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WEAR OF HUMAN TEETH: A TRIBOLOGICAL PERSPECTIVE

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ABSTRACT

The four main types of wear in teeth are attrition (enamel on enamel contact), abrasion (wear due to abrasive particles in food or toothpaste), abfraction (cracking in enamel and subsequent material loss) and erosion (chemical decomposition of the tooth). They occur as a result of a number of mechanisms including thegosis (sliding of teeth into their lateral position), bruxism (tooth grinding), mastication (chewing), toothbrushing, tooth flexure and chemical effects. In this paper the current understanding of wear of enamel and dentine in teeth is reviewed in terms of these mechanisms and the major influencing factors are examined. *In vitro* tooth wear simulation and *in vivo* wear measurement and ranking are also discussed.

Keywords: Tooth wear mechanisms, tooth wear testing

1 INTRODUCTION

Teeth are used in all the major functions of the mouth including, speech, breathing, taste and chewing. Initially humans have twenty primary (or baby) teeth. These are eventually replaced, during childhood, with 32 secondary (or adult) teeth. To allow chewing, the mouth is arranged into two opposing arches of teeth. Within each arch are different types of tooth (as shown in Figure 1), which each have a different function. Incisor teeth are used for shearing; the canines evolved for holding prey and molars are used for chewing.

Figure 1 also illustrates the different surfaces of teeth. The buccal side is the side nearest the lips or cheek; the lingual side is that closest to the tongue. The occlusal surface, which will be mentioned frequently in describing various wear processes, is that which meets a tooth or teeth in the opposite jaw during chewing or biting.

Tooth wear is becoming more of an issue as life expectancy is increasing and teeth are required to last longer. Dental practitioners need to be aware of the underlying issues and influencing factors as well as manufacturers of dental products such as toothpastes and brushes. It is important that toothpastes designed to give cosmetically appealing white teeth are not doing damage to teeth while removing stain and plaque. An understanding of tooth wear mechanisms will also help in developing improved restoration materials.

Manufacturers of food products and particularly soft drinks, which contain acids, need to be aware of how levels of acidity will affect teeth, particularly in children who will consume larger amounts of their products. An understanding of the mechanisms and controlling factors in tooth enamel wear is therefore critically important.

1.1 Tooth Structure and Orientation

Figure 2 shows the schematic of a section through a healthy tooth. It illustrates the different layers of the tooth and internal structure as well as how the tooth is positioned relative to the gum and surrounding jaw bone.

The crown of the tooth is the part visible above the gum (gingiva). The neck region is that part at the gum line, between the crown and the root. The root is embedded in the gum. Some teeth have just one root, such as incisors, whereas each molar has four roots per tooth.

The two most important elements of the tooth from the tribological perspective are the outer enamel layer and the dentine, which lies underneath. Initially the enamel is exposed to the loads and chemical environment within the mouth as a result of chewing etc. If this layer is breached due to tooth fracture or wear then the underlying dentine is exposed.

Enamel is thickest at the tip of each tooth (2-3mm) and tapers to its thinnest at the cemento-enamel junction (CEJ).

Enamel and dentine have very different structures and properties (the properties of enamel and dentine are given in Table 1). Enamel, which comprises about 97% inorganic material, is the most highly calcified and hardest tissue in the human body. The inorganic component is hydroxyapatite in the form of large elongated, hexagonal crystals. These crystals extend through the thickness of the enamel and are nearly perpendicular to the surface. They are approximately uniform in size and have a thickness of about 30nm and a width of 60nm with lengths ranging between 100 and 500nm [**1**].

Dentine has a much higher organic content than enamel. It is composed of 70% inorganic and 18% organic material, with the remainder being water. The inorganic component, as with enamel, is hydroxyapatite. The crystals, however, are much smaller than those found in enamel, being 3nm across and about 20nm in length. Dentine is much softer and more ductile than enamel (see Table 1). This means that it acts as a cushioning layer to reduce the effect of chewing loads on the enamel.

As reported by Rees [**3**] failure loads for enamel vary widely (see Table 2). This variation is probably due to the difficulties in producing pure enamel specimens with no inherent flaws.

Theoretical calculations suggest that failure stresses for many materials lie in the range of $E/5$ to $E/30$, where E is the elastic modulus of the material. However, for brittle materials, because of flaws, this may be nearer $E/1000$ [**4**]. Using this approach and a value of 80GPa for the elastic modulus of enamel, Rees et al. [**5**] calculated a theoretical failure stress for enamel of 80MPa. This is similar to the value measured by Tyldesley [**6**].

Enamel has often been viewed as a homogeneous material (see for example [**11**, **12**]). Other investigations have shown, however, that mechanical properties of enamel vary with location on a tooth, local chemistry and prism orientation. Results of microhardness testing [**13**] and compression tests [**14**] indicated that modulus of elasticity (E) and hardness (H) may be slightly higher for surface enamel than for sub-surface enamel. Vickers indentation measurements have shown that these parameters obtained for a occlusal section of enamel are generally higher than those obtained for an axial section [**15**].

Cuy et al [**16**] carried out a comprehensive mapping of enamel hardness and modulus of elasticity using a nano-indentation process. Results indicated values of H were much higher than those previously reported. At the enamel surface $H > 6$GPa and $E > 115$GPa, while enamel at the enamel-dentine junction $H < 3$GPa and $E < 70$GPa. These variations were shown to correspond to changes in the chemistry, microstructure and prism alignment. Mechanical properties of enamel were also shown to vary between the lingual and buccal side of the molar.

Other studies have shown that enamel in the cervical region of a tooth (lower part near the cemento-enamel junction) has poorer properties than enamel near the top of a tooth. Stanford et al. [**7**] showed that enamel in the cervical region has a 30% lower compressive strength. It has also been shown that the crystal structure is barely definable in this region [**17**] and there are less areas of *gnarled* enamel [**18**], where the enamel rods inter-twine, which leads to greater fracture resistance.

1.2 Chewing Parameters and Chemistry of the Mouth

The chemistry of the mouth is extremely complex and plays a critical role in the wear of teeth. One of the most important components of this chemistry is saliva. This has a number of functions in the mouth: it acts as lubricant to make chewing and swallowing easier; it is a buffer to acids produced in plaque and it supplies calcium and phosphate ions, which act to remineralise enamel.

Saliva is pH7 (neutral). However, the mouth of a person with a particularly acidic diet could be at pH3 and regurgitated gastric acid is pH1.2. Soft drinks contain a range of different acids, which can range from pH1 to pH6. The UK's soft drink consumption has risen by 56% in the ten years before 1996, when one million litres were consumed [**19**]. This averages at 0.5 Litre per person per day. This implies that exposure of teeth to an acid environment is increasing, which will obviously have an effect on wear of teeth. Chemical effects on teeth wear mechanisms will be discussed in a later section.

A number of different techniques have been used to determine chewing loads, which have shown that they can be of the order of several hundred N (see Table 3). Tooth on tooth sliding distances have been measured and are around 0.9 - 1.2mm [**20**]. During chewing these contacts last about 100ms and these periods add up to fifteen to thirty minutes of actual contact loading each day [**21**].

The different magnitudes of load and pH as well as food slurry, environmental factors and teeth cleaning etc. mean that the mouth provides an extremely complex tribological system. The key to understanding teeth wear mechanisms lies in interpreting how these factors interact.

1.3 Wear Types and Terminology

The four terms attrition, abrasion, abfraction and erosion are used in the dental literature for describing the wear of teeth and dental materials. Attrition describes wear at sites of tooth to tooth (occlusal) contact; abrasion is used for wear at non-contact sites; abfraction (a relatively new term) refers to loss of enamel and dentine as a result of cracks formed during tooth flexure in the cervical region of the tooth (see Figure 2) and erosion is used to describe material loss attributed to chemical effects.

These terms have caused confusion, because they are very different from the terminology used by tribologists to describe similar wear processes and because they describe “clinical manifestations” rather than the underlying wear mechanisms [**26**]. Mair et al. [**27**] suggest that each case should be considered in terms of its aetiology (causes) rather than its nomenclature. The aetiology of tooth wear may be considered in terms of site, timing and mechanism. The mechanisms and their interactions are shown in Figures 3 and 4.

Definitions for the mechanisms are given below:

Thegosis is the action of sliding teeth into lateral positions. It has been suggested that this is a genetically determined habit originally established to sharpen teeth [**28**] (see Figure 4a).

Bruxism is the action of grinding of teeth without the presence of food (see Figure 4a).

Mastication is the action of chewing food, which may contain abrasive particles. As shown in Figure 4c and d, two stages occur; during the first the teeth are brought together to a position of near contact (open phase), the abrasive particles are suspended and free to move in the food, which therefore acts as a slurry; in the second stage (closed phase) load is applied to the food so the abrasive particles become trapped between the two tooth surfaces.

In the following sections, *in vitro* and *in vivo* test methods for assessing wear are discussed. The current understanding of the wear mechanisms, shown above in Figures 3 and 4, that lead to wear of enamel and dentine are then outlined as well as the major influencing factors on wear and how the mechanisms interact.

