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Synthesis of metal ion–histidine complex functionalized mesoporous silica nanocatalysts for enhanced light-free tooth bleaching

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ABSTRACT

Several metal ion–histidine complex functionalized mesoporous silica nanoparticles (MSN) were synthesized and utilized as efficient catalysts for enhanced and light-free tooth bleaching. Fe(II), Mn(II), and Cu(II) ions were successfully immobilized in histidine-functionalized MSN and their catalytic abilities against discoloration of a dye (Orange II) in both test tubes and extracted tooth models were compared and discussed. Through direct observation of test tubes and calculation of mean color changes of extracted teeth we concluded that Fe(II)–his–MSN exhibited better catalytic competence than Mn(II)–his–MSN and Cu(II)–his–MSN because of its intrinsic redox ability. In test tubes Orange II was completely degraded within 6 h when Fe(II)–his–MSN was used as the catalyst. For the extracted tooth model the presence of Fe(II)– or Mn(II)–his–MSN significantly enhanced the efficacy of tooth bleaching for three regions, the enamel, outer dentin, and inner dentin, of stained teeth compared with H_2O_2 alone. Furthermore, unlike current tooth bleaching techniques that need an LED or laser to catalyze H_2O_2 bleaching, we demonstrated a light-free tooth bleaching system using Fe(II)–his–MSN as an efficient and reliable catalyst.

1. Introduction

Tooth discoloration can have a negative impact on self-image and self-confidence. Dental assistance to cosmetically improve tooth discoloration is widely offered but has limited effectiveness for certain types of discoloration. The causes of tooth discoloration can be classified as extrinsic, intrinsic, and internalized discoloration [1]. Extrinsic stains can easily be corrected through routine prophylactic procedures, microabrasion, or macroabrasion. However, improvement of intrinsic discoloration requires tooth bleaching. Materials currently used for tooth bleaching are based on hydrogen peroxide (H_2O_2) as the active agent. Hydrogen peroxide can be applied directly or released from the decomposition of carbamide peroxide or sodium perborate [2]. Irrespective of the bleaching agent used, tooth bleaching has limitations for severely discolored teeth [3]. A thermocatalytic technique, which consists of applying heat or light (an LED or laser) to activate the bleaching agent, is frequently used to enhance the bleaching efficiency of these materials [4]. However, cervical root resorption is a possible serious consequence of this technique [5], with reported prevalences of 7% or 3.9% after 1–8 years follow-up [6]. Because cervical root resorption is usually asymptomatic and is often only detected by sporadic radiographic examination [7], tooth extraction may be required in the case of the formation of large lesions. To enhance tooth bleaching efficiency a new catalyst which does not use heat or light needs to be developed.

Mesoporous silica nanoparticles (MSN) have shown great potential as biomaterials because of their large surface area and pore volume, uniform particle and pore size, and ordered structure. In addition, abundant silanol groups on the surface allow further functionalization, and functionalized MSN have been used in many catalytic reactions. For example, (1) carbonyl activation (e.g. aldol and Henry reactions) using 3-[2-(2-aminoethylamino)ethylamino]-propyl (AEP) and ureidopropyl (UDP) functionalized MSN [8], (2) coupling reactions (e.g. Suzuki–Miyamura reaction) using Pd-loaded mercaptopropyl (MP) functionalized SBA-15 [9], and (3) enantio-selective hydrogenation using Ru complex functionalized

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SBA-15 [10]. For H_2O_2-associated redox reactions most attention has been given to mesoporous metal oxides (known as Fenton catalysts) due to their intrinsic photo-electronic properties [11,12]. These materials have shown a good ability to catalyze redox reactions, but light is needed. Enzyme-immobilized mesoporous materials have also been used [13], however, the ready denaturation and the long reaction time of enzymes usually result in low efficiency. Therefore, metal complex functionalized MSN could be an alternative for light-free and effective H_2O_2-associated redox reactions. Most importantly, many reports have proved that MSN-based biomaterials exhibit excellent biocompatibility for biomedical application as drug and gene delivery carriers [14,15], biosensors [16], and biomarkers in cell function studies [17–19]. However, to the best of our knowledge no prior study has reported on using functionalized MSN as a biocatalyst for biomedical applications, especially not for dental applications.

In this work we synthesized MSN with different metal–histidine complexes, including Fe(II)–, Cu(II)–, and Mn(II)–histidine, via co-condensation of histidine-containing silane. Characterization of the metal ion–histidine complex functionalized MSN using powder X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and nitrogen sorption analysis revealed that the synthesized materials exhibited a worm-like mesostructure, uniform particle morphology, and large surface area. Furthermore, inductively coupled plasma (ICP) and TEM energy dispersive X-ray spectroscopy (EDS) results confirmed successful loading and an uniform distribution of metal ions in histidine–MSN. The metal ion–histidine complex functionalized MSN were further used as a catalyst for tooth bleaching without light irradiation (e.g. LED or laser). Fe(II)–histidine–MSN exhibited a higher efficiency for tooth bleaching than Cu(II)– or Mn(II)–histidine–MSN.

