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How to simulate wear? Overview of existing methods

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ABSTRACT

Objectives. The aim of the overview is to critically analyse the contributing factors to the biological wear process and to screen the wear simulators in dentistry for their capacity to mimic the wear conditions. An overview of the types of wear, grouped as biotribocorrosion, combined with a description of the different wear simulating devices will allow us to better understand the multifactorial nature of wear.

Methods. A search on keywords highlights the most common in-vitro wear simulators and their use in the laboratories for various simulation applications.

Results. Wear is a complex process that can hardly be simulated while controlling all variables. Especially the extrapolation of the in-vitro wear results to the in-vivo situation is difficult because there is a lot of interplay with biological factors that are difficult to mimic.

Significance. It is not the degree of sophistication, but the right mix of controllable variables that will make a wear simulator predictive.

1. Wear terminology

Weartribology and biotribocorrosion define wear as a complex phenomenon and an 'overall effect' of a number of interrelated processes. Tribologists describe these with five terms.

1.1. *Two-body abrasion*

Surfaces are rubbed away by direct contact. At a microscopic level no surfaces are smooth and therefore they contact by the meeting of their asperities. During the movement the asperities must either fracture or deform. If both surfaces are 'brittle', there is fracture of the asperities. If one surface is 'soft', then the harder surface will plough into it, raising up 'chips' which eventually fracture away. In time all the asperities fracture and the cumulative effect of microscopic loss manifests as wear [1]. Two-body abrasion can be recognized because it results in mating surfaces. In the mouth these conditions occur predominantly during 'non-masticatory tooth movement' and are particularly prevalent in 'bruxism'. 'Attrition' is a form of two-body abrasion tooth wear that can be considered 'physiological' as it has been described as a prerequisite for 'balanced occlusion'. It is the physiological wearing away of dental hard tissues as a result of tooth-to-tooth contact without the intervention of foreign substances that causes localized wear at occlusal contacts [1]. The wear rate of enamel at occlusal contact areas in molars is about 41 μm per year [2].

1.2. *Three body abrasion*

Surfaces are rubbed away by an 'intervening slurry of abrasive particles'. The pressure between the surfaces is transferred to the particles which then cut away the asperities. In the mouth this type of wear occurs during 'mastication' and is prevalent in patients who eat an abrasive diet such as graned bread. Dur-

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ing the ‘early stage’, when the occlusal surfaces are separated by the food bolus, the abrasive particles act as a slurry and abrade the whole surface. They preferentially abrade the surface in the ‘food shedding pathways’ because of the shearing action of food on contact stress. This process is very common in restorations with ‘buccal or palatal extensions’, as these take the main force of the masticatory slurry in the escape root of the groove. The process tends to hollow out the softer regions on a surface [1]. In composite filling materials the slurry preferentially abrades the softer polymer matrix, exposing the filler particles. As the teeth begin to approximate during the ‘later stages’ of mastication, the remaining slurry particles get trapped between the asperities, in pits and in surface grooves. These particles then scratch away the opposing surface. If both surfaces are of similar morphology then the abrasive particles may transfer between scratches and cause more or less equal loss of both surfaces. Surfaces that are subject to this type of wear will mate because the abrasive particles have effectively become part of the surface [1].

Pallav et al. [3] studied the influence of sliding action of the antagonist on occlusal three-body wear of composites and an amalgam in vitro by gradual change in the distance between the opposing substrates. When the distance was decreased from 10 μm to approximately 3 μm, wear increased significantly by a factor of two to three and was exclusively of erosive nature. At a slurry-film thickness of approximately 1 μm, direct contacts between the antagonist and protruding composite filler particles started to occur. This consequently slowed the erosive wear. Ultimately, direct contact phenomena predominated, decreasing the wear rate of the various materials to different degrees. From this study, it can be concluded that minor alterations of the food-film thickness at the contact areas result in considerable changes in wear rates and wear-rate ranking of composite materials, which may partly explain inconsistencies among clinical trials [3].

1.3. *Fatigue wear*

Some of the movement of the surface molecules is transferred to the subsurface causing rupture of intermolecular bonds and a zone of ‘subsurface damage’. Eventually ‘microcracks’ form within the subsurface and, if these coalesce to the surface, then there can be loss of a fragment of material inducing fatigue wear. Wu and Cobb [4], Wu et al. [5], Mair [6] studied the subsurface damage layer of in vivo worn dental composite restorations with a ‘crack silver staining solution’ to stain subsurface damage in composites.

