Tooth Wear Index (TWI) to assess the clinical wear of human enamel [40]. The index, which comprises 4 scores, was designed to record levels of tooth wear regardless of the etiology. Each visible tooth surface (buccal, lingual, occlusal/incisial) is recorded together with a separate score for the buccal cervical area, which sometimes has a different wear pattern.

In the early seventies, a scoring system was developed to assess the clinical performance of restorative materials, known as the United States Public Health Services (USPHS) criteria [41]. The reason for developing this system was to provide a more or less standardizable and structured tool to evaluate and compare the clinical work of general practitioners and collect data for insurance companies. Later on, the system started to be applied to new materials so that they could be compared with clinically proven materials, such as amalgam or ceramic inlays [42]. Among many other criteria, wear of material is evaluated as part of the USPHS scoring system. The evaluation, however, is very subjective and the wear cannot be accurately assessed [43]. As research workers recognized the shortcomings of this scoring system, they modified the criteria according to their needs, which led to many different modified USPHS criteria. Only recently, a group of renowned scientists have further developed the USPHS criteria by systematically structuring them based on evidence and normative and subjective guidelines, acknowledging, however, that wear can only be quantified by sophisticated equipment [44].
In the eighties, a method which related the loss of material at the restoration margins to the overall wear of the material was developed. For this purpose, impressions of the teeth were taken and the cast models were compared to a set of standards derived from clinical restorations, such as the Leinfelder scale with 6 standards [45] or the Moffa-Lugassy scale (M-L scale), which is based on dies with cylindrical defects and includes 18 standards [46]. The latter was modified by V. Rheinberger using tooth-sized dies with restoration-like incremental defects known as the Vivadent scale [47]. However, it has been proven that the actual wear is systematically underestimated when those scales are used [48].

With the development of mechanical and electro-optical sensors, which are used in industrial manufacturing for different applications (topography, roughness, material loss, etc), these systems or principles became also available for the quantification of clinical wear. However, it is necessary to take impressions as a system that measures wear directly in the oral cavity is not available to date. The quality of the impression is therefore crucial for accurate measurements. Optical systems that use optical technology have advantages over mechanical sensors. Especially one system has been identified so far to measure wear with an accuracy of 10 µm [49]. Impressions should be taken for each restored tooth under investigation, using a light-body polyvinylsiloxane material in a conventional partial tray after thorough cleaning of the teeth with pumice and a rotating brush. The author’s own experience has shown that it is advisable to make a second impression and discard the first one, as plaque remnants that were not removed by the tooth cleaning procedure tend to be removed by the first impression. A recent comparative analysis of accuracy of clinical wear measurement using replica models revealed no difference between individually fitted and conventional trays [50].

Clinical importance of wear of teeth and dental materials

Wear of natural teeth can have mainly two consequences: (1) aesthetical effects that compromise the appearance of a restoration; (2) functional effects that alter the relationship between the tooth and antagonist(s) and/or tooth and adjacent tooth by promoting phenomena like elongation of antagonists, movement of teeth or reduction of vertical height with consequences to the TMJ. For artificial materials, another side effect of material wear becomes apparent: swallowed or inhaled worn particles may have biological/toxicological effects. Little is known about the systemic effects of material components, such as clearance of the worn material, adverse effects, chemical reactions or a possible incorporation of worn material into body cells or tissues.
With composites, there is a certain amount of concern that, besides the leaching of monomer components, micro- and nano-sized inorganic filler particles of composite resins that are worn, swallowed or inhaled and accumulated into tissues could be linked to diseases of the liver, kidney and intestine [51,52]. There is, however, no scientific evidence to date that the absorbed particles pose a health risk to the patient. In vivo measurements of 31 composite fillings (14 premolars, 17 molars; Tetric EvoCeram) revealed a mean volume loss in premolars of 0.25 mm$^3$ and in molars of 0.75 mm$^3$ after 2 years of clinical service with a maximum of 0.4 mm$^3$ in premolars and 1.0 mm$^3$ in molars (Figure 2 A) [53]. The increase of material loss of composite resin materials is not linear, although long-term measurements in vivo are missing. The material loss per mm$^2$ was calculated to be 0.01 mm$^3$ for premolars and 0.02 mm$^3$ for molars (Figure 2 B).

![Figure 2](image)

Figure 2: (A) Volumetric wear in vivo (mm$^3$) and (B) volumetric wear in relation to surface area in vivo (mm$^3$/mm$^2$) of a fine-hybrid composite material in relation to tooth type and time.