2 METHODS OF WEAR ASSESSMENT

2.1 *In Vitro* Wear Testing

As mentioned in the introduction, one of the main reasons for studying the causes of tooth wear is to improve tooth restorative materials. Clearly this requires a machine that will closely simulate the oral environment as well as loading cycles that occur during chewing etc.

Many attempts have been made to achieve this and, as observed by Roulet [**29**], “there were almost as many wear testing devices as there were scientists who are interested in wear” (de Gee et al. [**30**] include a comprehensive list of previously used *in vitro* test-rigs to illustrate this point). Indeed most of the work cited in this paper has been carried out on different test-rigs, using different loads, speeds, lubricants, abrasives etc., which makes comparison of results difficult. To a certain extent the same problem has existed in the field of tribology, although a large of number of standard test-rigs do now exist. The same cannot be said of dental research.

At the most simple level, pin-on-disc sliding test-rigs have been utilised [**31**]. More complex reciprocating wear test machines have been utilised to give a more accurate simulation of the sliding action of the teeth (such as those used by [**32**, **33**, **34**, **35, 36**]). Other rigs have incorporated a uni-directional sliding motion, in which the test specimens return to their original position at the end of cycle (for example see [**37**]).

Most of the devices mentioned above have been used for two-body wear studies. Clearly though during the chewing cycle, abrasive material is present in the mouth so rigs have been designed to incorporate abrasive discs or slurries to account for this, such as the twin-disc approach used by de Gee et al. [**30**] and the ball cratering rig used by Vale Antunes [**38**].

A test-rig for the study of abrasion and attrition has been developed by Condon et al. [**39**]. It uses an extension of the uni-directional sliding in that an enamel tipped stylus is loaded against and driven across a test material in one direction in the precense of an abrasive slurry. At the end of each pass, however, the vertical load is increased and then released. The results have been shown to produce a strong correlation with clinical observations for both abrasion and attrition. De Long and Douglas [**40**] developed the *artificial mouth* concept, which allows natural teeth to be loaded in a manner that simulates physiological movement. A summary of the different test geometries used in tooth wear testing is shown in Figure 5.

As with any test simulation, a number of deficiencies exist with the rigs described above that may restrict how well they represent reality. This may be in that flat specimens are used, or water is used as a lubricant, or no abrasive slurry is incorporated. It must also be noted that, except in a few cases, very little correlation exists between test results and clinical measurements. However, in many cases these rigs are used to rank materials and it could be argued that these are not big drawbacks. It must be understood that the oral environment is very complex and has many variables, as long as the most influential have been identified and can be used and controlled in the test-rig being used this should be satisfactory. *In vitro* testing offers researchers much more control over experimental variables and the opportunity to take far more accurate wear measurements than *in vivo* testing, as will be further highlighted in the next section.

As with test-rigs to study wear due to contact between teeth, there are many different *in vitro* toothbrushing test-rigs. Again, they offer greater control over experimental variables than in vivo testing, but suffer the same deficiencies as their contact wear counterparts. *In situ* testing provides a partial compromise between the *in vivo* and *in vitro*. As will be further explained in the toothbrushing and chemical effects sections, dentine or enamel specimens are mounted in devices worn in the mouth by subjects and then removed for *ex vivo* testing. Specimens can therefore be exposed to the chemical environment within the mouth, without experiencing the varying loads from chewing, tooth grinding etc.

2.2 *In Vivo* Tooth Wear Measurement and Ranking

In vivo clinical studies of tooth wear have been noted to be problematic [**41**]. A number of mechanisms can contribute to tooth wear, as explained in the preceding sections, and there is no evidence to show whether any dominate. It is also impossible to isolate and vary key parameters that may influence wear. Clearly wear cannot be accelerated *in vivo* and studies are reliant on volunteer compliance [**42**]. While measures can be taken to try and unify testing conditions amongst the subjects, for example dietary regimes can be set and checks made on living/working environment and possible recent illness to remove the likelihood of unanticipated factors affecting test results [**43**], it is still evident that each subject is indeed a variable, which leads to problems in interpreting results.

The sensitivity of the measurement technique is also an important consideration. Lambrechts et al. [**44**] quantified enamel wear over a 48 month period using impressions of teeth which were compares using stereomicroscopy images and computerised image fitting. Savill et al. [**45**] used a similar approach. Replicas were taken of teeth, which were then digitised using a co-ordinate measuring machine fitted with an infra-red probe. Images taken at different time were overlaid to determine any morphological changes. These, however, are advanced techniques using expensive equipment. Most studies have used much less sophisticated qualitative approaches involving subjective comparison of surface features.

There are a number of indices for classifying tooth wear. Most are based on a quantification of wear loss by evaluation of changes in the occlusal surface. This can be combined with estimations of the degree of worn enamel and the amount of exposed dentin [**46**, **47**]. In others a qualitative assessment is combined with an estimation of the need for treatment [**48**]. Both types, however, have elements that rely on a degree of subjective evaluation. This, as well as the fact they are hard to use, has restricted their use in research studies [**41**].

3 WEAR AT SITES OF OCCLUSAL CONTACT

3.1 Thegosis and Bruxism

Most work on wear of enamel and dentine due to occlusal contact with sliding (as a result of thegosis and bruxism) has been in the form of *in vitro* experiments carried out on simple wear test apparatus. A large variety of test methods have been used with differing contact geometries, loads, sliding speeds, lubricants etc., which makes comparison of results quite difficult. It is, however, possible to identify common trends as will be evident in the material presented.

Kaidonis et al. [**32**] carried out enamel against enamel uni-directional sliding wear tests (3mm stroke length, 1.33Hz). Extracted teeth were used, with each tooth being halved and then used in an upright position (crown parts in contact) as the top and bottom specimens in the tests. Wear was quantified using mass loss measurements. Initial tests revealed that wear of enamel appeared to be independent of sliding velocity.

Figure 6 shows results for a test run with a load of 3.2kg in dry conditions. Two phases of wear are apparent, which were also observed at all other loads at which tests were run. This pattern has been observed in other *in vitro* experimentation [**49**] and is also consistent with the results of clinical trials [**44**]. During the clinical studies primary and secondary phases described as *running-in* wear and *steady-state* wear were identified. The initial phase appeared to last for a period of 2 years before transition to the slower secondary phase.

The running in wear phenomena is commonly seen in engineering contacts. It is attributed to the process of asperity smoothing, which leads to a more conformal contact and a subsequent reduction in the wear rate. It is probably the same process seen with the enamel testing.

Kaidonis et al. [**32**] also conducted tests over a range of different loads. The different wear rates seen in each phase of wear are shown in Figure 7 and clearly increase as load is increased. The results of tests for dry conditions and a pH7 lubricant (water) at varying loads are shown in Figure 8. Enamel wear rates increased steadily with increasing load. Similar magnitudes of wear were observed by Shabanian et al. [**50**] for lubricated conditions (pH7). It was postulated that three-body abrasion was occurring and that the enamel particles in the contact acted as a dry lubricant, although no visual evidence was offered to back this up. The results of the lubricated tests, however, may add weight to this argument. Whereas at light loads the lubricant reduced wear rates to below those of the dry tests, as load was increased a threshold was reached above which the wear rates increased substantially. It was observed that at these loads the water was displaced from the contact, also washing away any particles, which may have acted as a solid lubricant.

Results are also shown in Figure 8 for wear of dentine (versus enamel) [**51**] from tests carried out on the same test apparatus using the same test parameters as Kaidonis et al. [**32**]. The differences in wear rates at low load were explained by the different structures of the two materials. At lower loads the high mineral content of enamel and its corresponding hardness result in relatively low wear rates compared to dentine, with its higher organic content and relative softness. At higher loads, however, the brittle nature of enamel was thought to contribute to its higher wear rate. Dentine has a connective tissue matrix, which makes it less prone to fracture under these conditions.

The load thresholds observed, above which wear of enamel increases rapidly, are much lower than loads associated with bruxism [**52**].

Zheng et al. [**34**] used reciprocating wear test apparatus with artificial saliva to study the wear rate of enamel and dentine (from extracted teeth) against titanium balls. Wear behaviour and change in hardness in directions parallel and perpendicular to the occlusal surface were investigated (see Figure 9). Tests were carried out with a force of 20N, amplitude of 500μm and a frequency of 2Hz.

Figure 10 shows hardness measurements taken from the occlusal surface down into a tooth. Wear scar depths and hardness decrease as test locations move through the enamel and dento-enamel junction (DEJ) to the dentine. Hardness decreases by 17% from the outer surface of the enamel to the DEJ and by a further 77% form the DEJ to the dentine. Different occlusal layers of enamel in a tooth clearly exhibit different properties. This ties in with the observations of Cuy et al. [**16**], mentioned in the section on tooth structure and orientation.

Significant differences were noted in the wear scar morphologies between the enamel and dentine. Many particles were observed on the surface of the worn enamel, whereas ploughing marks were observed in the surface of the dentine in the sliding direction. Based on the fact that enamel is more brittle than dentine (see Table 1) it was inferred that the enamel particles were mainly the product of micro-cracking and the ploughs as a result of plastic deformation.

