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Review

Human tooth wear in the past and the present: Tribological mechanisms, scoring systems, dental and skeletal compensations

Emmanuel d'Incau [a,b,*], *Christine Couture* [b], *Bruno Maureille* [b]

[a] *Université Bordeaux Segalen, Faculté d'Odontologie, 16-20 cours de la Marne, 33082 Bordeaux Cedex, France*

[b] *Université Bordeaux, UMR 5199 PACEA, "Anthropologie des Populations Passées et Présentes", Université Bordeaux 1, Avenue des Facultés, 33405 Talence Cedex, France*

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ABSTRACT

This review of human tooth wear describes the fundamental mechanisms underlying this process. Using the tribological approach they can be systematised and this in turn aids our understanding of them. In past populations wear was ubiquitous, intense, abrasive and physiological as it was related to their food and their technologies. In these populations, it affected the proximal surfaces, and the occlusal surfaces which modified the occlusal plane profoundly. To categorise this wear many different classification systems are used, from which we can determine diet, cultural changes and the age at death of individuals. They also illustrate the evolution of certain functional dental and skeletal compensations in the masticatory apparatus such as continuous dental eruption, mesial drift of the arches and incisor lingual tipping which can then be monitored. These physiological adaptations related mainly to function and ontogenesis can also be found in present-day populations where wear is moderate, although they are much less obtrusive. Apart from certain pathological cases associated with a specific parafunction, iatrogenic tooth brushing or an eating disorder and encouraged by an acid environment, they are the result of a physiological process that should not be halted. To ensure this, it is essential to prevent lesions related to tooth wear, to detect them early and establish a reliable diagnosis. Types of tooth wear that had remained unchanged since the origin of humanity have undergone profound changes in a very short space of time. Today's tribochemical pathological model has replaced the abrasive physiological model of the past.

Contents

* *Corresponding author at*: Université Bordeaux Segalen, Faculté d'Odontologie, 16-20 cours de la Marne, 33082 Bordeaux Cedex, France. Tel.: +33 557 107 957.
E-mail address: e.dincau@pacea.u-bordeaux1.fr (E. d'Incau).

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1. Introduction

Wear is deterioration as a result of use. Tooth wear has existed since the beginning of humanity and in all civilisations. It occurred systematically and intensively in past populations, but is considered a physiological process. However, this notion is often unclear as nowadays, although the process is less well developed, it is sometimes pathological in nature. In addition, it depends on many complex mechanisms, synchronous or sequential, synergetic or additive which can also often mask its true origin. With the aim of improving the diagnosis of tooth wear and for a better understanding of its various manifestations, in this review we first present the fundamental mechanisms of wear and their consequences, both in past populations and in contemporary industrialised populations. The second part looks at the categorisation of wear and choosing the most appropriate of the scoring systems used in odontology and dental anthropology according to origin, location and the populations studied. The last part covers dental and skeletal compensation mechanisms and explains how the masticatory apparatus adapts as wear progresses in order to maintain a functional occlusion throughout our lifetime.

2. Fundamental wear mechanisms

In dentistry, wear is a generic term commonly used to describe phenomena of attrition (proximal and occlusal inter-dental friction), abrasion (friction with the intervention of particles) and erosion (chemical dissolution). Although this longstanding terminology introduced by Hunter[1] is the one that is normally used, it does not entirely take into account the reality and variety of the physical and chemical mechanisms involved. In addition, it suggests that these three phenomena act independently, whereas in fact it is more often the case that they interact together, which makes diagnosis all the more difficult.[2] Another approach is to use terminology borrowed from the science and technology of tribology (from the Greek *tribein*, meaning to rub) which covers the study of friction, wear and lubrication.[3–5] To facilitate diagnosis of the different forms of wear of dental tissues and restorative materials, the oral cavity can be likened to a tribological system made up of four elements[6]:

- a solid body represented by a tooth, which may or may not be restored,
- a counter body usually represented by a solid (opposing tooth, tongue, soft tissue, object, etc.) less frequently by a liquid, a gas or a combination of these different elements,
- there may be an interfacial element represented by a solid (particles in the food bolus, in toothpaste, etc.), a liquid which lubricates to varying degrees (saliva), less frequently a gas or a combination of these different elements,
- an environment, usually represented by air.

Within this tribological system, four basic wear mechanisms can be described.[6] Their occurrence depends on many different parameters and enables us to qualify the behaviour of the dental tissue and the restorative materials. These may be (1) flexible or rigid depending on their capacity to deform reversibly, (2) hard or soft depending on their capacity for irreversible plastic deformation, (3) brittle or ductile depending on their capacity to resist crack propagation, and act as a shock-or energy-absorber.

2.1. *Abrasive wear*

Abrasive wear is the most common type of wear.[6] At the microscopic scale, no surface is entirely smooth. When there is contact between different materials it is through asperities which act as abrasive particles. Depending on the microroughness of these materials a number of microcontacts are made and define the real surface area, which is in fact much smaller than the maximal theoretical surface area. In addition, even though the overall pressure exerted between different materials may be low, the pressure developed locally at each microcontact is sometimes so great during displacement that it may lead to deformation or to rupture. Depending on the number of materials in contact, tribology distinguishes two types of abrasive wear: two-body abrasion and three-body abrasion.[3–6]

2.1.1. *Two-body abrasion*

This type of abrasion (from the Latin verb *abradere*, to abrade) is the friction between two solid bodies in movement where the surfaces are in direct contact. Tribology distinguishes four models of two-body abrasion, determined according to the angle of attack and the geometry of the asperities, the friction coefficient, the speed of the displacement, the pressure, the distance and the differential hardness between the two surfaces in contact.[7,8]

When two surfaces have very different levels of hardness, microasperities on the harder surface move across the softer surface with a microploughing mechanism. At microscopic level, a prow is formed ahead of the abrading particle and material is continuously displaced sideways to form ridges adjacent to the groove produced. With repeated passes, many grooves are formed parallel to the direction of displacement of the abrasive asperities. The proximity of the grooves eventually weakens the more ductile material which deforms locally and matter is removed with a microfatigue mechanism.[6]

When two brittle surfaces have a similar, high level of hardness (metals hardened to a high degree, dental ceramics), the microasperities on the harder surface cut the more ductile surface cleanly, with no plastic deformation, using a microcutting mechanism. The shape and volume of the groove that is formed correspond exactly to the volume of material displaced. If in addition these two surfaces are subjected to high pressure, some surface asperities may become detached by a microcracking mechanism. Small cracks then form along a main groove, they propagate then nucleate within the material, and blocks may then become detached.[6] With repeated passes, all the surface asperities are subjected to one or more of these models and become dissociated so that the cumulative effect of these microscopic losses results in macroscopic wear.