If all posterior teeth were restored with medium-sized composite fillings, the maximum total material loss would be about 11 mm$^3$ within two years of clinical service, based on the data of the above-mentioned clinical study. However, other composite materials may wear more quickly (or to a larger extent) and the wear of crowns and bridges made of composite material is generally larger than that of intracoronal restorations [54,55].

As far as the biological consequences on the stomatognathic system are concerned, there is little evidence that occlusal wear as such leads to the dysfunction of the TMJ, to muscle pain or periodontal disease [56-61]. Even severe loss of occlusal tooth substance due to wear is compatible with good oral health, as the stomatognathic system is highly adaptive.
to changes. Even the loss of posterior support does not increase the wear of anterior teeth [62].

However, if the loss of material becomes clinically visible, the wear affects the aesthetic appearance of the restoration, especially in the anterior region. Excessive wear may lead to premature failure and replacement of the restoration. According to a clinical study on 1007 individuals in southeast England, the percentage of excessive wear on natural teeth varied between 3% and 9% of tooth surfaces according to the different age groups [62]. Based on the evidence available, it may be concluded that wear as such is an aesthetical problem in the first place, which may, however, lead to the premature failure and replacement of a restoration. Aesthetical effects of material loss are obviously depending on the severity and location of the restoration.

**Wear behaviour of natural teeth**

Dental enamel is highly resistant to wear with an annual wear rate of about 30 to 40 µm [53,63], although the wear seems not to increase on a linear basis and is independent of the tooth type (Figure 3). The excellent wear resistance of dental enamel is mainly attributed to the intricate crystallite orientation of the enamel prisms, which give the enamel unparalleled hardness. Only diamond burs with high speed are able to cut enamel. The wear of enamel is mainly resulting from microfracture processes and characterized by delamination and microploughing. In contrast the wear of dentine is determined by ductile chip formation. 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 (steady-state phase). A similar pattern can be observed with restorative materials. However, the surface hardness of enamel and its wear depth varies with age: lower hardness and higher wear depths were observed in patients belonging to older age groups compared with patients belonging to young age or middle aged groups.

![Figure 3: Box plot of enamel loss in vivo of 34 teeth with intracoronal restorations. Data from [53].](image-url)
Wear behaviour of composite resins

The various artificial dental materials can be grouped into five different categories: metal alloys, ceramics, amalgams, composites and unfilled polymers. Of all these materials, the composite resins show a particular wear pattern, because many characteristics, which are associated with their composition, directly influence 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 sizes, so-called pre-polymer fillers. The polymers are produced from different monomers, such as bisphenol-glycidyl methacrylate (BIS-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA) and other monomers, which are polymerized with initiators that are sensitive to halogen light [64]. Optimally, the loading force is completely transferred from the matrix to the filler particles. The size, shape and hardness of the fillers, the quality of the bonding between fillers and polymer matrix, the polymerization dynamics of the polymer all have an effect on the wear characteristics of a dental material. The various components of the composition, on the other hand, influence the physical properties of the composite, such as flexural strength, fracture toughness, Vickers hardness, modulus of elasticity, curing depth, etc. These properties, in turn, may influence the wear of the composite. In direct contact between composite resin and antagonist, the wear pattern is mostly a combination of attrition/abrasive wear and microfatigue (see Figure 5d). 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 elastic modulus leads to higher contact areas and consequently to lower pressures. Large filler particles, on the other hand, are combined 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, which contained large fillers and showed excessive wear in the posterior region. This was clinically visible as loss of contour. The composites had been continuously optimized since then and the composites of the late nineties did not show this excessive wear any more [65] but their wear rate was still larger than that of enamel. Nowadays, wear is more likely to occur at occlusal contact areas (OCA) than on contact-free areas (CFA). In a clinical trial on 31 posterior resin restorations, the median vertical loss after 2 years was 143 µm for molars and 114 µm for premolars [53]; the difference was, however, statistically significant only for the 1-year recall (Figure 4). Yet, the variability was very high and the distribution was uneven amongst the individuals of the
test group: about 60% of total wear was limited to 30% of restorations. Even the measurable high amount of material loss at localized sites of a restoration is generally not visible by clinical inspection (Figures 5a-5d).