1.4. *Tribochemical wear (dental erosion)*

To some extent this is not a wear process in its own right. It is caused when chemicals weaken the inter-molecular bonds of the surface and therefore potentiate the other wear processes. There is an interplay of erosion, attrition and three body abrasion in tooth wear. In the mouth this effect is normally caused by acids, which may be ‘extrinsic’ such as dietary acids or ‘intrinsic’ resulting from gastric reflux. The most important thing to understand is that acids weaken only the surface molecules. These are then rubbed away by the movement of the surfaces and immediately the underlying (previously unaffected) surface is attacked by the acid. Mechanical tooth wear and chemical dissolution act simultaneously [1].

1.5. *Adhesive wear*

This occurs when there is a high attraction between surfaces such that ‘cold welds’ occur between the asperities. As the movement continues these micro-welds fracture, but not along their original line of fusion. The overall effect is that plates of one surface build up on the other surface. Although this type of wear is normally associated with metals it has been shown to occur between two surfaces of polymethylmethacrylate [1].

2. Wear location

In most wear studies they make a distinction between OCA and CFOA wear. OCA wear stands for attritional wear in occlusal contact areas. CFOA wear stands for wear in contact-free occlusal areas.

An often forgotten wear location is the approximal wear at proximal contacts. Schmidlin et al. [7] studied with a computer-controlled masticator the approximal wear of two composites (P-50, 3M and Tetric Ceram, Ivoclar-Vivadent) which was assessed in a two-body wear test after thermomechanical loading. Wear showed a non-linear pattern, which was comparable to occlusal abrasion. After the first loading cycle, wear increased significantly, and subsequently decreased. After a 5-year-equivalent, the mean substance loss for composite specimens was 20.3 ± 15.6 μm for P-50 and 17.5 ± 3.1 μm for Tetric Ceram. Approximal wear between enamel surfaces was 3.9 ± 4.3 μm. Also Wendt et al. [8] focussed on this approximal wear.

3. Wear testing devices and wear simulation techniques

Several research centres developed wear testing devices of different degree of complexity. Three main mechanical approaches can be considered with different wear simulation techniques.

3.1. *Toothbrushing machines*

In general a toothbrush/dentifrice abrasion concept is used [9–13] consisting of the following elements; Toothbrush (Oral-B 40). Programmable brushing techniques and paths. Medium: dry, wet, dentifrice abrasive slurry (Colgate Fluoriguard). Cycles: 20,000–35,600 strokes. Time: 60–100 min. Vertical load: 50–300 g.

In order to design a reliable toothbrushing machine attention should be paid to a number of set-up variables which clinically also seem to play a role.

3.1.1. *Brush-design*

Brush tip geometry and end-rounding can vary significantly. (Non-end-rounded bristles with sharp edges, ‘Roman’-shaped end-rounding, ‘Gothic’-shaped end-rounding.) [14,15] Filament stiffness, filament diameter and bristle splaying also affect the contact area with the interacting surface [16].

3.1.2. *Brushing-behaviour*

Brushing technique potentially influences the abrasion of dental hard tissues during toothbrushing [14,17] and again a number of variables should be considered.

Manual (vertical, horizontal, circular, "figure 8" motion) or electrical (rotation, reciprocal, vibration). Brushing force (212–375 N), manual (318–471 g) electrical (92–175 g). Time spent brushing (1–3 min). Frequency of brushing (one to three times per day).

Toothbrushing with abrasives can cause loss of dental hard tissue, while little damage occurs with toothbrushing alone. Nordbo and Skogedal [17] studied the rate of abrasion by tooth brushing with toothpaste which seems to be 0.2 μm per day.

3.1.3. *Dentifrice*

Because of the enamel wear/dentine wear by toothpastes, the toothpaste abrasiveness should be mentioned in simulation studies using the REA (relative enamel abrasivity), RDA (relative dentine abrasivity) index [18,19] in order to rank the selected toothpaste.

3.2. *Two-body wear machines*

Several two-body wear simulators have been designed and used with varying degree of success to imitate clinical wear.