This inference was backed up by the results of indentation work carried out by Xu et al. [**15**] on enamel and dentine. This indicated that during indentation of enamel cracks formed, but none could be seen in dentine. It led to the conclusion that enamel wear results from micro-fracture process and dentine as a result of a ductile chip formation.

Figure 11 shows how depth of wear scar varied at the different test locations and with test orientation. This is consistent with observations made by Xu et al. [**15**]. The differences in wear rates between tests sliding parallel to and perpendicular to the occlusal surface were attributed to the orientation of the crystals making up the enamel structure.

3.2 Mastication (Closed Phase)

During the closed phase of mastication (see Figure 4), food particles are trapped between the tooth surfaces and can cause abrasion to the enamel surface. The entrapment of particles is clearly influenced by the nature of the contacting surfaces. Rougher surfaces, for example, may trap more particles than a smooth surface. Although this will depend on the relative size of the particles compared to the roughness. It has been shown that scratches in enamel as a result of thegosis may act as particle traps during mastication [**28**].

Most work studying abrasive wear due to mastication has been carried out on restorative materials and has focussed simply on ranking wear performance of different materials, rather than investigating the mechanism of wear [**38**, **53**].

Maas [**54**] carried out tests *in vitro* compression to investigate the microscopic wear features which appear on the occlusal surfaces of teeth, as a result of abrasion by food particles (typically categorised as pits (length:width ratio < 4) or striations (length:width ratio > 4)). Abrasive particles (silicon carbide) of varying size and different loads were used to study the generation of these features in enamel. Two loads were used; 50 and 100kg; and particle sizes of 14, 23 and 73µm. It is not clear whether the silicon carbide or the particle sizes are representative of particles found in food slurry. In the tests, specimens of equal size were covered in a single layer of the abrasive particles (hence far more small particles were used than larger). Unsurprisingly, results showed that the larger particles produced fewer, larger wear features than the small particles. Total wear was determined using an area approach, which showed that the total wear area increased with particle size. This goes against the normal abrasive wear expectation, in which smaller particles would produce more wear simply because there are far more present. This issue, however, was not addressed. Interestingly, wear seemed to be independent of load. The results were very different from a study carried out with shearing, which should simulate more what actually occurs during chewing [**55**].

4 WEAR AT CONTACT FREE SITES

4.1 Mastication (Open Phase)

Very little work has been attempted to study abrasive wear due to food slurry with no tooth contact. This is probably because it is a minor problem compared to the other tooth wear mechanisms as loads are low. Mair et al. [**27**] notes, however, that it is problem with some composites used in tooth restoration. Tests have also shown that it may cause a problem in the cavities in the surface of teeth that form part of the food shedding system [**56**].

4.2 Toothbrushing

A comprehensive study of the role that abrasive particles in toothpastes and toothbrushing play in tooth wear has been carried out in which the literature from 1966 to 2002 was searched for data [**41**] relating to abrasion of enamel and dentine. The main findings of the work were that, while there was a small amount of concern regarding the potential for tooth wear, most investigations concluded that the abrasives would have a minimal effect on enamel, their effect being more pronounced on dentine and dental restoratives. As a result, most work on toothpaste abrasivity has been conducted on these materials [**57 - 62**].

Most of the tests carried out have been *in vitro*, on a wide variety of testing machines. More recently *in situ* tests have been carried out to study the effects of abrasive wear of dentine [**63**] and enamel [**64**]. In these tests dentine or enamel specimens were mounted on removable appliances worn in the mouth. The specimens were removed and brushed *ex vivo* for a set time. Results for both materials indicated that wear was very low, as shown in Figure 12a and b, but measurable abrasion occurred and varying abrasion rates were found between different toothpastes. Wear rates for dentine were an order of magnitude higher than those for enamel.

While initially studies dealt with the effect of the toothpaste, work has been carried out to establish the effect of toothbrush design on abrasion [**45**, **58**, **65**] and other factors such as brushing time and brushing force and speed [**58**, **60**, **66**]. The toothpaste was, however, found to have the most significant effect on abrasion.

It is interesting to note that tests to simulate *automatic* versus *manual* brushing showed that automatic gave lower abrasive wear for the same toothpaste [**58**, **65**], as shown in Figure 13.

Work carried out recently by Lewis et al. [**67**] has studied how abrasive particles interact with toothbrush filaments, which has furthered understanding of what is happening in a tooth cleaning contact (see Figure 14).

4.3 Tooth Flexure

Abfraction, a relatively new term coined by Grippo [**68**], relates to cracking and subsequent enamel loss in the cervical region of a tooth, around the cemento-enamel junction (see Figure 2). This is thought to be caused by shear stresses resulting from tooth flexure, which lead to disruption of the bonds between the hydroxyapatite crystals that make up the structure of enamel [**69**, **70**]. The enamel in this region of the tooth has been noted to be less resilient (see section on tooth orientation and structure).

Finite element studies [**71**] and strain gauge measurements [**72**] have been used to study the stresses in the cervical area of a tooth and have shown that they exceed the failure stresses for enamel (shown in Table 2). Fracture of the enamel is most likely to occur along the boundaries of the hydroxyapatite crystals [**73**]. In the cervical region the crystals are approximately horizontal (perpendicular to the surface), which is the same direction as the principal stresses determined by Rees [**71**].

Clinical observations had suggested that damage due to abfraction was more prevalent in maxillary (upper jaw) incisors [**68**, **74**]. A finite element study of stresses induced in threes different tooth types [**5**], indicated that stresses in maxillary incisors were several times larger than those in canines and molars, which explained these observations. The reason for the difference in stresses between the tooth types is likely to be related to the area of periontological ligament associated with each tooth and their mobility under loading. Rudd et al. [**75**] examined horizontal displacement of teeth under load and found that the mobility of incisors was greater than that of canines and molars. Jepson [**76**] calculated that incisors also had a smaller ligament area. This indicates that incisors are less well adapted to manage applied occlusal loads.

Damage due to abfraction has been reported to occur more commonly amongst bruxists [**77**, **78**], where occlusal loads and hence tooth excursions are greater.

5 CHEMICAL EFFECTS

5.1 Influence on Mechanical Properties

Increasing acidity (decreasing pH) has been clearly shown to decrease both the hardness and elastic modulus of enamel [**79**, **80**]. Figure 15 shows how the hardness and reduced elastic modulus of enamel changes with exposure to citric acid of varying pH [**79**]. Extracted teeth were used in the tests and immersed in 50ml of the appropriate solution, which was being stirred. Exposure time was 120 seconds. This was based on the clearance time for citric acid *in vivo* [**81**, **82**]. The values of modulus and hardness were determined using nanoindentation. The reduction in hardness implies that wear rates of enamel in an acidic environment will increase. To a certain extent this is a correct assumption as will become evident in the subsequent discussions.

Figure 16 shows enamel hardness against exposure time for water, Bordeaux red wine and Coca-Cola^{TM} [**80**]. Clearly hardness decreases with exposure time, so consideration of this parameter is important in assessing and comparing results. Wine tasters in the Bordeaux region appear to be unlikely to suffer too many ill effects to their teeth from their job though!

5.2 Effect on Material Loss (with no load or sliding)

Figure 15a shows an approximately linear relationship between enamel hardness and solution pH. Tests to measure material loss have revealed different trends (extracted teeth were used in the tests and agitated in the appropriate solution, material loss was determined using profilometry), however, as shown by the example in Figure 17a [**83**]. This could be for a number of reasons; the exposure time was much longer for these tests (30 minutes) and samples were agitated. This is a good example of the general lack of uniformity in dental test methods, which means that only broad trends can be drawn when comparing data. The results for dentine specimens in the same publication (Figure 17b), for example, were only exposed for 10 minutes meaning direct comparison with the enamel is impossible! It is clear, however, that material loss increases with decreasing pH. The acids used in the tests are typical of those found in soft drinks. Clearly the citric acids (CANaOH and CATC) give the highest material losses. The results are a good guide to drinks manufacturers on what acids may be detrimental to teeth and what levels of pH may be unacceptable.

5.3 Material Loss with Load Applied (no sliding)

Wear also increases when static or cyclic load is applied to enamel, while exposed to an acidic environment [**84**, **85**]. Tests carried out to determine wear of enamel in different areas of a tooth (see Figure 18) as a result of no load application (for 28 hours) and simulated occlusal cyclic loading (0 to 100N at 2Hz for 200000 cycles - 28 hours) in lactic acid (pH 4.5) indicated that load application clearly increases the wear rate [**85**] (see Figure 19) (extracted teeth were used and either placed in a bath of solution or mounted in a servo-hydraulic test machine and surrounded by the appropriate solution, while being cyclically loaded, material loss was determined using profilometry of impressions of the test teeth). Wear was found to be higher in the cervical region of a tooth. This ties in with the observations, noted in the section on tooth structure and orientation, that enamel in this region of the tooth is thinner, softer and less resilient than enamel nearer the top of the tooth.