According to prospective clinical trials, which evaluated modern composite resins, composite fillings fail and have to be replaced not due to wear but due to secondary caries, marginal and/or bulk staining and fractures [66,67]. Even a clinical trial over a period of 20 years involving three composite resins demonstrated that wear was not the primary cause of failure [68].
A composite resin restoration at baseline (a) and at the 24-month recall (b) with markings of the occlusal stops. (c) Differential picture of the same restoration: wear quantification: the redder the area, the higher is the material loss; the wear in the red occlusal areas is between 100 and 150 µm. (d) SEM picture (x154) of the same restoration: wear facet caused by attrition (see arrow) as in Figure 5b after 24 months in situ.

(Clinical pictures by Arnd Peschke)

**Laboratory methods to test dental materials for wear**

Dental research has become especially aware of the problem of wear of dental materials in the nineteen eighties when the first studies with posterior composite resins showed a large amount of wear within a short period of time. For decades, posterior teeth were
mainly restored with amalgam and gold alloys and later on with ceramic materials and the clinical experience was that these materials did not exhibit much wear over time. It was also in the nineteen eighties, when people thought of methods to predict wear through laboratory tests. The first wear testing methods were developed. The first reliable test on frictional wear was carried out by Charles Hatchett (1760-1820), who used a simple reciprocating machine to evaluate the wear on gold coins. He found that compared with self-mated coins, coins with grits between them wore at a faster rate. In industrial engineering, the wear resistance of artificial materials is typically evaluated with pin-on-disc machines and the wear resistance of varnishes and other covering materials is assessed by scratch tests. Norms established by the ATMS are used.

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 [69] (Table 2).

<table>
<thead>
<tr>
<th>Method</th>
<th>Stylus</th>
<th>Medium</th>
<th>Movement</th>
<th>Force</th>
<th>Number of cycles</th>
<th>Reference material</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN</td>
<td>Al2O3</td>
<td>water</td>
<td>sliding</td>
<td>8-10 MPa</td>
<td>?</td>
<td>PMMA</td>
</tr>
<tr>
<td>ACTA</td>
<td>steel</td>
<td>millet</td>
<td>sliding</td>
<td>15 N</td>
<td>200,000</td>
<td>-</td>
</tr>
<tr>
<td>Zurich</td>
<td>enamel</td>
<td>water + alcohol</td>
<td>impact (+sliding)</td>
<td>49 N</td>
<td>1,200,000</td>
<td>last test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alabama</td>
<td>poly-acetal</td>
<td>PMMA beads</td>
<td>impact+sliding</td>
<td>75 N</td>
<td>400,000</td>
<td>-</td>
</tr>
<tr>
<td>Freiburg</td>
<td>Al2O3</td>
<td>water</td>
<td>sliding</td>
<td>8 MPa</td>
<td>500,000</td>
<td>PMMA</td>
</tr>
<tr>
<td>Minnesota</td>
<td>tooth</td>
<td>water</td>
<td>sliding</td>
<td>13.35 N</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>OHSU</td>
<td>enamel</td>
<td>poppy seeds/PMMA beads</td>
<td>impact+sliding</td>
<td>20/70 N</td>
<td>50,000</td>
<td>-</td>
</tr>
<tr>
<td>Newcastle</td>
<td>steatite</td>
<td>water</td>
<td>sliding</td>
<td>15 N</td>
<td>10,000</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Two-/three-body wear methods listed in the ISO Technical Specification No 14569-2 [69].

The different test methods vary with regard to load, number of cycles and their frequency, abrasive medium, type of force actuator, sliding movement, etc. However, an assessment of the different wear methods was not performed. Furthermore, many of these tests fail to define a qualification protocol for the test equipment or a validation procedure for the test method, which is run in conjunction with the equipment. Both qualification and validation, however, are indispensable prerequisites for a test to become a standard laboratory test [70]. Therefore, the reproducibility of test results is a prerequisite for a test method to fulfill the criteria of a validated test method. Otherwise, it is always necessary to repeat wear tests with a reference or standard material, which is time-consuming and reduces the
significance and validity of the test method. At present, only two chewing simulators which use two axes of movement (vertical and horizontal) and whose force is regulated are commercially available: the MTS chewing simulator [37,71] and the Bose ElectroForce 3330 Dental Wear Simulator (www.bose-electroforce.com). However, some institutes developed their own systems such as the OHSU machine [72], the Alabama machine [73], the Zurich machine [74], the Regensburg simulator [75] and the BIOMAT simulator [76]. More recently, a complex system with six actuators has been developed at the University of Bristol: the Dento-Munch Robo-Simulator [77]. This simulator tries to mimic the entire process of movements of the lower jaw by using a Stewart platform. As all simulators follow different approaches because they are based on different operational concepts, the results cannot be compared, even if an effort is made to use the same wear parameters. 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. Preferably, calibration should not be necessary for the testing of each material.
- A lateral movement of the stylus should be integrated in the system to be able to test the material for microfatigue.
- Constant water exchange should also be integrated to remove abraded particles from the interface between stylus and material.
- All movements should be computer-controlled and adjustable.