- Capsule, compule concept [20]
- Two-body abrasion single-pass sliding [21]
- Two-body wear rotating countersample [22,23]
- Taber Abraser [24]
- Two-body machine sliding wear [25–31]
- Pin-on-disk Tribometer [32,33]
- Abrasive disk [34]
- Oscillatory wear test [35]
- Modified polisher (two-body) [36]
- Fretting test. Oscillating friction and wear test rig, MTM Leuven [37]

Several variables need to be precisely described on order to be able to make comparative statements. Among them, force, frequency, displacement, number of cycles, lubricant, hardness, Poisson ratio and elastic modulus of the counterbody, running-in period, force of friction, force–displacement loop with coefficient of friction and dissipated energy. Because of a lack of information of these parameters, wear results are difficult to interpret in two-body wear machines.

3.3. *Three-body wear machines*

With three-body wear simulators research centres are trying to mimic the oral environment and biological variables intending to rank restorative material according to their wear resistance in comparison to reference materials.

3.3.1. *ACTA wear machine (three body) [38–45]*

- Stylus: a textured and hardened steel counter-wheel
- Medium: rice/millet seed shells suspension
- Movement: sliding
- Force: 15–20 N (adjustable press load 0–50 N)
- Loading: spring
- Frequency: 1.0 Hz
- Cycles: 100,000–200,000 cycles
- Set-up: sample chamber with multi-chambered sample wheel, holding up to 12 sample materials
- Rotational speed of both motors: 0–170 rpm independently adjustable
- Variable: contact stress, moving speed, mutual slip (15%), and third-body composition.

Using unaffected surfaces as references, the abrasion volumes can be exactly determined and compared. The TMA Measurement System has been designed to analyse the results of three body abrasion tests automatically. After putting a sample wheel in its special rack, the 3D measurement can be started immediately on the control computer. TMA software creates Microsoft Excel compatible files (.dbf) including surface coordinates of complete sample wheels. Special Excel macros feature automatical scientific analysis of twelve specimens per sample wheel. Abrasion volumes of all samples are listed in a ranking diagram for quick comparison. The 3D visualisation tool enables perfect presentation.

3.3.2. *OHSU: Oregon Health Sciences University Oral Wear Simulator [46–54]*

- Set-up: multi-mode simulator
- Stylus: enamel, conical
- Medium: poppy seeds + PMMA beads
- Movement: impact + sliding
- Force: abrasion load 20 N and attrition load 70 N
- Loading: electro-magnetic
- Frequency: 1.2 Hz
- Cycles: 50,000–100,000 cycles

3.3.3. *University of Alabama Wear Simulator: four-station Leinfelder-type three-body wear device [55–68]*

- Stylus: polyacetal, conical
- Medium: PMMA beads
- Movement: impact + sliding
- Force: 75.6 N, vertical
- Frequency: 1.2 Hz
- Cycles: 100,000–200,000–400,000 cycles
- Set-up: four-station device

In this wear set-up the researchers are looking to multiple wear patterns. Generalized wear as simulation of the wear during mastication. Localized wear as simulation of attrition by occlusal contact. Antagonistic enamel wear, which simulated the wear of enamel created by direct contact with the restorative materials. Vertical wear is measured as enamel height loss, material stylus height loss, and total vertical height loss (the sum of the enamel height loss and the restorative material height loss).

3.3.4. *Zurich computer-controlled masticator [7,69–78]*

- Stylus: enamel
- Medium: water (+alcohol + toothbrushing)
- Movement: impact (+sliding)

- Lateral movement: 0.2 mm
- Force: 49 N
- Frequency: 1.7 Hz
- Loading: electro-magnetic
- Cycles: 120,000, 240,000, 640,000 and 1,200,000 load cycles
- Set-up: masticator
- Variable: toothbrush/toothpaste abrasion and chemical degradation

3.3.5. *BIOMAT wear simulator [79,80]*

- Stylus: SS304 counter-body
- Medium: water
- Movement: impact (+sliding)
- Force: 20 MPa contact stress
- Loading: weights
- Set-up: reciprocal compression-sliding wear instrumentation
- Variable: shock absorbing layer, 37 °C

3.3.6. *Minnesota: MTS wear simulator [81]*

- Stylus: tooth
- Medium: water
- Movement: sliding
- Force: 13.35 N
- Loading: hydraulic
- Cycles: 120,000, 240,000, 640,000 and 1,200,000 load cycles
- Set-up: masticator
- Variable: contact stress, moving speed, mutual slip, and third-body composition

3.3.7. *Willytec Munich and Muc3 [82]*

- Stylus: enamel, empress (diameter 2.36 mm)
- Medium: water or other
- Movement: gnashing, slippage, striking
- Lateral movement: 0.7 mm
- Force: 50 N
- Frequency: range Hz
- Loading: weights
- Cycles: 120,000 cycles
- Set-up: masticator
- Thermocycling: programmable (5–55 °C)
- Variable: speed of impact, intensity of the impact, impact load path, sliding load path