Note that if a third solid moving body is often interposed between two surfaces, then each wears separately with a two-body abrasion mechanism. If the body is removed, the contact surfaces do not correspond.[3]

Within the oral cavity, two-body abrasion is often called attrition (from the Latin *attritio*, friction), which could lead to confusion because attrition is not a tribological process in its own right. As it occurs at sites of direct contact between surfaces it will have contributions from the two-body processes of abrasion, adhesive wear or fatigue wear[9] (see Sections 2.2 and 2.3 below). This is a gradual phenomenon which is mainly the result of physiological or pathological proximal and occlusal inter-dental friction.

In terms of proximal contact, this type of wear is linked mainly to masticatory forces and their cumulative effect. Two simultaneous factors are responsible.[10] The first is a relative lateral movement which leads to friction across adjacent teeth. It occurs along a plane perpendicular to the line linking their contact points and it is due to the visco-elasticity of the periodontal ligament. The second factor is a posterior-anterior movement which distributes the mesial component of the occlusal forces across the entire dental arch, pushing the distal tooth onto the mesial tooth. If the curve of Spee is absent or decreased, and this is associated with considerable occlusal wear, this movement is significantly intensified.[11] To these two factors should be added the axial depressibility of the periodontal ligament when a tooth is subjected to occlusal pressure. Its value can reach 28 μm.[12]

In past populations, interproximal wear started in childhood and was often heavy in adults.[13] There was generally a difference between the very worn mesial surfaces, which were strongly concave, and the distal surfaces which remained convex (Fig. 1). According to Gaspard[14] this has to be considered in relation to the form of the masticatory cycle. For Kubein and Krüger[15] this uneven wear represents a difference in oscillation speed between the two teeth in contact, with the mesial tooth oscillating at a higher frequency than the distal tooth.

Fig. 1 – Interproximal two-body abrasion linked to masticatory forces and their cumulative effects observed in a Nubian adult individual (Mirgissa sample, 1890–1580 BC housed in Pessac, Gironde, France). Mesial surfaces are often concave whilst distal remained convex.

Another form of two-body abrasion which is independent of mastication is also described at interproximal level. Originally described by Siffre[16] in two molars of the Neandertal La Quina H5, it has the aspect of a fairly regular groove, usually located on or close to the neck of the posterior teeth (Fig. 2). Its origin is interpreted in different ways in the literature,[17] but is usually attributed to the frequent passage of a solid body like a tooth-pick between the teeth (made of bone, horn or plant material).[16–22] The reason for this action would be therapeutic, palliative or idiopathic. Less frequently, these grooves which are found exclusively in human fossil taxons[17] are located at the level of the anterior teeth.[23] Their presence in modern-day individuals, on the other hand, has not been much reported in the literature.[24] Note that this type of wear may also result from a three-body abrasion when mineral particles penetrate between the tooth and the solid moving body. It appears to increase the speed of wear and to produce deeper scratches.[22]

At the occlusal level, physiological two-body abrasive wear can theoretically occur since there is evidence of fleeting and inconsistent inter-dental contacts during swallowing and mastication.[25] However, a longitudinal study by Kaidonis et al.[26] in a sample of Australian aborigines contradicts this idea. These authors show that the definition of facets typical of two-body abrasion is not constant over time despite the continual influence of abrasive particles in the food. Thus the occurrence of this type of facet could be linked with frequent grinding episodes, independent of any masticatory action.

When two-body abrasion predominates, it is characterised by well-defined, smooth, shiny wear facets at sharp angles. The cusps and the free edges of the incisors are flat. When the dentine is exposed, it is at the same level as the enamel, with no margin.[3,9] Whether they are located on dental tissue, restorative material or on both at the same time, the facets come together, they match up and remain in close contact

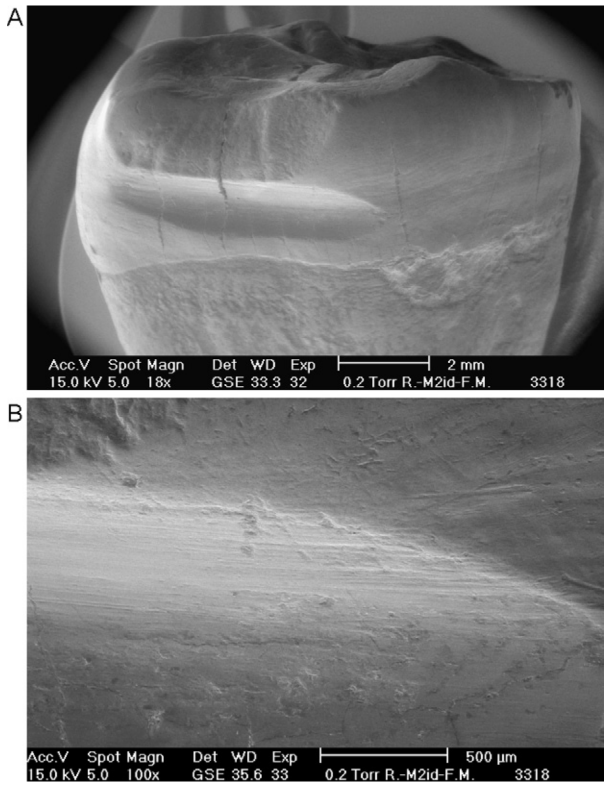

Fig. 2 – (A) Environmental scanning electron microscope (ESEM) micrograph of interproximal groove on the mesial facet of a second lower right molar belonging to the neandertal dental remains from the Rochelot cave (Saint-Amant-de-Bonnieure, Charente, France). (B) Microwear detail of the same groove as A at higher magnification showing parallel striations on the enamel.