One of the best compromises in terms of cost and efficiency is the two-axis chewing simulator Willytec or "Munich" simulator [78]. This chewing simulator operates with dead weights that are put on vertical bars, which are descended with stepping motors. The weight can be varied between 1 and 11 kg. Additionally, a lateral movement, which is also driven by a stepping motor, can be integrated into the wear method. Both the vertical and horizontal axes are computer-controlled. The chewing simulator includes eight chambers so that eight specimens can be tested at the same time. Simultaneous flooding and evacuation of each chamber with water of different temperatures (thermocycling) is integrated into the system. The Willytec chewing simulator can be used for different purposes: wear testing, loading of prosthodontic reconstructions like crowns, bridges, implant systems or fillings, which are placed in extracted teeth. Early in 2008, a questionnaire was sent to all dental universities and dental companies which use the Willytec simulator. Currently, 22 simulators are in operation: 18 at dental universities and 4 at dental companies. A simulator, which was used in the USA (New Orleans), was destroyed during the 2005 flooding. Two of the 22 simulators use pneumatic actuators to lift the weights from the specimen to be tested. Three dental universities have 2 or even 3
simulators and 1 dental company has two. Seventeen of them are located in Germany and 5 in other countries. In spite of having sent them two reminders, only eleven dental universities with 15 simulators and two dental companies with 3 simulators have responded to the questionnaire. The results of the questionnaire are presented in Figure 6. Most research institutes (11 out of 13) use the simulator for wear tests and many use it also for other purposes, such as loading of crowns and bridges or implants.

Figure 6: Research areas (in percentage of respondents) with regard to the use of the Willytec chewing simulator (multiple answers were possible). Data of an unpublished survey.

The following wear influencing factors should be taken into consideration:

Surface roughness of specimen: The surface roughness of the specimens prior to carrying out the wear generating processes may have an influence on the wear rate of composite materials.

Number of specimens: The scattering of the results expressed by the standard deviation rate 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 reproducible test parameters such as force, speed of stylus, etc. can be maintained, the lower is the variability.

Storage of specimens prior to testing

Loading force: It may be assumed that higher forces 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. To date, this has been verified with two composite resin materials (Figure 6).

![Figure 6: Wear of two composite materials in relation to load (2kg/5kg/10kg). HM = Heliomolar (microfilled composite), TC = Tetric Ceram (fine-particle hybrid)](image)

**Size and shape of stylus:** From theoretical considerations it can be assumed that a sharp stylus produces more wear than a sphere-shaped stylus, because the contact area between stylus and material is larger in the latter and hence produces less fatigue stress on the material.

**Sliding of stylus:** Sliding is an essential component of a wear testing method because a material is subjected 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 \((F = m \times a, \text{N})\). Furthermore, the time during which the force is exerted is another variable, i.e. the force impulse is the product of the force and the time the force is applied \((F = F \times t, \text{Ns})\).

**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 run-in phase with a steep increase in wear in the initial phase and a flattening of the curve thereafter (Figure 7).
Figure 7: Percentage of cycles (left axis) in relation to the percentage of mean final wear (right axis) of ten materials. An example in conjunction with the Ivoclar method: after 8.3% of the total number of cycles 41 % of the final wear has already occurred. Unpublished data of Round Robin test for ACTA, Ivoclar, Munich, Zurich and Alabama in conjunction with 4 materials: [79,80].

**Abrasive medium:** An abrasive medium can decrease or increase the wear depending on whether it is used in dry or wet conditions.

Another decisive question is whether or not the simulation method correlates with clinical wear. In a workshop report on wear (mechanisms, manifestations and measurement), it was stated that laboratory simulation methods are useful to study fundamental wear mechanisms but they are not able to predict clinical wear [23]. It should be, however, the goal of any laboratory method to at least roughly assess the clinical wear properties of a dental restorative material prior to the insertion into the oral cavity. This is especially useful for dental companies which develop many different variants of the same material (concept) or which are pursuing completely new and innovative material technologies. Therefore, the wear resistance of dental materials should be evaluated in the laboratory by reliable wear testing methods before the materials are tested in clinical trials.
References


Short description of the studies and experiments

The following six chapters describe experiments, which investigate specific questions related to the wear of dental restorative materials, specifically the wear of resin composites. Composite resins are nowadays the most frequently used material in dentistry and in many countries they have replaced amalgam as the main material (material of choice) even for restorations in the posterior region. Composite resins are also used for indirect restorations, such as inlays/onlays as well as crowns and bridges. The studies address topics like qualification and validation protocols for wear testing devices and methods, wear quantification possibilities, possible substitutes for enamel as stylus material, the relationship of physical parameters to the wear rate of contemporary resin materials, comparison of different wear testing methods and the correlation of in vitro and in vivo wear.