2. Experimental

2.1. Synthesis of metal ion–histidine complex functionalized MSN

A histidine-containing silane was first prepared following a published procedure [20]. Briefly, triethylamine (0.966 ml, 9.5 mmol) and ethyl chloroformate (0.55 ml, 50 mmol) were added to a cooled (0 °C) solution of di-boc-histidine (1 g, 2.7 mmol) in chloroform (15 ml) and stirred for 15 min. Subsequently (3-aminopropyl)triethoxysilane (APTES) (1 ml, 4.5 mmol) and triethylamine (0.966 ml, 9.5 mmol) were added and the solution was stirred at 0 °C for 90 min. The cold mixture was then added to dichloromethane and the solvent was removed using a rotatory evaporator.

A surfactant cetyltrimethylammonium bromide (CTAB) (1.0 g) and NaOH (2 N, 3.5 ml) were added to distilled water (480 ml) and the mixture was heated to 80 °C. To this solution was added the histidine-containing silane (4.2 mmol in 0.5 ml of chloroform) before the addition of tetraethoxysilane (TEOS) (5 ml). Both histidine–silane and TEOS were added drop by drop at a rate of 0.5 ml min^{-1}. After reaction at 80 °C for 2 h the white precipitate was collected and dried under vacuum. To remove the surfactant the as-synthesized histidine-functionalized MSN (1.0 g) was added to a solution containing 1.0 ml of concentrated HCl and 150 ml of methanol, followed by refluxing at 60 °C for 6 h. The surfactant-free material, termed as his–MSN, was washed with methanol and distilled water and then dried under vacuum. Metal ions including Fe(II), Mn(II), and Cu(II) were incorporated into the his–MSN by immersion of 0.5 g his–MSN in 150 ml of various aqueous solutions containing different metal ions ($FeCl_2{\cdot}4H_2O$, $Mn(NO_3)_2{\cdot}xH_2O$, and $CuCl_2{\cdot}2H_2O$, with the concentrations of the metal chlorides kept at 19.2 mmol) with stirring at room temperature for 24 h. The samples, termed *M*–MSN (*M* = Fe(II), Mn(II), or

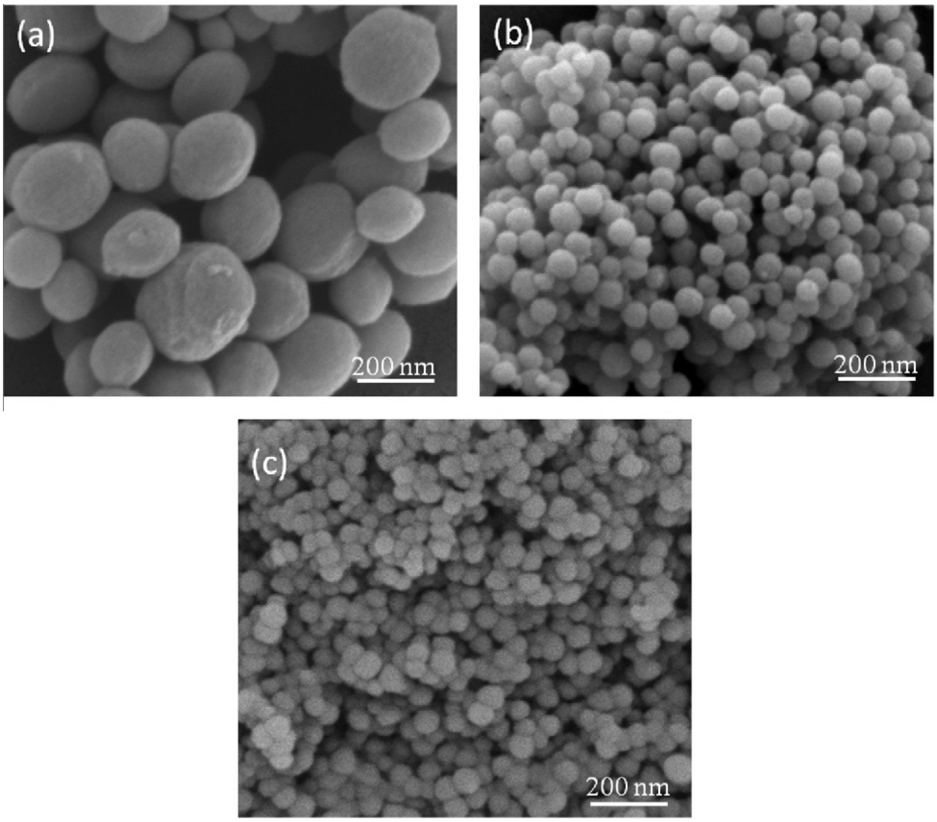

Fig. 1. SEM photographs of (a) MSN, (b) his–MSN, (c) Fe(II)–his–MSN.