The effects of immobilized carboxylic-functional groups on the dynamics of phase transformation from amorphous to octacalcium phosphate†

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ABSTRACT

The influence of carboxylic-functional groups (-COOH) on the phase transformation from amorphous calcium phosphate (ACP) to octacalcium phosphate (OCP) was investigated. 11-Mercaptoundecanoic acid, a carboxylic thiol, was immobilized on gold nanoparticles via covalent bond formation. Time-resolved static light scattering measurements indicated that a structural-reconstruction-type phase transformation occurred with or without the presence of -COOH on the nanoparticles. When it dispersed in calcium phosphate solutions, these nanoparticles inhibited the phase transformation dynamics and also changed the reaction path, forming HPO4-OH-layer-deficient OCP at pH 6.5 an intermediate phase, which did not show the typical OCP X-ray diffraction (XRD) peak at 2θ = 4.7°. This phase was not observed in the reference solution containing gold nanoparticles without bound -COOH. The HPO4-OH-layer-deficient OCP transformed to conventional OCP gradually, as revealed by XRD, nuclear magnetic resonance, and Raman analyses. Thus, the immobilized -COOH appeared to behave as a negative catalyst, resulting in the formation of the intermediate phase. Such a mechanism partially clarifies complex biomineralization processes, for example teeth enamel and dentin formation, in vivo.

Keywords: Biomineralization, calcium phosphate, phase transformation, early tooth formation, intermediate phase

INTRODUCTION

Biological organisms can construct complex functional hybrid structures from inorganic minerals and organic materials, such as nacre and bones (Mann 2001; Sunagawa 2005; Weiner and Dove 2003). During formation of these organs, organic molecules, polypeptides, and proteins act as templates for mineral nucleation and growth (Nudelman et al. 2013; Sunagawa 2005; Veis 2003), by providing preferential sites for mineral nucleation and control of the orientation of the precipitated crystals (Hamm et al. 2014). Some organic functional groups, such as -COOH, interact with Ca ions (Addadi et al. 2003; Gebauer et al. 2008; Falini et al. 1996). These groups greatly influence the nucleation and growth of Ca-containing minerals, particularly during amorphous phase formation (Addadi et al. 2003; Gebauer et al. 2008; Falini et al. 1996).

Tooth enamel is the hardest material in vertebrates (Nylen et al. 1963; Sunagawa 2005). It comprises highly organized hydroxyapatite (HAP) crystals elongated along their c-axis with a ribbon-like morphology. This structure is a proposed pseudomorph of octacalcium phosphate (OCP) (Brown et al. 1962; Iijima et al. 1992; Nelson et al. 1989; Wang and Nancollas 2008), which contains very few matrix proteins (Sunagawa 2005). When a tooth forms, HAP mineralization is aided by numerous organic molecules, whose roles have been investigated extensively. HAP mineralization is accelerated by polypeptides rich in -COOH such as dentin matrix protein (He et al. 2003). Tsui et al. 2008 also showed that soluble artificial proteins rich in -COOH accelerate the phase transformation from amorphous calcium phosphate (ACP) to HAP. Furthermore, self-assembled organic monolayers with terminal -COOH can form on noble metal substrates and facilitate nucleation of calcium phosphate (CP) in pseudo-physiological solutions (Dey et al. 2010; Nonoyama et al. 2011). Among the -COOH containing materials, citrate is known to have a definitive effect on the formation of HAP (Delgado-Lopez et al. 2012, 2014; Hu et al. 2010; Xie and Nancollas 2010).

However, the role of carboxylic rich materials in HAP precursor mineralization processes, such as those for OCP, remained unclear until a recent investigation indicated that they can alter the OCP structure through the modification of the HPO4-OH layer (Davies et al. 2014). To the best of our knowledge, there have been few studies on the phases of ACP–OCP transformation in the presence of organic materials rich in -COOH, despite the fact that this transformation is essential in the early stages of tooth enamel formation (Zhao et al. 2012). In this study, immobilized -COOH were prepared using 11-Mercaptoundecanoic acid [MUA: HS(CH2)10-COOH]. The sulfur atoms of MUA covalently bind with gold atoms, forming a self-assembled carboxyl-termi-