Regulation of enamel hardness by its crystallographic dimensions

Hazem Eimar, Elnaz Ghadimi, Benedetto Marelli, Hojatollah Vali, Showan N. Nazhat, Wala M. Amin, Jesus Torres, Ovidiu Ciobanu, Rubens F. Albuquerque Junior, Faleh Tamimi

A R T I C L E   I N F O
Article history:
Received 15 January 2012
Received in revised form 16 May 2012
Accepted 1 June 2012
Available online 8 June 2012

Keywords:
Enamel
Microhardness
Apatite
Nanocrystals

A B S T R A C T
Enamel is a composite biomaterial comprising a minor organic matrix (~2%) and a hierarchically organized inorganic ultrastructure (~96–98%). Surprisingly, to date there is no available information in the literature regarding the possible role of the enamel ultrastructure on the nanoscale level in tooth macroscopic properties. Understanding this relationship is of especial interest for restorative purposes in dentistry. Accordingly, this study was designed to investigate how enamel nanocrystals regulate its hardness. We performed microindentation analysis on 100 extracted human teeth. The tooth enamel hardness was quantified and correlated with changes in enamel chemical composition and crystallographic dimensions obtained from Fourier transform infrared spectroscopy and X-ray diffraction, respectively. Enamel hardness was not related to the variability in organic content, but was associated with the size of apatite crystals along the c-axis. This association followed the Hall–Petch model for polycrystalline materials, indicating that the optimal size of apatite nanocrystals (larger than the critical size) provides enamel with the greatest hardness, which enables teeth to survive the heavy wear over a human lifetime.

© 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Teeth should express optimal mechanical properties in order to maintain function as food masticators throughout the human lifetime. Each tooth consists of four distinct tissues: pulp, dentin, cementum and enamel. Tooth enamel is known to be the hardest material in vertebrate mammals [1]. Hardness is an extremely important mechanical property of tooth enamel since it defines its resistance to wear (attrition, abrasion and erosion) and enables the heavy duty performance of this tissue [2–4]. Understanding this unique mechanical property of tooth enamel is of especial interest in developing new dental restorative materials that match the physical properties of teeth [5–7].

Tooth enamel is a composite substance made up of a minor organic phase (less than 2%) and a major inorganic phase (around 96–98%) [8,9]. The organic phase is made up of non-collagenous phosphorylated proteins: amelogenin [8], enamelin [10], ameloblastin [11], amelin [12] and proteinases [13,14]. The inorganic phase is a hierarchically organized structure, exhibiting distinct structural entities on the micro-, meso- and nanoscales (Fig. 1) [15]. Microstructurally tooth enamel is composed of parallel ~5 µm thick rods (prisms) that span the entire thickness of the enamel [15]. The rods consist of well-packed carbonate apatite (CAP) nanocrystals [16,17]. Human tooth enamel crystals are hexagonal and contain relatively large amounts of carbonate ions (~2–5 wt.%) and small amounts of incorporated trace elements such as F, Cl, Mg, K, and Fe [18,19]. The carbonate of enamel CAP is di-vided into two types, type A and type B. Type ACAP (~11% of overall enamel CAP) is formed when the carbonate ion replaces the hydroxyl ion (OH−) within the crystal [20,21]. Type B CAP (~89% of overall enamel CAP) is formed when the carbonate ion replaces the phosphate ion (PO43−) within the crystal [21].

The crystal size of polycrystalline materials is known to influence their macroscopic physical and mechanical properties [22,23]. Previously we demonstrated that the size of enamel CAP nanocrystals determines the tooth optical properties [24]. Accordingly, variations in enamel crystallography on the nanoscale might also affect the macroscopic mechanical properties of tooth enamel. Surprisingly, to date there is no available information in the literature regarding the possible role of enamel crystallographic dimensions in tooth physical and mechanical properties. Understanding the above role is required in order to explain the mechanical behavior of enamel on higher scale levels, thus providing robust