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Account/Revue

Mineral studies in enamel, an exemplary model system at the interface between physics, chemistry and medical sciences

L'interface entre la physique, la chimie et l'odontologie au cours des dix dernières années : la contribution de l'émail

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ABSTRACT

Enamel is an exemplary material for physicochemical analyses of biological mineral. Hereditary and environmental enamel defects as well as secondary decay processes induce degradation and destruction of enamel matter. This exceptional mineralized tissue is unable to regenerate due to the loss of the cell forming enamel: the ameloblasts. Deciphering mechanisms of enamel degradation represent a scientific challenge of economic interest. The interface between physics, chemistry, and biomedical science has been initiated for a long time. An updated review of a classical and routinely available set of different techniques is proposed to illustrate the interface between oral sciences and physico-chemistry. Research in this field has greatly evolved over the past decade thanks to various extremely sensitive techniques in Materials Science available for translational research in biomedicine.

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RÉSUMÉ

L'émail dentaire est un matériau modèle pour appliquer une approche physicochimique. Des pathologies ou l'environnement peuvent induire une destruction, une dégradation ou des malformations amélaires. Contrairement à la plupart des autres tissus biologiques minéralisés, l'émail est incapable de se régénérer naturellement. Comprendre les mécanismes de dégradation de l'émail présente un intérêt scientifique et économique. Cette revue se propose de donner un aperçu bibliographique des travaux des dix dernières années. Les études de l'émail par des techniques physiques ou chimiques classiques et disponibles ont été présentées et commentées à la lumière d'exemples récents. L'interface entre la physique, la chimie et la science orale est très active depuis plusieurs décennies, avec un important regain au cours de ces dernières années en raison de l'accès à des techniques très sensibles de la science des matériaux.

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1. Introduction

Physico-chemistry offers efficient tools in the field of normal and pathological biomineralizations or nano-inorganics concretions which are complex to identify [1].The obtained data are discriminant for diagnosis, guiding the design specific therapeutic strategies [2]. Furthermore, physico-chemistry provides insights and breakthroughs in biology. Evidence of specific mineral morphology or composition may be evidence of physiological or pathological mechanisms. These mechanisms reveal conditions of the mineral formation. Minerals may show singular morphologies or surface states that prove an identified origin or cause for initial nucleation, such as the bacterial activity as the initiator of calcifications in prostatic stones [3].

Biominerals may be observed under “solid state” methodologies. In this domain, enamel is the best inorganic candidate for characterization by Materials Science techniques. Enamel is exemplary for calibrating physicochemical investigations. Indeed, enamel is the most mineralized biological tissue (97% mineral) and based on a non-collagenous matrix scaffold in contrast to bone or dentine.

Different from the two previous mineralized tissues, enamel loses its capacities to regenerate after the end of its mineralization. Consequently, the decay of enamel exposes patients to several complications. At the end, a definitive loss of normal dental behavior (mechanic, chemical endurance, etc.) may occur. Heavy and expensive surgeries could be the lone therapeutic issues. Additionally, prevalence of dental diseases has increased over the past 20 years. According to the World Health Organization [4], an estimated 5 billion people worldwide suffer from dental caries and in industrialized countries, the treatment of dental diseases accounts for 5–10% of total health care expenditure and remains a financial burden for societies.

The present review summarizes the last ten years of data on enamel based on physical, chemical, and materials characterization methodologies. This review is addressed to both the medical community and physicists. Each technique will be presented with the same design: basic science principles followed by a summary of its late applications in biology and enamel.

2. Biological patterns of enamel and amelogenesis

Enamel is original because of its highly organized crystalline architecture is preceded by a labile scaffold [5]. Enamel is made of 97% of mineralized calcium phosphate, namely hydroxyapatite (HAP), the remainder consisting of 3–4% of water and residual protein [6,7]. Amelogenesis results from the secretion of an acellular matrix by epithelial cells, the ameloblasts. Mineralization is completed during the maturation stage of ameloblasts which intervene in several ways by controlling the availability of ions for growing minerals while degrading the extracellular matrix scaffold.

Two structures, the intraprismatic and interprismatic enamel, are imbricated. With the same composition, they differ in their crystal orientation. The major component of intraprismatic and interprismatic enamel is hexagonal HAP crystals, space group symmetry $P6_3/m$, with lattice parameters $a = 9.43$ Å and $c = 6.88$ Å [8]. The basic unit of the enamel is HAP crystal of formula $Ca_5(PO_4)_3(OH)$ and presents numerous substitutions of Ca^{2+} and PO_4^{3-} [9]. In a biological context, the crystal surface is modulated by enamel matrix proteins (EMPs) chelation which controls the surface energy and crystal growth [10].

At first, crystals form mineral nanofibrils which align lengthwise and aggregate into fibrils which themselves will form thicker fibers. Fibrils and fibers will assemble in the intraprismatic and interprismatic enamel. Prisms present differing arrangements along the enamel thickness, which gives strong mechanical and physical properties to enamel continuously aggressed in the buccal environment. The boundary between intraprimastic and interprismatic enamel is a narrow space filled with an organic material and called the prism sheath. At both the internal and external limits of enamel, an aprismatic layer in which all crystals are parallel is described [11].

Several EMPs play a major role in enamel, notably three major species, amelogenins (AMEL), ameloblastin (AMBN), and enamelin (ENAM).

AMEL (90% of the total proteins) is a family of isoform proteins due to numerous alternative spliced RNAs. These proteins may be cleaved into different peptides in order to regulate further mineralization. They may be degraded by the extracellular proteolysis from specific enzymes. These peptides have a preponderant role in amelogenesis [12]. They are key mineralization proteins via the formation of labile nanospheres on the mineral surface. These nanospheres regulate the development of crystals and form a Ca^{2+} and PO_4^{3-} ion reservoir. Thus, the amount of amelogenin peptides control the thickness of enamel and their quality and supramolecular organization drive the crystal and prism pattern.

The second major peptide, AMBN (5% of total proteins) is expressed throughout amelogenesis. Located at the boundary between intra- and inter-prismatic enamel, AMBN has also been called sheathlin [13]. AMBN ensures the supracrystalline organization of enamel prisms and the initiation of mineralization [14,15].

ENAM (1% of the total proteins) is the immediate environment of the crystal, responsible for its growth and elongation [16]. The native protein inhibits the crystal growth while ENAM proteolytic products promote the formation of apatite, due to their association with amelogenins.

Knowledge on the mechanisms through which EMPs self-assemble, organize and modulate the crystal growth in a coordinated manner is progressively emerging. In general, hydrophobic domains are known to be responsible for the scaffold of the matrix, while their hydrophilic counterparts are involved in the regulation of crystal nucleation and growth. AMBN and ENAM bind AMEL nanospheres via lectin-type domains and therefore stabilize amelogenins within the matrix.

In summary, macromolecular self-assemblies of AMEL, AMBN, and ENAM control enamel morphogenesis and participate in the control of mineralization.

In the development of teeth, long and thin mineralized enamel beads are formed almost simultaneously with EMP

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