during the small excursive mandibular movements.[3,9] This characteristic is fundamental when diagnosing this wear mechanism, especially in patients presenting with a parafunction during awake or sleep bruxism.[27,28]

It should be noted, however, that the presence of major wear should not systematically assume a diagnosis of this last pathology,[29] characterised by a grinding and/or involuntary and stereotypical clenching of the teeth, as some young individuals with confirmed sleep bruxism do not show major tooth wear.[30]

If the surfaces do not correspond exactly one with another or if there is a difference in the degree of wear between two opposing dental arches, then one or several other wear mechanisms prevail or exist in addition and should be looked for.[31] It may be acid dissolution in the dental tissue (erosion in the odontological sense) or three-body abrasion caused by the abrasive load of food in the exposed dentinal areas.[3,9] Differential diagnosis is often difficult. If possible, it can be refined by microscopic examination of the facets which can reveal parallel striations when two-body abrasive wear predominates.[32]

According to Every[33] and his theory of ''thegosis'' (from the Greek *thego*, to sharpen, to hone), another form of occlusal two-body abrasion can be considered as physiological. Every stated that most mammals, including Man, deliberately sharpen their teeth to use them as a weapon and to make them more efficient during mastication. This genetically determined ancestral behaviour is an indication of the aggressiveness in every individual which manifests itself during episodes of stress. In this case, two-body abrasion wear facets are formed which are independent of mastication.[34] For Murray and Sanson[35] this theory was proposed on the basis of various different points but is based on suppositions rather than facts.

Lastly, we should note that extra-masticatory two-body abrasion can sometimes follow certain rituals or certain tasks regularly carried out by past populations[36] but in modern populations too.[24] It gives rise to cuts, notches or chips, which may be vestibular, incisal or occlusal.

2.1.2. *Three-body abrasion*

Three-body abrasion is the displacement of two bodies, one across the other, with the interposition of abrasive particles which constitute the third body. In odontology and dental anthropology it is often called abrasion. In general it is associated with the size, the shape and the hardness of the interstitial particles. In tribology two types of three-body abrasion are distinguished, according to the proximity of the moving solid bodies[3,37]:

- when the two bodies are distant, the abrasive particles are free to move and they act like a slurry across all surfaces. Only a small proportion of particles (10%) are responsible for the three-body abrasion.[8] The surfaces of the two bodies do not correspond as they are not in direct contact,
- when the two bodies are sufficiently close together, the abrasive particles are gradually trapped between the surface of one or both bodies and are no longer in suspension. They are then carried away by the two bodies in movement causing specific types of grooves and striations, especially when the surfaces of these bodies are rough. Surfaces subjected to this type of wear sometimes do correspond one with another as the particles become an integral part of the bodies.

In the oral cavity, three-body abrasion can be generalised and/or localised. When it is generalised, it is associated mainly with the abrasive load of the food bolus, which affects all tooth surfaces during mastication. During this function, there are two phases that succeed one another and which correspond to the tribological model.[3,37] Their occurrence depends on the proximity of the opposing teeth and the dilaceration of the food bolus.

In the first crushing phase, the particles contained in the bolus are free to move around and preferentially abrase non-occlusal contact areas. On the vestibular and lingual surfaces where there is no bacterial plaque, friction by the tongue and the soft tissues also contributes to developing this wear. It is particularly visible in restorative materials like glass-ionomers or composites where abrasion of the matrices exposes the loads which eventually become dissociated.[3,37]

During the second sliding phase, the teeth come closer and closer together as the food bolus is shredded and the abrasive particles are gradually dragged in then trapped between their surfaces. They then form temporary and haphazardly arranged microscopic gouges, furrows, pits and scratches which when studied for microwear provide a great deal of information for the paleoanthropologist[38] and the odontologist[39] as their depth, length and width are characteristic of specific masticatory cycles and masticated foods (Fig. 3).[40] The rougher the dental tissue or restorative material, the more the particles have a tendency to become incorporated into the surface microgrooves. During this rapid and uneven masticatory phase, inter-dental connections are established around the occlusal contact areas. At the same time, the particles trapped between the teeth cause a three-body abrasion in the occlusal areas without contact.[3,37] Contacts persist during the swallowing phase and even afterwards, during self-cleaning movements of the teeth and the oral cavity. The cumulative effect of these mechanisms is to produce enamel surfaces that are blunted and smooth, with rounded edges.[3] When the dentine is exposed, its softness combined with its organic content produces differential wear with the enamel.[41] There is then a margin separating these two tissues as the dentine surfaces wear more quickly.[3,9,37] They become concave in shape and orangey brown in colour. Making a differential diagnosis between this and corrosive occlusal lesions is sometimes difficult (see Section 2.4 below); if possible, the diagnosis can be refined by microscopic examination of the surfaces which reveals a smear layer obstructing the tubuli when the wear is abrasive in origin.[32]

In ancient populations, three-body abrasion was associated mainly with mastication, sometimes called ''*demastication*''. It was ubiquitous, intense and progressed rapidly.[42–44] In these populations it involved opposing teeth and food that was not necessarily abrasive in itself but which contained particles that were harder than the dental tissue (phytoliths, quartz, amorphous silica).[45,46] Cusp morphology is gradually altered by a macroscopic process which exposes wear facets on the enamel then the dentine in the form of points and islets that gradually coalesce.[47,48] When individuals remain dentate and well balanced functionally, the topography of the occlusal plane can take on different forms, depending on diet and morphological factors such as the shape and size of the dental arch and the type of occlusion.[49] Traditionally, three forms are described. (1) Helicoidal, which is the most common in France, from the Neolithic to the Bronze Age[50] and from the Gallo-Roman period to the Middle Ages.[51] In Europe, it is also often found from the Middle Palaeolithic until the present day.[52,53] The total abrasion surface, normally the mandibular, takes the form of a double helicoid[54] in which the location of the worn flat surface depends on the progress of the occlusal wear.[55] When the large blade, oriented *ad vestibulum*, includes on each side the two premolars, the first molar (M1) and the mesial half of the second molar (M2), then the small blade, oriented *ad linguam*, includes the distal half of M2 and the third molar (M3), with the pitch of the helicoid oriented *ad planum* and located in the middle of M2 (Fig. 4). This particular topography results from masticating food that requires considerable muscular force[56] and a particular masticatory cycle.[57–59] Alongside these main factors, the differential wear associated with the chronology of tooth eruption[60,61] and the original orientation of the molars[58,59] are also relevant, as is the relative width of the dental arches[58,62–64] and the lesser tissue resistance in M1.[65,66] (2) the second form is the horizontal *ad planum* form with the flattening of the sagittal (Spee) and frontal (Wilson) compensation curves. This form characterises the occlusal