5.4 Material Loss with Load and Sliding

Wear rates with the application of load and sliding have shown slightly different trends to those seen with load and no load in an acidic environment. Tests have indicated that wear at around pH3 is lower than that at pH7 [**32**, **35**, **36**], but for pH1, wear increases to a level well above that at pH7 [**32**, **50**]. Results of sliding tests carried out by Kaidonis et al. [**32**], illustrating this effect, are shown in Figure 20 (for test details see section on thegosis and bruxism).

With sliding, wear rates would be expected to increase, as a synergistic effect is likely to occur. The outer layer of enamel will be softened by the effect of the acidic solution and its hardness will decrease. The application of load and sliding will then break this layer down causing it's removal. This will expose fresh enamel, which will be softened and the process is repeated. Increasing the acidity of the solution would therefore be expected to increase wear as hardness decreases linearly with decreasing pH.

Eisenburger et al. [**35**, **36**], in similar work carried out to closely investigate interaction of chemical effects with enamel to enamel sliding contact, offered a possible explanation for this apparent anomaly. Observation of the wear surfaces for the different conditions revealed, that the specimens in the more acidic solutions had smoother surfaces. It was hypothesised that this would decrease the friction at the specimen interface and thereby reduce fatigue wear. Eisenburger et al. [**35**, **36**], however, did not test up to pH1, and therefore offered no reason for any change at this level of acidity.

Tests run to study the interaction of wear due to toothbrushing [**86**] and mastication [**87**] with chemical effects have shown that wear increases with decreasing pH. In these situations, however, the wear is being caused by abrasive particles rather than an opposing surface undergoing a similar wear process.

In situ testing, similar to that described for toothbrushing (see section on toothbrushing), has been used to evaluate erosive wear of enamel and dentine [**88**, **89**]. These tests consisted of mounting enamel or dentine specimens onto an intra-oral device, which was then exposed to an acid environment (with orange juice for example). Tissue loss was then recorded using surface profilometry. These tests showed lower material losses than *in vitro* tests. One reason for this may be that erosion *in vivo* is influenced by factors including remineralisation and pellicle formation.

6 DISCUSSION

6.1 Wear Mechanisms

The terms used in clinical dentistry for wear mechanisms differ from those used in conventional engineering tribology (and in some cases are misleading). Table 4 shows the correspondence between commonly used terms.

It evident from the analysis of the mechanisms leading to wear in teeth, that those associated with occlusal contact cause the most wear problems. The non-contact wear mechanisms, such as open phase mastication and toothbrushing have a lesser impact on enamel wear. It is not evident, however, which of the contact mechanisms is the most dominant as it is very difficult to study *in vitro* how they interact (and few attempts have been made) and completely impossible *in vivo*. It is possible that dominant wear mechanisms will differ from person to person.

Dentine wear is a much greater concern than that of enamel. This is not unexpected as it is softer and less resilient than enamel and it does not remineralise as enamel is able to do. It is difficult to say what can be done to alleviate problems encountered when the enamel layer is breached as the tooth cannot be redesigned. Information on the wear processes and mechanisms is extremely important, however, in developing and assessing the performance of restorative materials used to repair damaged or decaying teeth.

Most examples of excessive teeth wear rates occur where exceptional conditions are encountered. This may be because of hyper-function (such as bruxism), where higher contact loads exist between teeth and greater sliding occurs leading to increased tooth flexure; or because of severe climate or environmental conditions, such as dusty, dry surroundings or excessively acidic atmospheres, which may be experienced at home or at work; or because of conditions such as anorexia, where teeth are frequently exposed to gastric acids.

The biggest single influencing factor on the wear of teeth is clearly that of the chemical environment to which teeth may be exposed. All wear mechanisms are synergised, including those, which in normal conditions would not lead to excessive wear. The main reason for this is the reduction in hardness of enamel and dentine and erosive material loss in acidic conditions, which are further increase with load application and motion (apart from the slight anomaly with sliding wear material loss). This is a significant observation for the manufacturers of soft drinks, which can contain high levels of citric acid.

Surprisingly the synergistic effects of chemical and mechanical tooth wear have not been investigated. Research in conventional engineering tribo-corrosion is advanced [**90**] and there are several techniques for testing and modelling the processes. It is possible that some of these techniques might find merit in the dental world.

6.2 Wear Testing

Figure 21 summarises the range of tests used for studying and assessing tooth wear mechanisms and the effect of influencing factors.

There seems to be a high level of suspicion levelled at the results and conclusions drawn from *in vitro* testing amongst the dental world. Researchers publishing results from such tests are at pains to point out the drawbacks and the lack of correlation with *in vivo* observations. This should not be the case as *in vitro* laboratory testing provides the only means to satisfactorily vary and control critical parameters influencing a wear process. Laboratory tests must, however, be as representative as possible and simplistic approaches such as using a pin-on-disc test are not. The results of *in vivo* testing, however, are largely subjective and can often only provide a qualitative assessment of wear and should be subject to much greater scrutiny given the large number of variables that cannot be assessed or controlled. As in conventional engineering the best approach is probably to understand, as far as possible, the wear mechanism before trying to simulate it. Indeed, as Mair et al. [**27**] noted, increased understanding of tooth wear has been “hindered by the unnecessary inclination to classify and reproduce clinical manifestations rather than understand their underlying mechanisms”, so this is where efforts would be best focussed using the best methods available. It seems that the problems inherent in wear assessment of engineering components, and the difficulties of finding a representative test, are common with tooth wear. The added complication is that there are no sound approaches for tooth wear testing in the real environment.

6.2 Wear Modelling

No attempt has been made at modelling wear of enamel or dentine. This is probably because of the complexity of the oral and loading environment to which teeth are exposed. The same is true in conventional engineering. However, sometimes simple models, while they may not give a completely accurate representation, can be useful in comparing and contrasting wear situations. One simple approach that could be used is the Archard sliding wear model [**91**]:

$$K = \frac{Vh}{Pd} \qquad (1)$$

where K is the dimensionless wear coefficient, V is the wear volume, P is the normal load, d is the sliding distance and h is the material hardness.

Clearly knowledge of the dimensionless wear coefficient, *K*, is vital in order to apply Equation 1. These can be derived from, for example, pin-on-disc sliding tests. In Table 5, sliding wear coefficients for typical engineering materials (from [**92**]) are compared with those calculated for enamel and dentine (from the results of Kaidonis et al. [**32**] and Burak et al. [**51**] respectively). The values of *K* for enamel and dentine are of the same order of magnitude of those for the engineering materials.

Using the tooth load data, sliding distances and times during which teeth are in contact presented in section 1.3 (see [**20 – 25**] and Table 3), it was possible to calculate a tooth wear rate using Equation 1. A summary of the calculation is shown in Table 6.

The final result of 96μm wear depth per year compares well to the depth of 65μm per year measured by Lambrechts et al. [**93**]. To get the same order of magnitude with a wear model with such a large number of assumptions is encouraging. Sufferers of bruxism have been observed to subject teeth to loads of up to 11N for several hours per day [**21**]. If this additional loading is added into the calculation outlined in Table 5, using a daily contact time of two hours as a result of the bruxism at 11N, the total wear becomes 181μm. This ties in with the measurements made by Xhonga [**77**], who noted that suffers of bruxism could experience wear rates three to four times higher than the 65μm seen by Lambrechts et al. [**93**].

A good understanding clearly exists of the mechanisms leading to the wear of teeth and of the critical influencing factors. One of the main challenges to researchers is to improve testing techniques to enhance the applicability of results and to gain a better understanding of how the mechanisms interact and assess which may be the most dominant. Perhaps some of the lessons learnt in engineering tribology can help in this regard.

7 CONCLUSIONS

Many different tooth wear mechanisms have been identified. The main cause of enamel and dentine wear, however, is occlusal contact, either during chewing and thegosis and is particularly prevalent in sufferers of hyper-function such as bruxism. The occlusal contact wear mechanism involves a running in process, typical of wear seen in engineering component contacts. This can actually be beneficial as it causes contacts to become more conformal and leads to reduced wear rates. Wear during toothbrushing due to abrasive particles in toothpaste appears to be only a problem with dentine and some restorative materials.

The major influencing factor on all the different wear mechanisms is the acidity of the oral environment. Increasing acidity reduces the hardness and Young’s modulus of enamel and dentine, which leads to increased wear rates. Despite the importance of the effect of acidity, synergistic effects have not been studied. This is an important challenge to researchers.

There are a wide variety of test platforms used in tooth wear studies. In most cases there has been great difficulty in relating results to in vivo tooth wear. This is further complicated by the lack of techniques for quantifying wear in living teeth.

Predictive wear models for teeth have not been developed, probably due to the great complexity of the oral environment and teeth loading conditions. A simple wear model put forward in this paper has been shown to produce reasonable estimates of enamel wear and could be further developed to predict wear of restoratives.

Most work in this area has been carried out in the dental field, rather than by engineering tribologists. As noted previously, collaboration between the two in the future will help advance this field of study.