4. Complicating factors for in-vitro wear simulation

4.1. *Standardization of the antagonist: countersample materials*

Any laboratory investigation of the wear resistance of dental materials needs to consider oral conditions so that in vitro wear results can be correlated with in vivo findings. For differences among materials to be easily detected, low variation in in vitro wear tests is desirable. The choice of the countersample is a critical factor in establishing the pattern of tribological wear and in achieving an efficient in vitro wear testing system. A variety of factors including hardness, wear surface evolution and frictional coefficients have to be considered, relative to the tribology of the in vivo situation. Assessment of potential countersample materials should be based on the essential tribological simulation supported by investigations of mechanical, chemical and structural properties [37,75,83].

Antagonists standardized for shape and size and according to materials should show mean values similar to those found in natural, non-standardized cusps. Krejci et al. [75] measured the shapes and sizes of palatal cusps of non-erupted human upper third molars. The cusp cupola was best described by the formula $y = 0.001x^2$ and was symmetrical around the axis of rotation. Up to 200 μm of the y-axis, this parabola corresponded best to a ball radius of 0.6 mm. Natural enamel antagonists are preferable for the simulation of wear in the occlusal contact area.

4.1.1. *Composition of the antagonist*

- Enamel
- Gold, ceramic and composite
- Stainless-steel
- Annealed chromium-steel counterbodies
- Alumina ball: diameter 10 mm
- Dental porcelain
- Steatite (a semi porous ceramic)

4.1.2. *Shape of the antagonist*

- Flat, ball or rounded
- Flattened enamel surfaces
- Enamel harvested from extracted human third molars and machined into cusps with a 5 mm spherical radius or hemispherically
- Standardized human enamel cusps with a uniform contact area of 0.384 mm^2

4.2. *Load/force*

In the load/force diagram several variations are possible [74].

- Static and/or sinusoidal cyclic and dynamic
- Contact loads: ranging from 1, 10, 20, 25, 50, 75, 100 N
- Contact loads: ranging from 1.7, 3.2, 4, 6.7, 9.95, 16.2 kgf/cm^2
- Chewing force: 53 or 75.6 N maximum force
- Abrasion load: 20 N and attrition load: 90 N
- Resilience of the periodontal ligament

4.3. *Contact area size: force per unit surface area. Facet area*

The importance of the effect of contact area dimensions on the wear of composite specimens and their opposing enamel cusps was evaluated in vitro by Krejci et al. [73]. Standardized contact area dimensions of 0.26, 0.38, 1.18, and 4.10 mm^2 were tested. The contact surfaces of the restorations and of the antagonistic enamel cusps were evaluated by SEM. Increases in enamel contact areas after being loaded were measured by means of a digitizer and expressed in percent of the initial size before stress exposure. The wear of the composite specimens varied from 69.8 ± 19.9 to 9.5 ± 3.6 μm, and that of antagonistic enamel cusps from 31.3 ± 3.4 to 8.8 ± 1.5 μm. The increase in contact area varied between 27.8 and 0.1%.

4.4. *Number of cycles*

In order to compare results from different studies, one should take the number of cycles into consideration.

Ranging from 5000, 10,000, 25,000, 50,000, 100,000 to 120,000.

4.5. *Chewing frequency: frequency of load cycles*

The chewing frequency used in in vitro studies varies from 1.2 to 1.7 Hz [67,73].

4.6. *Duration of tooth contact*

The duration of tooth contact during the in vitro loading should mimic the in vivo situation [84]. Load and time significantly influence wear.

4.7. *Sliding speed: relative speed of opposing surfaces*

The sliding speed (2.5 mm/s) during the in vitro simulation should be comparable with the in vivo situation [32,84].

4.8. *Temperature of ambient medium*

One should take into account the temperature changes that can occur in the mouth because temperature can have a plasticizing effect. One should consider a Constant temperature (20, 37 °C) or thermocycling (5–55 °C).