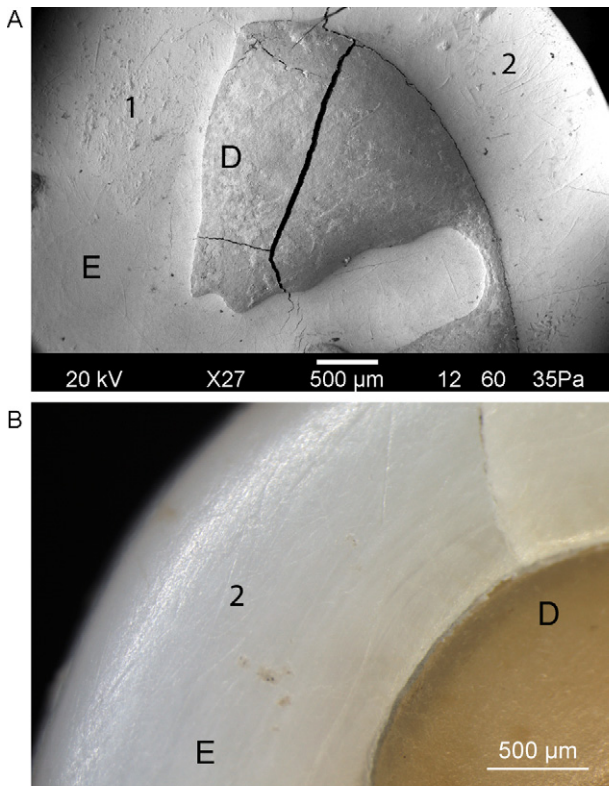

Fig. 3 – (A) SEM micrograph of occlusal surface of a first upper left molar in a medieval adult individual (Sains-en-Gohelle, Pas-de-Calais, France, 7–15th centuries). E = enamel, D = dentine. Top left is an area with a predominance of pits (1) and top right is an area with predominance of scratches (2). (B) Stereomicroscopy (50×) of the same molar as A in an other area showing on the left scratches (2) on the enamel. E = enamel, D = dentine.

Fig. 4 – Helicoidal occlusal plane in a medieval adult individual (Sains-en-Gohelle, Pas-de-Calais, France, 7–15th centuries). The topography that develops with wear results from masticating food that requires considerable muscular force and a particular masticatory cycle.

plane of the hunter-gatherers whilst in prehistoric agriculturalists the Wilson curves (*ad vestibulum* wear) were usually inverted as occlusal wear progressed.[67] In the Bronze Age, Maytié[50] estimates this at 1.4% in France compared with 95.5% for helicoidal wear. Curiously, Gisclard and Lavergne[68] found this form more often than helicoidal wear in certain sites in Languedoc. (3) the third form is the *ad vestibulum* form characterised by a high level of abrasion of the cusp supports for all the mandibular molars. This may be the result of the evolution of helicoidal wear if there is a "severe attrition syndrome"[64] but when it is generalised across the dental arch, it is an atypical form. Maytié[50] evaluates it at 3% in France, from the Neolithic to the Bronze Age.

In today's industrialised populations, three-body abrasive wear, although it is limited, is physiological wear when viewed in correlation with ageing and individual diets. It gives rise to wear facets where the surface area increases with age.[69] In the incisors, these surface areas are associated with proclusion/retroclusion movements. Meanwhile, the other teeth are associated with lateroclusion/medioclusion movements. In the premolars and molars, two types of facet coexist: working facets and non-working facets, both of which are functional.[69] They form during the different masticatory cycles and in turn they guide these cycles.[29,57,70–72]

When it is localised, generally at the cervico-vestibular level, three-body abrasion is basically associated with tooth brushing.[73] The abrasive particles in the toothpaste are the third body, interposed between the brush and the teeth. In some pathological cases accentuated by acid attack, the dentine in the roots is exposed to varying degrees and there is heavy wear in cases of iatrogenic brushing. In these cases, extended lesions or notches form around the exposed root dentine.[24] There is often associated hypersensitivity.[73]

2.2. *Adhesive wear*

This wear mechanism is associated mainly with metals and polymers and can occur when two bodies subjected to strong pressure slide one against the other.[3,6] From a tribological point of view, the surface asperities that come into contact undergo plastic deformation and can come together locally, as happens in cold welding. In such cases varying amounts of material are transferred from one surface to the other, depending on the distance separating the materials, their properties, their roughness, the pressure, the temperature or the environment.[6] This mass of transferred material may break up as the movements increase but not necessarily along the original line of fusion. If it is interposed between the two bodies, a three-body abrasion begins.[3,6]

In the oral cavity, this type of wear can theoretically occur. Indeed, two-body friction tests *in vitro* reveal a transfer of material onto the enamel or an analogue, from restorative materials such as amalgam,[74] gold[75] and some composite materials under great pressure.[76] Other results show that this type of wear can also occur between two poly(methyl methacrylate) surfaces.[77] In the oral cavity, however, adhesive wear is limited, thanks to the lubricating action of saliva, which reduces the friction coefficient. In addition, three-body abrasion caused by the food bolus tends to remove the layer of displaced material.[3]

2.3. *Fatigue wear*

When one surface under high pressure slides over another, a compression zone is created ahead of the movement whilst a tension zone is created behind. These deformations which concern the surface molecules can propagate in the subsurface of brittle materials causing ruptures to the intermolecular bonds.[6] Depending on the nature of the materials, micro-cracks may then be initiated around the damaged subsurface zone and propagate as the cycles are repeated. When propagation reaches the surface, fairly large fragments of material can become detached and interposed between the two surfaces in contact giving rise to three-body abrasion.[6] Generally, surface delamination is the result of interactions between abrasion, adhesion and fatigue mechanisms.