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Figure Captions

Figure 1.	Tooth Orientation
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Figure 1

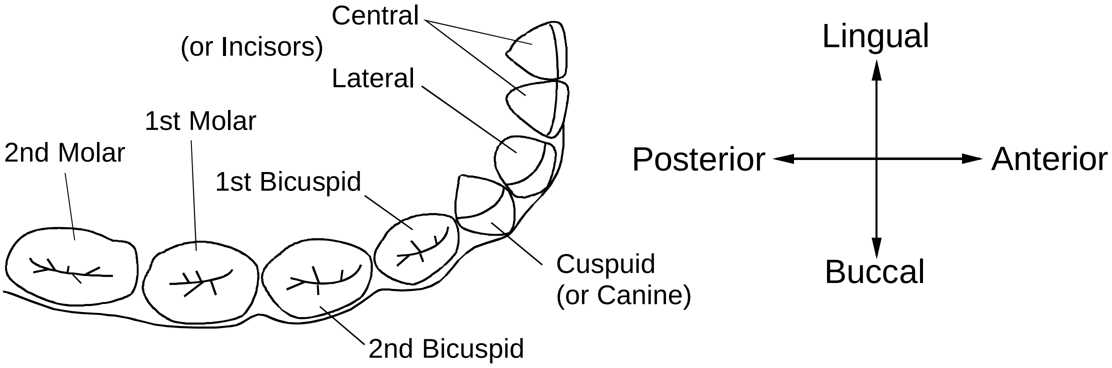


Figure 2

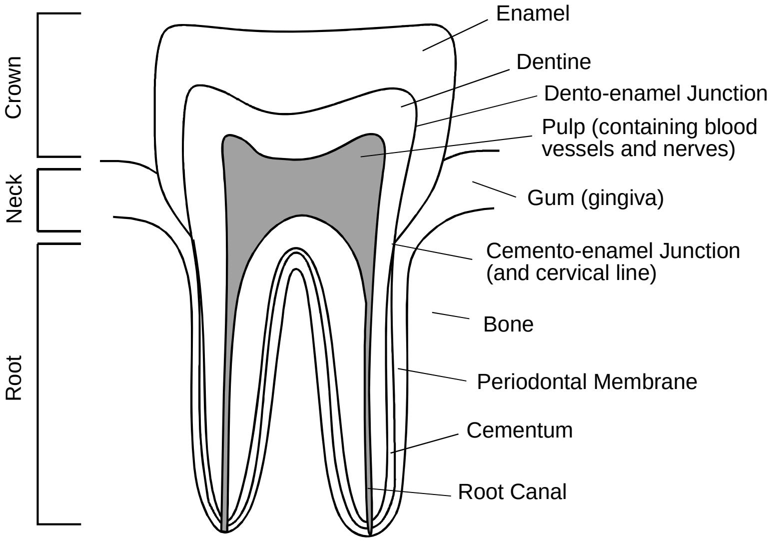


Figure 3

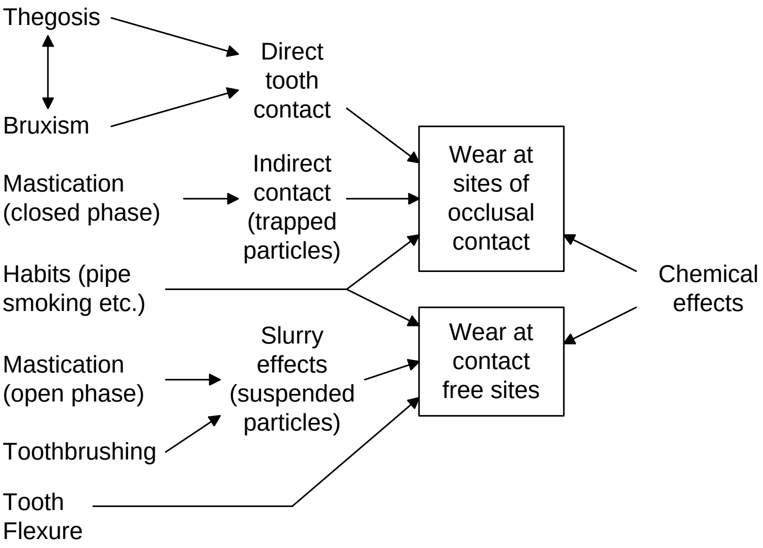
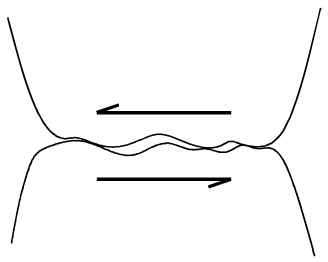
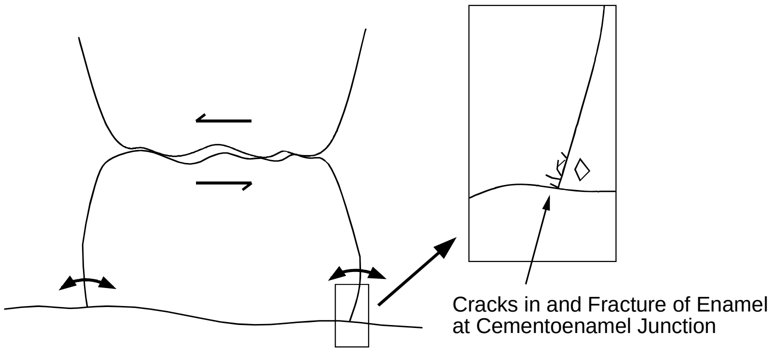

Thegosis
Bruxism
Mastication (closed phase)
Habits (pipe smoking etc.)
Mastication (open phase)
Toothbrushing
Tooth Flexure
Direct tooth contact
Indirect contact (trapped particles)
Slurry effects (suspended particles)
Wear at sites of occlusal contact
Wear at contact free sites
Chemical effects

Figure 4

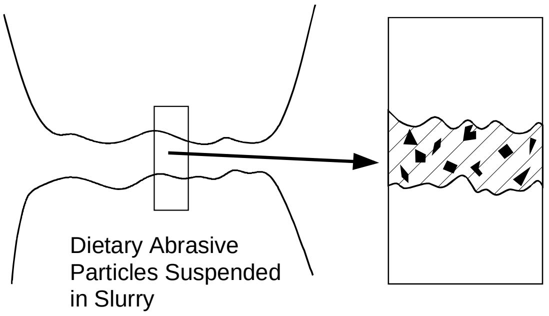
(a) Thegosis/Bruxism



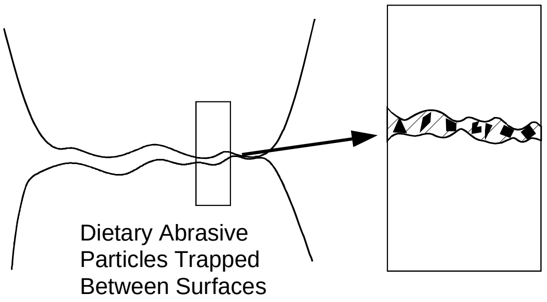
(b) Tooth Flexure



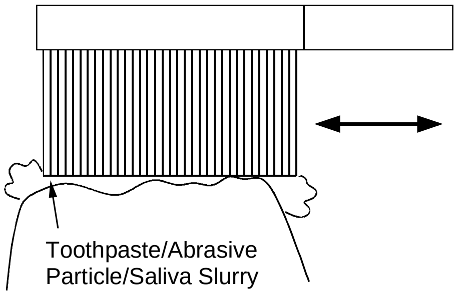
(c) Open Phase Mastication



(d) Closed Phase Mastication



(e) Toothbrushing



(f) Chemical Effects

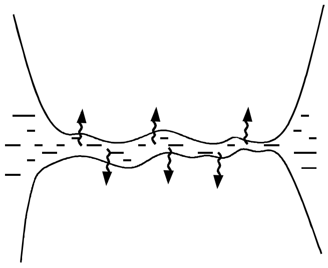
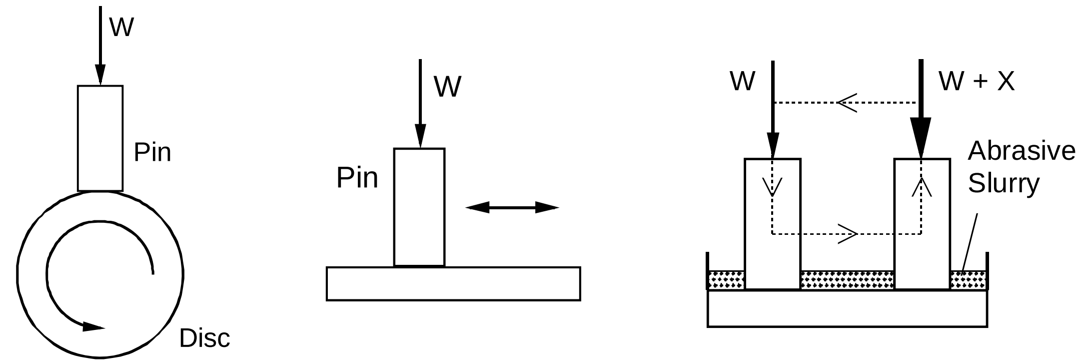