4.9. *Food bolus during mastication*

Several types of food bolus or slurry can be used during mastication movement simulating [38,45,69–71,85]. Because of the great variety, a significant spreading in results can be expected:

- A slurry of water and unplasticized polymethylmethacrylate beads
- Polymethylmethacrylate powder
- Hydroxyapatite slurry
- Green carborundum slurry
- Soft ($CaCO_3$) abrasive
- Hard (SiC) silicon carbide abrasive
- Millet-seed/PMMA-beads mixture

4.10. *Lubricant and friction*

Naturally, the oral lubricants consist of saliva, plaque and pellicle. Together they form a boundary lubrication system, because the thickness of the lubricant layer is insufficient to prevent asperity contact through the film. In general the effectiveness of boundary lubricants is more influenced by their chemical properties than their viscosity. This is especially important in the case of tribochemical wear which takes place because the chemical properties of the lubricant influence the reaction of fresh surface (exposed by the last pass of the abrading surface) to the corrosive agents [1]. Acids can for example be introduced in the system. The presence of even a minute film of lubricant can protect this freshly exposed surface from the acid, thereby preventing its removal during the next pass of the abrading surface. The buffering capacity of saliva and plaque is important in minimizing the corrosive effects of acids whilst the pellicle (thickness of 100–500 nm) may act as a protective layer. In addition to these effects the presence of the lubricant influences how much of the kinetic energy is absorbed by shearing of the inter-molecular bonds in the lubricant and how much is transferred to the teeth [1].

Several liquids are incorporated in the three-body wear machines, like: Water, alcohol, acids, olive-oil, olive-oil/CaF slurry, artificial saliva, yes or no inclusion of bacteria.

4.11. *Homogeneity of the testmaterial*

During most of the in vitro wear testing, there is not enough control over the porosity content of the test samples. Such pores can influence the wear results significantly and cause unpredictable variations in the test results. This could be overcome by using a non-destructive X-ray micro-CT scanning device to screen the samples in advance [86].

Also the degree of conversion (DC) (%) should be determined by transmission micro-FT-IR. Quantity of remaining double bonds and wear are found to decrease with increasing duration of post-cure. Low quantities of remaining double bonds are generally associated with low in vitro wear.

4.12. *Chemical cycling, liquids, hygroscopic expansion*

In vitro wear testing in liquids should pay special attention to the effect of hygroscopic expansion and hydrolytic degradation during the cyclic loading.

Sarrett et al. [87] studied the degrees of in vitro three-body wear resistance of a hybrid, a small-particle, and a microfilled composite after water storage for up to 24 months. The hybrid composite was the most wear-resistant, while the microfilled composite showed the most wear. The hybrid composite showed no loss of wear resistance as a result of water storage. The small-particle composite showed a decrease in wear resistance after water storage only when tested with silicon carbide abrasive. The wear resistance of the microfilled composite decreased following water storage when tested with either a soft ($CaCO_3$) or a hard (SiC) abrasive. For all composites, the soft abrasive was not capable of causing preferential wear of the polymer matrix, as observed on in vivo specimens. Instead, the filler particles became flattened, with minimal loss of interparticle substance. The hard abrasive did cause preferential wear of the matrix. All composites absorbed water and leached silicon during water storage, indicating that the filler-polymer bond was attacked by hydrolytic degradation. Scanning electron microscopic evaluation of the three-body wear specimens indicated that the in vitro wear method did not duplicate in vivo wear conditions (e.g., the hard abrasive caused excessive wear and chipping of the filler particles in vitro, a pattern that was not usually observed in vivo). Filler-polymer debonding was observed on in vivo specimens of all the composites, while it was found only on the in vitro microfilled composite specimens. These findings suggest that filler dislodging is a complex process that cannot be simulated with the in vitro wear method used in this study, not even after prolonged water storage. Beside of attritional wear in OCA, attention must be given to stable filler-matrix interfaces and prevention of water sorption [77,87].

4.13. *pH*

pH conditions seem to influence dramatically the wear conditions and therefore they should be controlled carefully during in vitro wear testing [84,88–91].