In the oral cavity, fatigue wear can occur on certain enamel occlusal contact surfaces subjected to considerable pressure, besides during mastication.[78] The high mineral content of this tissue means that it is harder than dentine but its high modulus of elasticity and its low tensile strength make it brittle. In Man, it is organised prismatically, and this controls microcrack propagation[79,80] which is least at occlusal level where the prisms are perpendicular to the surface and mineralisation is at a maximum.[41,81] When microcracks initiate in the enamel they cause delamination first of the interprismatic substance and then of the prisms[82] but they are unable to propagate into the dentine because of the enamel-dentine junction which disperses the stresses.[83]

For some authors, the formation of sub-vertical grooves at proximal level, which are frequently found in Neandertals,[84–87] is initiated by these microcracks (Fig. 5). The strength of axial[88] and/or lateral[85] forces in combination with a particular orientation of the Hunter-Schreger bands[86] and an acid environment[84] then amplify this mechanism to form veritable semi-circular radial grooves. Other authors[87] consider that the high frequency of these grooves on both anterior and posterior teeth showing little occlusal wear and no micro-cracks tends to invalidate these different sequential hypotheses.

In addition, the notion of fatigue is also central to the theory that tooth flexion initiates surface fragmentation in

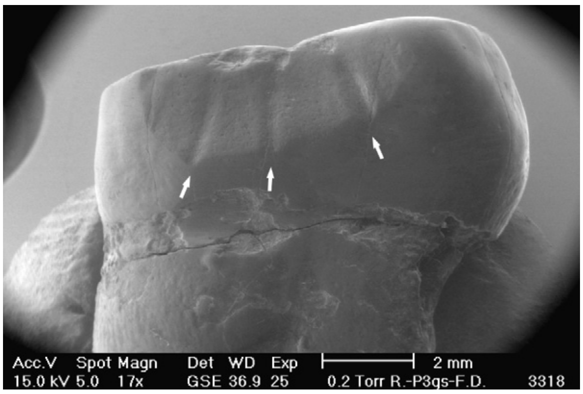

Fig. 5 – ESEM micrograph of sub-vertical grooves (white arrows) on the distal facet of a first upper left premolar belonging to the neandertal dental remains from the Rochelot cave (Saint-Amant-de-Bonnieure, Charente, France).

cervical enamel (abfraction).[89–91] Although various clinical and theoretical arguments have been put forward to justify this indirectly, a causal relationship nevertheless remains speculative.[92,93] Indeed, no non-carious cervical lesion of this type has been evidenced in past populations[94,95] and contemporary individuals with bruxism have no more abfraction lesions than others.[96]

2.4. *Corrosive wear*

Strictly speaking, tooth surface loss caused by chemical or electrochemical action is termed corrosion.[91] As far as terminology is concerned, it is often called erosion in dentistry (from the Latin verb *erodere*, to eat away). This may cause confusion with the tribological use of this term which is defined as the progressive loss of material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, impinging liquid or solid particles.[91] Tribochemical wear is caused when chemicals (acid, chelating agent) weaken the inter-molecular bonds of the surface and therefore potentiate the other mechanical wear process.[9,97] This situation can be particularly critical in cases of sleep bruxism where two-body abrasion following episodes of teeth clenching and/or grinding is often accompanied by intrabuccal acidity linked with gastroesophageal reflux disease (GERD).[98] Three-body abrasion linked with iatrogenic tooth brushing can also significantly aggravate occlusal and cervical lesions in an acid environment as surface molecules are driven away, only for the newly exposed surface to be immediately attacked by the corrosive environment.[3,73]

A diagnosis of corrosive wear is essentially based on the presence of concave cup-shaped zones, with rounded surfaces.[3,9,37,78] In the enamel, demineralisation of the prisms and the interprismatic substance forms a characteristic ''honeycomb'' structure whilst dissolution of the aprismatic enamel is more irregular.[99] The lesions are smooth and polished, without perikymata and with no variations in shade. In the dentine, the peritubular zones are affected before the intertubular zones, which enlarges the tubuli.[99] There is no deep-seated acid diffusion so that, in contrast to caries, the demineralised surface only concerns a thickness which is generally less than 100 μm. Concerning occlusion, the contact surfaces of opposing teeth do not correspond and restorations are generally not damaged, apart from glass-ionomers.[100] When the dentine is affected, differential diagnosis with three-body abrasion lesions is based on the location and the depth/width ratio of the cup-shaped areas of wear.[101] This ratio is greater than 0.25 and increases as the corrosive wear progresses, whereas it is less than 0.25 and varies little as the abrasive wear progresses if the nature of the food remains constant.[94] Whenever possible, diagnosis can be refined using scanning electron microscopy (SEM). The absence of smear layer on the tubuli suggests chemical origin rather than mechanical.[94]

In past populations, corrosive wear is reported only rarely. It is described, however, in a molar of a *Homo habilis* (OH 16, ca. 1 750 000) who fed on unripe fruit[102] and also in a pre-contact sample of New Zealand Maori[94] eating food that had been fermented.[32] For some authors[103,104] the origin of the lingual surface attrition of the maxillary teeth (LSAMAT) first described by Turner and Machado[105] in a sample from Brazil (4200–3000 BP) is partly corrosive as it is associated with acid regurgitations. For others[106–108] these particular lesions are not corrosive in origin and instead are linked with the consumption of abrasive food, like manioc.