Figure 5


(a) Pin-on-Disc (b) Reciprocating (c) One-way Slide and Static End Load

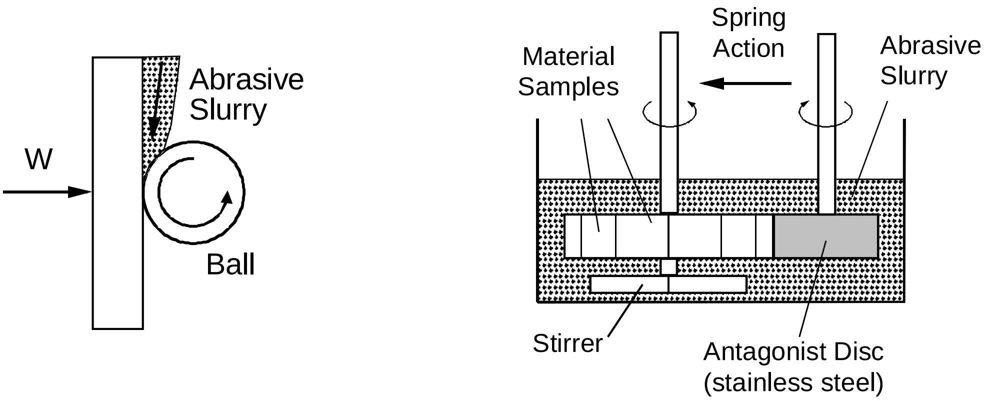

(d) Ball and Crater (e) Twin Disc

Figure 6

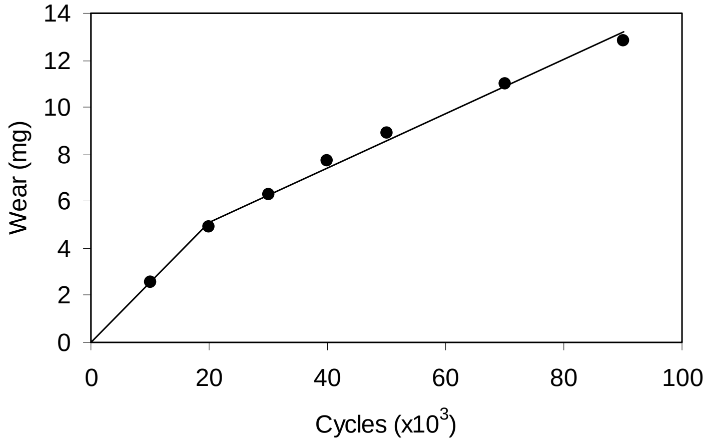


Figure 7

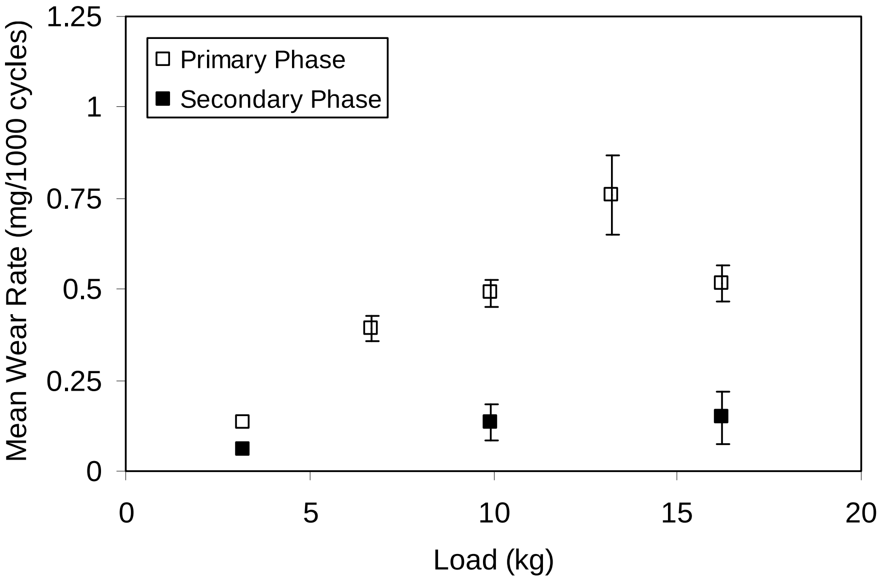


Figure 8

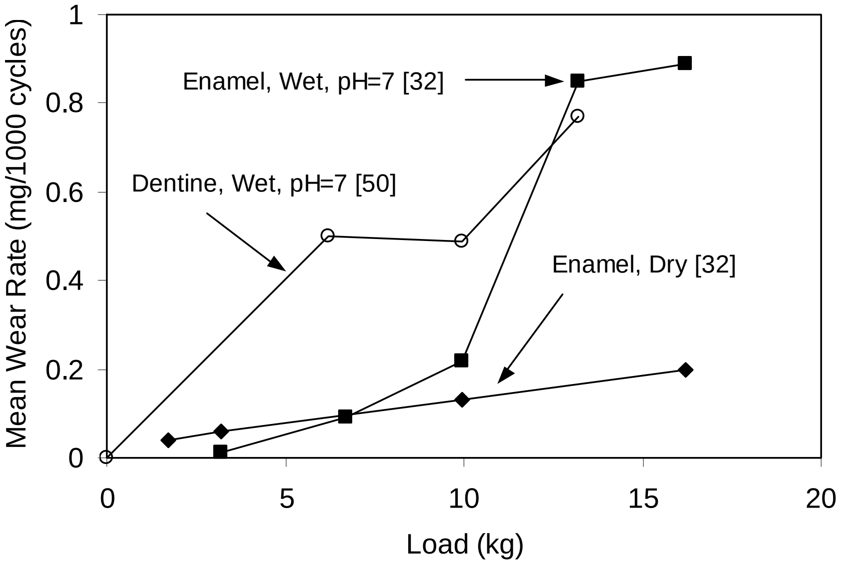


Figure 9

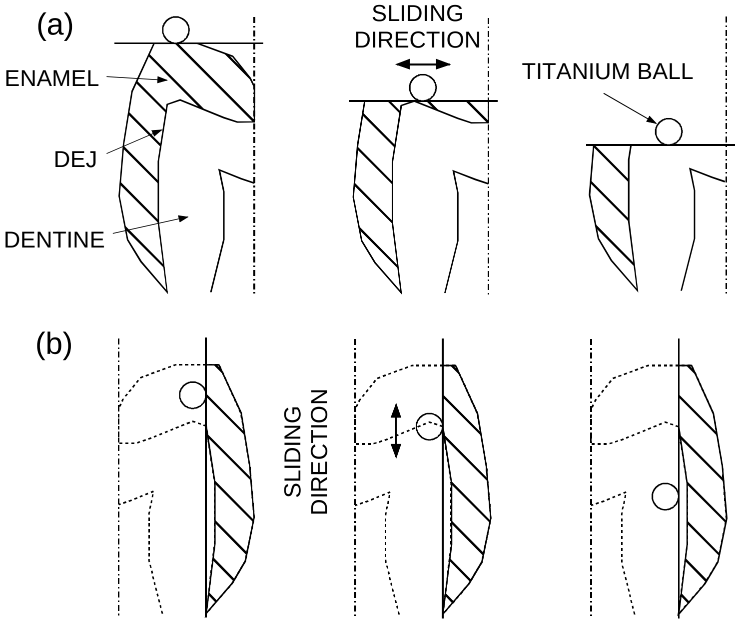


Figure 10

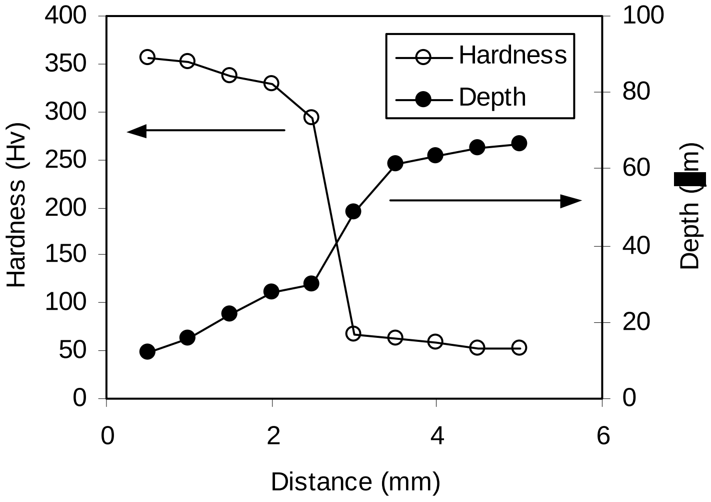


Figure 11

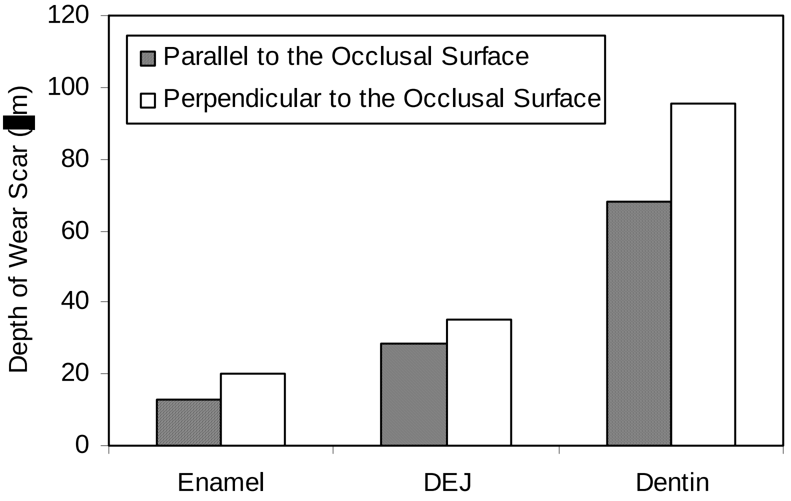


Figure 12

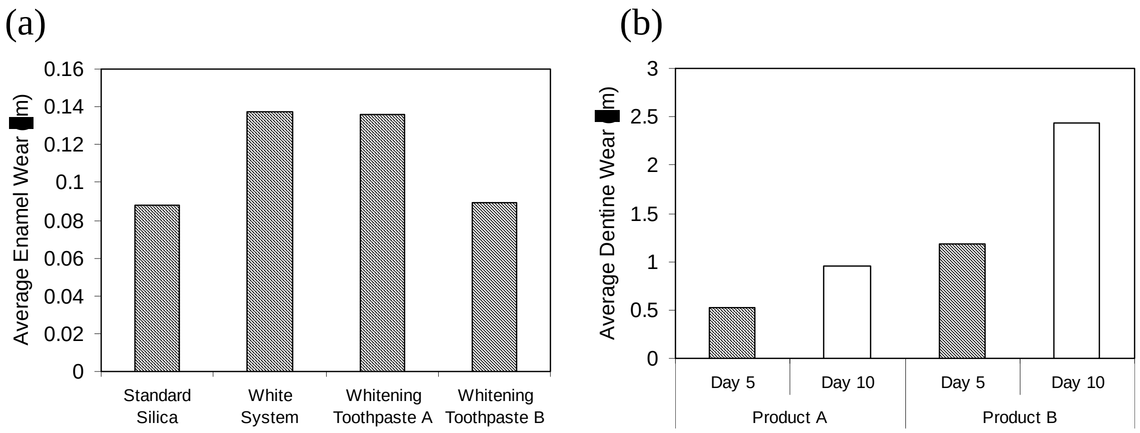


Figure 13

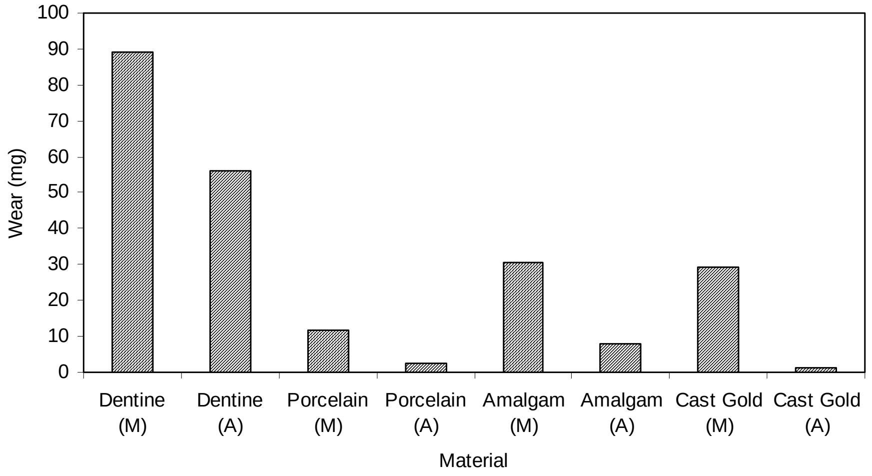


Figure 14

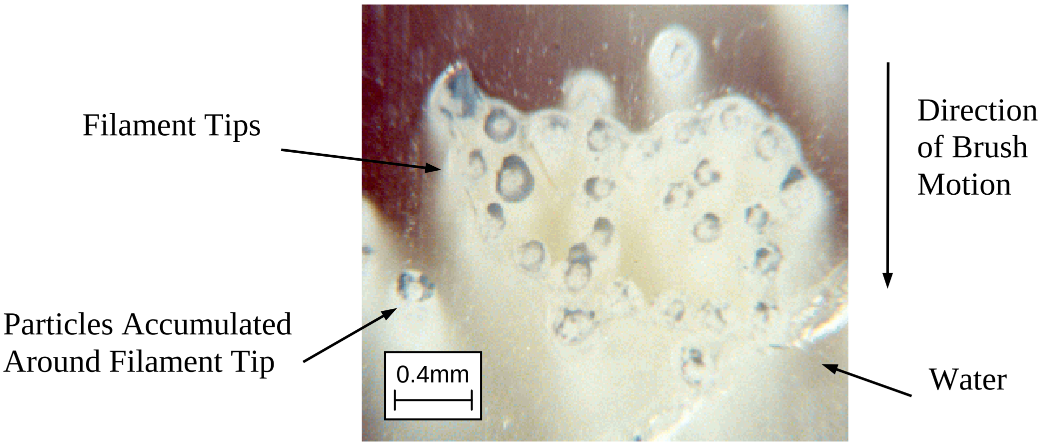


Figure 15

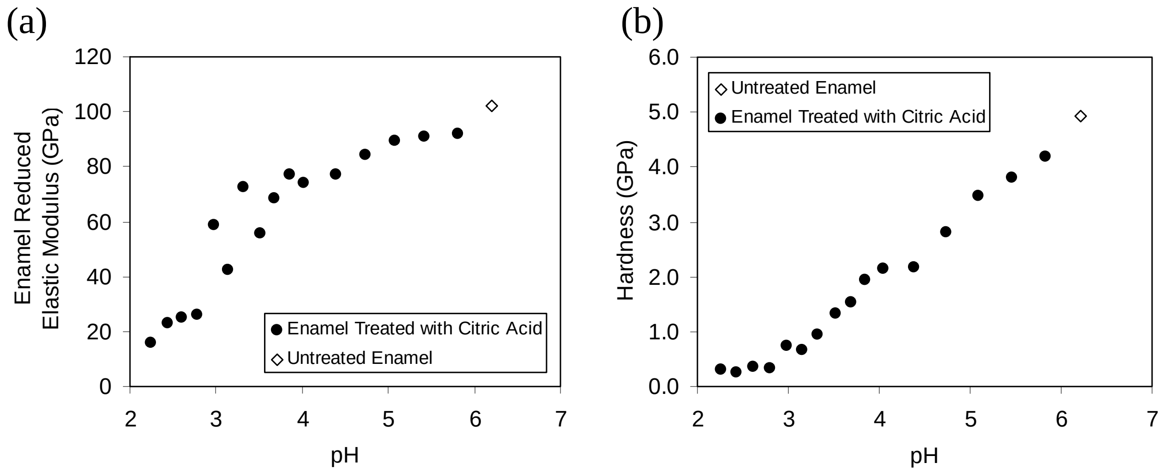


Figure 16

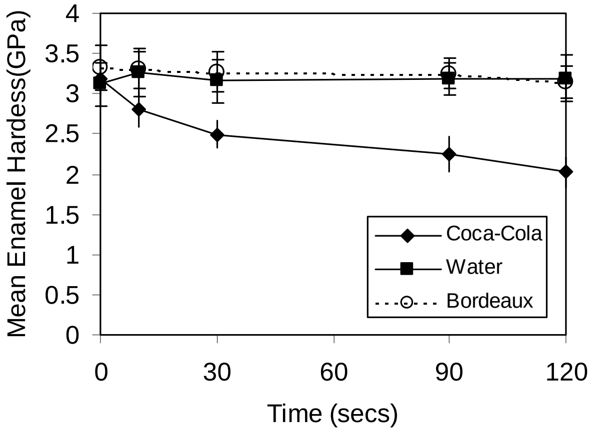


Figure 17

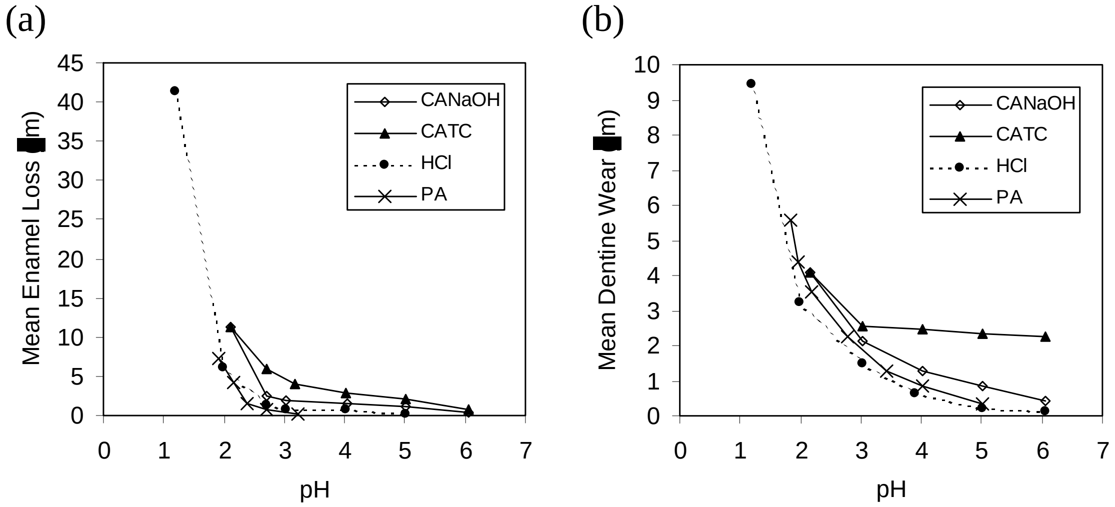


Figure 18

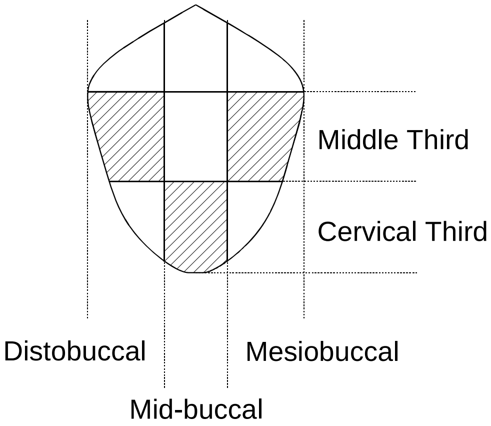


Figure 19

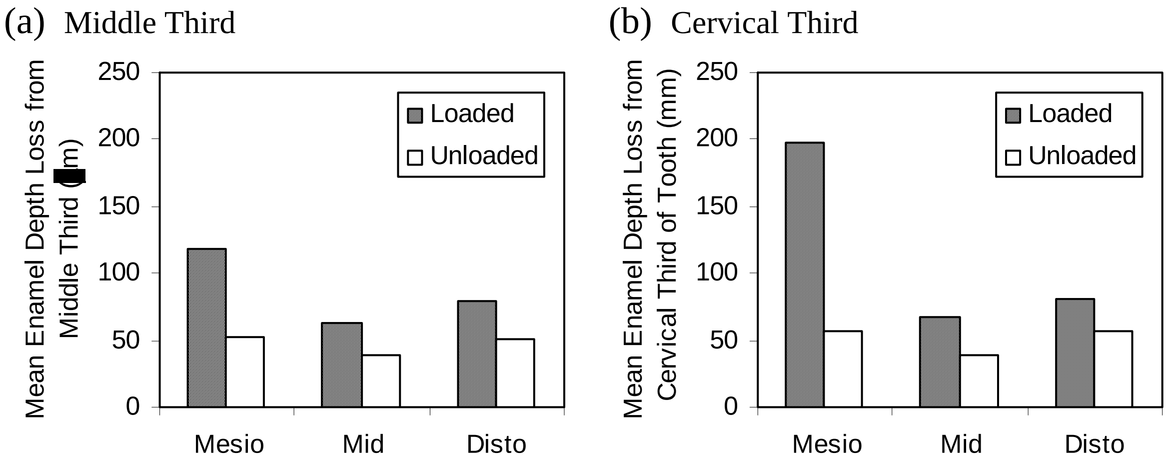


Figure 20

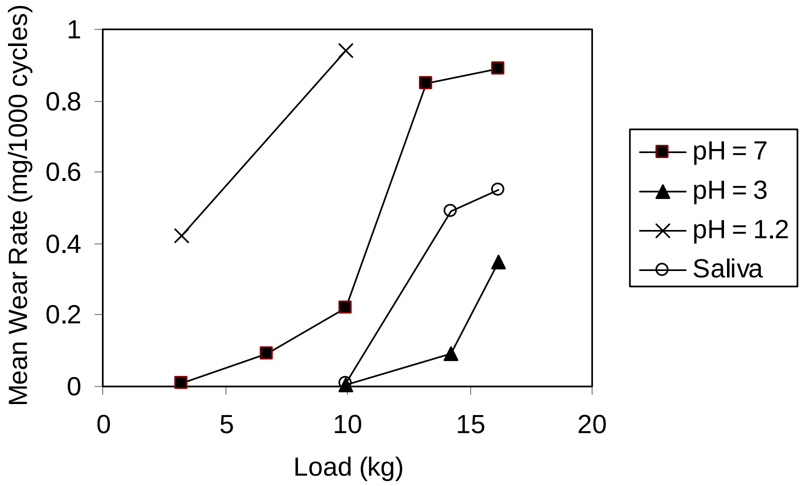