The different laboratory methods currently employed for wear testing follow different concepts and use different devices with different process qualities. It may be argued that current methods and systems may not be suitable for wear testing as they do not allow the test results to be reproduced and only offer a limited range of equipment. Therefore, in the second chapter both the principles of a qualification protocol for wear testing devices and the validation procedure to assess wear testing methods are described. For this purpose, the dental literature on wear was studied to find reports of laboratory tests which used wear evaluation devices and methods. In the process, the references to specific test methods were quantified and the reproducibility of the test results obtained with materials that were tested more than once with the same method and parameters was evaluated. Evidence from laboratory studies that assess the influence of different parameters on the wear result is presented. Furthermore, the literature is reviewed with regard to known facts of clinical wear in relation to enamel and the restorative material as well as their clinical importance.

The use of human enamel as stylus material is related to a number of shortcomings, including (1) non-standardization of shape and composition, which results in a large variability of test results; (2) difficult supply because of shortage of extracted teeth; (3) methods without lubricant, which may overestimate the wear caused by human enamel. A few rare reports dealing with the question of the stylus material were found in the literature. Therefore, the third chapter deals with the investigation into the wear generating effects
of two different ceramic materials that may serve as potential antagonist material and substitute for human enamel as stylus material. The material as well as antagonist wear is examined and the Ivoclar method is compared to the OHSU wear method, which includes an abrasive medium.

To quantify the wear generated by a laboratory method, it is indispensable to have an efficient and accurate analyzing method. However, different quantifying methods may yield different results. In the fourth chapter, three different sensors are compared with regard to volumetric and vertical loss of wear facets created on flat specimens: a mechanical sensor (Perthometer), a laser sensor (Laserscan 3D) and a white light interferometry sensor (FRT MicroProf). The wear facets are created with the Ivoclar wear method on 16 composite materials.

In the past, efforts to correlate physical parameters with wear were not truly successful. However, if a laboratory wear method is validated and generates reproducible results, it may be assumed that it follows defined physical parameters. It should, therefore, be possible to create a wear formula based on physical parameters of composites. In the fifth chapter physical parameters like modulus of elasticity, Vickers hardness, fracture toughness, size and volume of filler particles are determined for 24 dental composite materials (11 experimental, 13 commercially available). The 24 composite materials are subjected to the Ivoclar method.

As different laboratory methods are used to assess the wear of dental materials, it is essential to know how these methods correlate with each other. There is, however, no round robin test found in the dental literature that evaluated the same dental materials with different wear methods. Therefore, a round robin test was conducted with five different wear methods and 10 materials. The results of this test are presented in chapter six. Besides the Ivoclar method used at Ivoclar, the following methods (and institutes) were included: University of Amsterdam (ACTA), Oregon Health and Science University (OHSU), University of Zurich, and University of Munich. The specimens were made at one spot and sent to the five test institutes. The test institutes did not know which composite material they were testing. An amalgam and ceramic material were used as test material. After completion of the wear generating and wear analysing processes, the wear results were sent to the main test centre for statistical analysis.
Finally, a laboratory wear method must not only produce reproducible results (internal validity) but must also proof to be clinically relevant (external validity). The wear method should predict - to a certain degree - the clinical wear behaviour of a restorative material. A systematic evaluation with regard to the correlation of in vitro and in vivo wear results has not been conducted so far. Therefore, the aim of the seventh chapter was to correlate in vivo wear data of a variety of dental materials with the most frequently used wear methods (ACTA, Alabama, OHSU, Munich, Zurich and Ivoclar). Another issue explored in this chapter is whether the combination of 2 or 3 laboratory methods may increase the correlation. The in vivo data used in chapter 7 come from one source (TRAC Research Foundation, USA), which measured the wear of many composite resins, amalgam and enamel in human beings. Typically, about 30 large three-surface posterior restorations were placed for each material and evaluated during a study period of up to 3 years. Wear was measured on replicas using a light microscope focussed in the z-direction.