In present-day industrialised populations, there is an increasing prevalence of corrosion resulting from food habits, especially in young individuals.[109,110] The corrosive agents involved here are acids of extrinsic and/or intrinsic origin, from non-bacterial sources. The main extrinsic sources are chemical environmental factors[111] or they are to be found in food.[112] These consist mainly of sodas, acid fruits, premix alcoholic drinks aimed at adolescents (alcopops), energy drinks, fruit juices, wine, etc., where the extreme acidity is rarely indicated. Some medical sources (ascorbic acid, acetylsalicylic acid) and some mouthwashes are also offenders.[110] The main intrinsic sources are regurgitations, GERD and vomiting, whether spontaneous (chronic alcoholism) or induced (anorexia-bulimia).[110] Finally, note that saliva plays an essential role in modulating corrosive wear, thanks to its buffer effect associated mainly with the presence of phosphate and bicarbonate ions which can compensate when pH values drop to so-called critical levels, i.e. pH of around 5.5.[110] In addition, it forms a protective protein film and has the ability to remineralise, which limits deleterious effects although without being able to prevent them.[2]

3. Scoring systems

Scoring systems for occlusal and interproximal wear can be qualitative and/or quantitative. Surface examination is carried out directly on teeth, photographs, drawings, replicas or computer reconstructions.[113] It can be visual or done with analogue and/or digital instruments. Scoring assesses tissue loss from an organ of which the primitive volume is unknown, and so dividing tooth wear into successive levels is a subjective process and varies with different authors. Nevertheless, it forms the basis of a vast number of classifications which can be used under certain conditions to determine food habits, paleodemography (age at death class) and the state of health of past populations. If some classifications are more frequently used[113,114] the main problem with different wear indices is that different populations cannot be directly compared. In some cases, classifications can also be used to follow the clinical evolution of wear, to carry out epidemiological studies, to establish links with certain pathologies or compensations of the masticatory apparatus, in specific classes of the current population.

3.1. *Qualitative and quantitative classifications*

Qualitative and quantitative classifications generally differ according to the field of study. In Odontology they can be used to code corrosive and abrasive wear. Almost all classifications used to determine the former type of wear derive from those of Eccles[115] and Smith and Knight.[116] They take into account the severity and the site of the erosion. However, they lack any standardisation and it is difficult to reconcile both clinical and experimental imperatives.[117] To overcome these limitations, Bartlett et al.[117] propose a Basic Erosive Wear Examination (BEWE) where the vestibular, occlusal and lingual faces of all the teeth, except the wisdom teeth, are examined for lesions. These are then classified according to one of four degrees of severity and the highest value in each sextant is used. The sum of these values then defines the degree of severity of the lesions due to acid attack and recommendations can then be formulated for the patient's subsequent care.

Classifications used to categorise abrasive wear mainly take into account the enamel facets, recording the mandibular kinematics of present-day populations which often show limited wear.[29,118,119] They can also be used for assessing the severity and progression of occlusal tooth wear.[120]

Anthropological classifications, first instigated by Broca,[121] are usually used for ancient populations, characterised by rapid and intense occlusal wear. They are unable to make clear distinctions between the first stages of enamel wear and are most often based on the amount of exposed dentine. Whilst some authors[13] have used the Broca scale,[121] others have taken it as a basis for proposing scales of 4–7 stages.[52] Currently, these classifications are only used for rapid coding of occlusal wear and they are often adjusted according to the populations being studied. With Murphy[47] a more elaborate system of measurement emerged. With an 8-point scale and many subdivisions, there were 25 levels with which to code wear across the entire dentition, irrespective of age. This classification was used for a long time and inspired Brothwell[122] but it was rather cumbersome and nowadays Scott's system[123] tends to be preferred when coding wear of molars in past populations.[114] This system is based on the amount of enamel that has disappeared rather than the amount of exposed dentine. In this way not only the intensity of tooth wear can be studied, but also the speed at which it occurred, and these two factors make it possible to study inter- and intra-population variability. When coding other teeth, Smith's system[67] is preferred.[114] As well as the rate of wear, the angle of the occlusal surfaces of the molars is determined. This system is one of several classifications[42,124] to associate different criteria such as the surface area of exposed dentine, the morphology and orientation of wear surfaces which as well as making isotopic or carious analyses possible can also be used to study food habits and technology in past populations. In these same populations, interproximal wear can sometimes be assessed even though it is difficult to code when the teeth are in place on their bone base. One method is to determine the reduction in length of a segment of worn arch and compare this value with values from segments without wear.[10,13,125,126] Another possibility is to measure the width of the proximal wear facet at the occlusal level and compare it with the occlusal[127] or proximal wear,[128] but the relation between these variables is only partial. Whilst interproximal attrition is associated mainly with the intensity and frequency of the masticatory forces, occlusal wear is influenced in addition by the abrasive properties of the food.[10]

3.2. *Qualitative and chronological classifications*

As soon as the chronological variability of tooth eruption was better understood, some authors established ratios for the relative differences in tooth wear in the same dental arch.[42,48,122,129–133] According to age, different tables were drawn up for the progress of wear in the dental arch, with the grading of abrasion according to date of tooth eruption being particularly remarkable in M1, M2 and M3. Indeed, the majority of authors were in agreement over the fact that abrasion of the M1 was greater than that of the M2, which was in turn greater than that of the M3.[123,131] This can be explained by the chronology of eruption, especially for M1 and M2 which demonstrate little variation between populations, whereas the eruption of M3 is more variable. Next, on the basis of the decreasing gradient of wear from M1 to M3, different chronological classifications were created to estimate the age at death of individuals from past populations. However, even though wear is increasing significantly with age in today's industrialised populations, care should still be taken when considering the age/tooth wear relationship especially in past populations. Wear varies significantly between different groups depending on their food and food preparation habits, especially since the first ''food revolution'' which occurred at the transition from the hunter-gatherer lifestyle to a food producer lifestyle,[67,134,135] but also since the second much more recent ''food revolution'', characterised by the consumption of food that is soft and not very abrasive.[42,136] Even though there is a strong relationship between these two variables, in individuals in the same population, the same generation and with the same food habits, the speed of abrasion is not constant over time. It varies according to tissues,[41] sex and occlusal function,[137] craniofacial morphology[138] and oro-facial musculature.[139–142]

4. Dental and skeletal compensations

The advance of occlusal and proximal wear modifies the distribution of occlusal stresses. This in turn leads to a change in the position of the teeth and a remodelling of the bone and cementum structures across the three spatial planes.[128] These compensatory mechanisms by the masticatory apparatus are universal[143] as they can be found in past populations, but also in modern industrialised populations, although in a more discrete form.[144] When the occlusion remains functional, the teeth undergo three types of migration (1) passive eruption at all levels (2) mesial drift at the posterior level and (3) lingual tipping at the anterior level, it therefore evolves physiologically with ontogenesis and the development of the wear. This pattern can be profoundly modified when there is edentation, carious and/or periodontal diseases (Fig. 6).