Following pH levels (1.2, 3.3, and 7.0) are frequently used during wear simulation. They should mimic plaque acids, gastric acids and dietary acids. Citric acid at pH 2.54, 3.2, 4.5, 5.5 and 6.0 is a good test medium for controlled in vitro testing. It is for example well known that attrition is modified by erosion. Especially if human enamel is used as counterbody, acidity of the medium has an impact on the wear behaviour. Interplay of abrasion, attrition and erosion of human enamel under several different pH conditions has been tested [84,88–91]. Combination of erosion and abrasion resulted in significantly greater wear than erosion alone. Simultaneous erosion and abrasion resulted in about 50% more wear than alternating erosion and abrasion. It is concluded that softened enamel is highly unstable and potentially easily removed by short and relatively gentle physical action. Chewing of acidic foods with some abrasive properties might cause enhanced tooth wear. Abrasion and erosion act synergistically to produce wear of enamel and dentine. Erosion also increases the susceptibility of enamel to toothpaste abrasion. Dentine is considerably more susceptible than enamel to erosion and abrasion alone or combined. Dentine loss appears to correlate with toothpaste abrasivity (RDA value). Wear of enamel and dentine can be dramatically increased if tooth brushing follows an erosive challenge. Load and time significantly influence enamel wear both in acid and neutral conditions. Depth of dentine erosion significantly increases non-linearly with time and significantly decreases with increasing pH. Dentine is susceptible to erosion even at relatively high pH, the tubule system is readily exposed and dentine, unlike enamel, shows little propensity to remineralise [88–91].

4.14. *Enzymes*

Just like acids, enzymes seem to have the potential to degrade the samples during in vitro testing. de Gee et al. [41] used and esterase solution in the ACTA wear machine. Chemical cycling can induced a generalized swelling of the composite samples and a modified wear curve. These enzymes can be generated in saliva and by bacterial metabolism.

4.15. *Enamel or dentine wear versus porcelain/composite restorative material/enamel*

Wear of human enamel is a clinical concern whenever opposing teeth need to be restored using ceramic restorations. This should be kept in mind if in vitro simulation test set-ups are designed. The effect of glazed versus unglazed porcelain needs to be considered and for wear rates, enamel versus human enamel should serve as control [28,29,92].

4.16. *Composite resin cement wear*

Not only restorative materials, but also luting agents can be studied in an in vitro wear simulator to evaluate the effect of gap dimension and degree of cure. Kawai et al. [93] and Guzman et al. [94] focussed on such a set-up design. The in vitro abrasion and attrition wear of two dual-cure cements (in dual-cure and self-cure modes) and two RMGI cements are compared when placed between ceramic and enamel to simulate the margin of a restoration. Cement wear was accompanied by marginal breakdown and increased surface roughness of enamel and ceramic. The activation mode of resin cements did not influence their wear resistance. The RMGIs underwent higher attrition wear than the resin cements. Increased submargination associated with marginal breakdown and increased roughness of the surrounding structures may be expected when ceramic inlays are cemented with resin-modified glass ionomers [93,94].

4.17. *Enamel structure and physiology related to microwear*

The anisotropic enamel microstructure is a factor that can obscure the predictive value of in vitro wear testing. The enamel structure has an effect on microwear. The direction of shearing force relative to enamel prisms and crystallite orientation for example is an important microstructural element. The different responses of prismatic and nonprismatic enamels to abrasion reflect the influence of structure, but at the level of organization of crystallites rather than prisms per se. Variation in crystallite orientation in prismatic enamels may contribute to optimal dental function through the property of differential wear in functionally distinct regions of teeth [95]. Following characteristics should be considered:

- Histological variation
- Structure
- Enamel microporosity, pore structure
- Prism orientation
- Prism shape and crystal orientation
- Crystal size and morphology
- Aprismatic enamel
- Piezoelectrical effect during loading

4.18. *Dentine structure and physiology related to microwear*

The same reflection should be made for the contribution of dentine structure towards microwear. Following characteristics should be considered:

- Developmental origins
- Dentine morphology
- Intratubular dentine
- Extent of odontoblast processes
- Dentine characteristics change with depth
- Fluid flow
- Permeability
- The pulpo-dentinal complex
- Innervation of dentine and pulp

4.19. *Wear debris*

In several disciplines, attention is payed to the impact of wear debris at the zone of impact and friction. This is not addressed enough in dental in vitro wear studies. Savio et al. [97] and Elfick et al. [96], are well aware of these factors. In wear tribology the interplay of wear debris should be analysed more carefully.

5. Conclusions and summary

5.1. *Advantages of in vitro models*

- Controlled exposure time
- Nature of the agent to be studied individually or in combination
- More defined substrate and tissue type
- Temperature
- Acidic environment and concentrations
- Larger numbers of samples can be examined over relatively short periods of time
- A high level of standardization can be achieved
- Possibility of controlling numerous variables
- The in vitro models are extremely useful for demonstrating the wear propensity of a substance

5.2. *Disadvantages of in vitro models*

The in vitro models cannot replicate the oral environment with all its biological variations.

Extrapolation to the oral environment is impossible to calculate.

Only trends and indications as to the true extent of wear can be obtained.

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