Figure 21

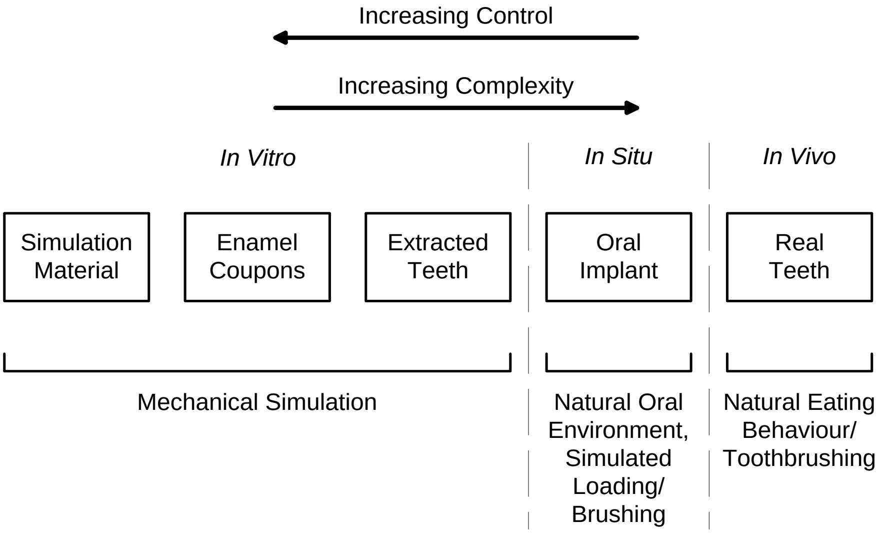


Table 1

Property	Dentine	Enamel
Young's Modulus (GPa)	10.2 - 15.6	20.0 - 84.2
Shear Modulus (GPa)	6.4 - 9.7	29
Bulk Modulus (GPa)	3.11 - 4.38	45, 65
Poissons Ratio	-0.11 - 0.07	0.23, 0.30
Compressive Strength (GPa)	0.249 - 0315	0.095 - 0.386
Tensile Strength (GPa)	0.040 - 0.276	0.030 - 0.035
Shear Strength (GPa)	0.012 - 0.138	0.06
Knoop Hardness	57 - 71	250 – 500
Density (Kg/m^3)	2900	2500

Table 2

Author	Test Type	Failure Stress (MPa)
Stanford et al. [**7**]	Compression	134-278
Cooper & Smith [**8**]	Punch Shear	64-93
Hannah [**9**]	Tensile	30-35
Bowen & Rodriguez [**10**]	Tensile	10
Tyldesley [**6**]	Flexural (4-point bending)	76

Table 3

Author	Measurement Technique	Chewing Load (N)
Anderson [**22**, **23**]	Strain Gauge Inlay	70-145
Proeschel [**24**]	Intra-oral Transducers	Avg. 220
Morneburg [**25**]	Strain Gauges in Implant Abutments	avg. 220, max. 450

Table 4