4.1. *Continuous eruption*

The idea that human teeth undergo continuous eruption throughout life was first proposed by Gottlieb[145] then developed further by other authors[13,146–148] although the actual biological mechanisms involved had not been completely understood or documented. Murphy[149] was the first to compare two samples from aboriginal Australians with and without wear and showed that this eruption was linked mainly to bone apposition in the alveoli (for 2/3) and cementum along the roots (for 1/3). He quantified it (4 mm in the sample with wear) and showed that it was not

Fig. 6 – Profoundly modified occlusion with edentation and periodontal diseases in a medieval adult individual (Sains-en-Gohelle, France, 7–15th centuries). Note that upper left molars have overerupted into open space.

associated systematically with major tooth wear. Thus according to the kinetics of occlusal wear and the way the phenomenon is expressed, three situations are possible.[150]

(1) When occlusal wear is heavy and progresses faster than the compensating tooth eruption, the anatomical and clinical crown heights decrease significantly. The occlusal vertical dimension (OVD) also decreases[149,151,152] whereas when at rest, interocclusal space (IS) increases.[150] This situation occurs when wear is at an advanced stage and it is mainly to the detriment of the dentine, which is less resistant than the enamel.[153,154] In the pulp chamber, reactional dentine sometimes forms too slowly and cannot prevent pulp effraction. Bacteria then spread to cause a chronic periapical inflammation often associated with severe bone lesions.[36,155,156]

(2) When occlusal wear is heavy but is compensated by continuous eruption of the teeth, OVD and IS do not vary significantly.[150] This situation has been demonstrated extensively from direct craniometric, radiological and/or histological measurements on various ancient samples from American Indians[157] (Knoll, 5000–4000 BC), Nubians[158] (1890–1580 BC), Romano-British[153,159,160] (100–400 AD), Anglo-Saxons[153,161] (700–900 AD), medieval individuals from Britain,[153] Finland[154,162] and Scotland,[163] Australian aborigines[164] and pre-industrial revolution Irish.[165] In terms of radiological observations, the distance between the upper edge of the inferior dental canal (IDC), a fixed reference point,[166] and the occlusal surface (OS) of the mandibular premolars and molars where wear occurs is constant whereas the distance between IDC and the cemento-enamel junction (CEJ) in these same teeth increases. In addition, the distance between IDC and the alveolar crest (AC) remains constant or increases slightly when bone apposition is concomitant with tooth eruption. In this latter case, promoted when wear progresses rapidly,[164] the distance between CEJ and AC remains constant, whereas it increases when eruption concerns the teeth only.[149,157] In periodontal terms, this continuous eruption leads to the epithelial attachment being relocated more apically, at the level of the cementum.[167] When the roots are exposed, we may also suspect bone atrophy or bone loss as a result of periodontal inflammation. Differential diagnosis can be refined by observing the aspect and the destruction of the interproximal bone septum. In health, it is smooth and forms convex to flat surfaces faciolingually.[168] In disease, the cortex is resorbed, and the surface becomes roughened.[152,163] The nutrient canals, which are normally small, become enlarged and can easily be seen. As resorption of the cortex continues, the underlying trabecular pattern of the cancellous bone is exposed.[168]

Lastly, note that continuous eruption of teeth to compensate for occlusal wear is also found in contemporary individuals with heavy occlusal wear.[169] Here again, although the height of the teeth decreases in anatomical terms, clinically speaking their height does not vary significantly.

(3) When occlusal wear is moderate and posterior dental stability is maintained, the OVD increases slightly throughout life[151,170–174] and IS decreases or remains constant.[150] This increase is suggestive of continuous eruption of the mandibular incisors which lead to a slight posterior mandibular rotation.[172] This usually occurs during the third decade of life.[172–174] In a British sample of determined age at death and with only moderate wear (Spitalfields, east London) Whittaker et al.[171] estimated that in 40 years the molars erupted 2.8 mm whilst the apex migrated coronally only 2.2 mm. This means that in one year, these teeth erupted 0.07 mm and that in 40 years 0.6 mm of cementum was deposited at the apex.

Finally, note that this eruption to compensate for occlusal wear can also be found in the deciduous dentition[175] and that it is not exclusive to the *Homo* genus having also been described in *Pongo*, *Gorilla*, and *Pan* genus.[176]

4.2. *Mesial drift*

The origin of physiological mesial drift of the posterior teeth has not been completely determined, but the role of the transseptal and supracrestal fibre systems is often mentioned.[177] It leads to a remodelling of the bone[178] and cementum[179] with distal apposition in areas of tension and resorption mesially in areas of compression. When heavy interproximal wear accompanies this drift, the length of the dental arches decreases significantly. This link has been repeatedly demonstrated and quantified in past populations.[10,13,57,125,126,155,157,158,180,181] Studying 9 mandibles from Australian aborigines, Begg[13] estimated that this reduction was about 10 mm, after eruption of the third molars. In a sample of native American Indians from New York state (10–19th centuries) Fishman[181] found a similar value, however Murphy[126] assessed it at less than half this in samples from Australian aborigines. This mesial drift is also found in present-day populations, at adolescence and in young adults, then it decreases with ontogenesis.[182–185] It brings about a reduction in the size of the dental arches of between 2 and 2.5 mm despite the absence of interproximal wear. According to Begg[13] and his ''attritional occlusion'' model, this absence of wear is responsible for the gradual development of malocclusions in present-day populations. Also, the growing frequency of dental crowding and third molar impaction or non-eruption is linked with a diet of soft foods. Some authors share these views[186–190] although others are less sure[191–193] and believe that the lack of space responsible for malocclusions is due to a reduction in masticatory strength, which leads in turn, by mechanomorphosis, to a reduction in the basal bone of the arches. The larger size of teeth that were not worn would have no influence. On the other hand, the high frequency of overcrowding found in an ancient sedentary population from the Copper Age (Roaix, France) tends to go against this idea, supporting instead a genetic origin.[194]

4.3. *Incisor lingual tipping*

In addition to continuous eruption and mesial drift of the posterior teeth, there is a third movement, lingual tipping, which can affect the anterior mandibular and/or maxillary teeth with wear and age. This change in axial inclination, which has not been extensively described in the literature, was first observed by Selmer-Olsen[195] in a Norwegian sample, then confirmed by metric and cephalometric studies also on ancient samples.[157,158,180,196–200] Depending on the arch under consideration, different situations occur: whilst Seddon[198] and Hasund[180] could detect no change in the axis of worn central mandibular incisors respectively in Romano-British (Poundbury, 4–5th centuries) and medieval Norwegian samples, Hylander[157] demonstrated significant lingual tipping of the central maxillary and mandibular incisors in a cephalometric study of American Indian skulls (Knoll, 5000–4000 BC). He also showed that the amount of inclination associated with wear was greater in the maxillary incisors. These same observations were made by Varrela[199] in a medieval Swedish sample, by Kaifu[200] in different prehistoric Japanese samples (Jomon, 5000–300 BC; Yayoi, 300 BC–AD 300), in medieval (Kamukura, AD 1333), premodern (Edo, 1600–1868 AD) or recent (1868 AD–1926 AD) samples and also by d'Incau and Rouas[158] in a Nubian sample (1890–1580 BC). On the other hand, Fishman[181] and also Mohlin et al.[187] found no significant inclination change in the maxillary incisors in samples of native Americans from New York state (10–19th centuries) and medieval Swedish samples respectively. Despite these divergences, most authors[157,180,195,200] nevertheless believe that this lingual tipping ensures that the proximal spaces caused by tooth wear are closed and also ensures that contact is maintained between adjacent teeth. In terms of mechanics, two tipping movements are theoretically possible[201]: in the first, the centre of rotation is more apical than the centre of resistance of the tooth. It is effective, but requires a considerable amount of energy. In the second, the centre of rotation is at the centre of resistance of the tooth. This is more economical and requires only a horizontal force at the level of the dental crown. It draws the apex towards the exterior and the free edge towards the interior. For some authors[125,157,195] this force originates in an imbalance between the action of the tongue and the lips, with the lips predominating. In modern-day populations where teeth undergo limited wear, a very slight antero-posterior movement of the maxillary incisors has been demonstrated by Fosberg[172] in a longitudinal study over 10 years and by Crétot[173] in a study of 723 individuals grouped by age class (15–22 years, 23–42 years, 43–80 years) and according to dento-facial morphology. Sarnäs and Solow[174] on the other hand, in a 5-year study, observed no significant change. Krogstad and Dahl[139] compared dento-facial morphology between a group of Norwegians with considerable tooth wear and a control group with limited or no wear. They demonstrated a verticalisation of the incisors in the first group. These results have been confirmed by other studies.[140–142] Lastly, we note that lingual tipping of the central incisors associated with tooth wear has also been observed in some great apes[176] and has been demonstrated indirectly in certain Hominid fossils, i.e. *Australopithecus robustus*[202] and Neandertals.[203]

5. Summary

In past populations tooth wear was ubiquitous, intense and progressed rapidly. It affected the occlusal surfaces with a three-body abrasion mechanism and profoundly changed the occlusal plane which, in the absence of edentation, usually took the shape of a double helicoid. The proximal surfaces, subjected to two-body abrasion, were also affected. In these same populations, by applying a scoring system for wear, diet and cultural change can be determined as well as the age at death of individuals. It is also possible to illustrate and monitor the evolution of certain dental and skeletal functional compensations in the masticatory apparatus: continuous eruption, mesial drift of the posterior teeth, incisor lingual tipping, especially of the maxillary teeth. These compensations, along with other factors, i.e. anterior mandibular rotation,[199] condylar growth,[157,204] a reduction in overbite[205] and in overjet,[205,206] are responsible for the genesis of the edge-to-edge bite (labiodontia) from an occlusion that was originally scissor bite (psalidontia) (Fig. 7).[13,62,143,149,155,157,200,204–207] These universal adaptations have also been described in certain present-day individuals with heavy tooth wear[140] and to a lesser extent in elderly people who have kept their teeth and remain balanced functionally,[173] however, they do not always result in the formation of an edge-to-edge bite.[139] Certain factors, such as the initial mesio-distal relation between the first mandibular molar and the first maxillary molar, seem to be determinant as despite the progress of tooth wear, a scissor bite persists in some dental class 2 prehistoric individuals.[205] These observations must also be compared with the fact that food has become more refined over time as have the associated technologies (use of chopsticks in Asia, and the fork in Europe) and this means that such physiological and ontogenic occlusal evolution is now virtually impossible.[208,209] On the other hand, in present-day industrialised populations overbite persists and when the force involved in eruption is not limited by the work involved in biting this sometimes leads to supraclusion of the incisors.[210] To this is added a growing prevalence of eating disorders (anorexia-bulimia), problems associated with consuming food and drinks that are too acid (soda), with awake or sleep bruxism, especially in the young. Types of tooth wear that had remained unchanged since the origin of humanity have undergone profound changes in a

Fig. 7 – Wear-related changes in dento-alveolar complex observed in a medieval adolescent individual with developing dentition (left) and an adult individual with extensive wear (right) (Sains-en-Gohelle, France, 7–15th centuries). Note continuous eruption, changes in incisor inclination and modification in anterior occlusion. Initial scissor bite during childhood is modified through edge-to-edge bite in adults with advanced wear.

very short space of time. Today's tribochemical pathological model has replaced the abrasive physiological model of the past.

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