Dental Tribology	Engineering Tribology
Attrition	Adhesion Two-Body Abrasion
Abrasion	Three Body Abrasion Erosion
Abfraction	Fatigue Wear
Erosion	Chemical Wear/Corrosion

Table 5

Material	*K*
Mild steel (on mild steel)	7×10^{-3}
α/β brass	6×10^{-4}
PTFE	2.5×10^{-5}
Hard tool steel	1.3×10^{-4}
Ferritic stainless steel	1.7×10^{-5}
Polythene	1.3×10^{-7}
PMMA	7×10^{-6}
Enamel (on enamel)	6.4×10^{-4}
Enamel (on enamel) with saliva lubrication	2.9×10^{-5}
Dentine (on enamel)	1.7×10^{-3}

Table 6

Parameter	Value
Tooth to tooth contact time during one chew	0.1s
Sliding distance in 1 chew	1mm
Total tooth to tooth contact time in 1 day	900s (15mins)
Total sliding distance in 1 day	$(900/0.1) \times 1 = 9000$mm
Total sliding distance in 1 year, *d*	3285000mm
Dimensionless sliding wear coefficient, *K*	2.9×10^{-5}
Enamel hardness, *h*	6×10^{9} N/m^2
Load, *P*	150N
Wear volume in 1 year, *V* (from Equation 1)	2.41mm^3
Tooth area	25mm^2
Tooth wear depth in 1 year	96µm