Bioactive SrO–SiO₂ glass with well-ordered mesopores: Characterization, physiochemistry and biological properties

Chengtie Wu a,b,* , Wei Fan b, Michael Gelinsky a, Yin Xiao b, Paul Simon c, Renate Schulze d, Thomas Doert d, Yongxiang Luoa, Gianarelio Cuniberti a,e

Abstract

For a biomaterial to be considered suitable for bone repair it should ideally be both bioactive and have a capacity for controllable drug delivery; as such, mesoporous SiO₂ glass has been proposed as a new class of bone regeneration material by virtue of its high drug-loading ability and generally good biocompatibility. It does, however, have less than optimum bioactivity and controllable drug delivery properties. In this study, we incorporated strontium (Sr) into mesoporous SiO₂ in an effort to develop a bioactive mesoporous SrO–SiO₂ (Sr–Si) glass with the capacity to deliver Sr²⁺ ions, as well as a drug, at a controlled rate, thereby producing a material better suited for bone repair. The effects of Sr²⁺ on the structure, physiochemistry, drug delivery and biological properties of mesoporous Sr–Si glass were investigated. The prepared mesoporous Sr–Si glass was found to have an excellent release profile of bioactive Sr²⁺ ions and dexamethasone, and the incorporation of Sr²⁺ improved structural properties, such as mesopore size, pore volume and specific surface area, as well as rate of dissolution and protein adsorption. The mesoporous Sr–Si glass had no cytotoxic effects and its release of Sr²⁺ and SiO₄⁴⁻ ions enhanced alkaline phosphatase activity – a marker of osteogenic cell differentiation – in human bone mesenchymal stem cells. Mesoporous Sr–Si glasses can be prepared to porous scaffolds which show a more sustained drug release. This study suggests that incorporating Sr²⁺ into mesoporous SiO₂ glass produces a material with a more optimal drug delivery profile coupled with improved bioactivity, making it an excellent material for bone repair applications.

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1. Introduction

Biomaterials with properties suitable for bone regeneration need to be bioactive, and at the same time possess the capacity for controlled drug delivery [1–3]. To this end, a number of different materials, such as inorganic bioglass [2,4,5], calcium phosphate ceramics [6] and polymers [7], have been studied for their suitability in bone tissue repair. Over the past several years, mesoporous SiO₂ has received a significant amount of attention. The chief advantage of mesoporous SiO₂ is that this material has, as the name implies, a highly ordered mesoporous structure, large surface area and pore volume – qualities that give it an excellent drug release profile [8,9]. For bone repair applications, however, the material’s bioactivity and controllable drug delivery properties are less than optimal [2,10,11]. Vallet-Regi et al. have been able to improve the controlled drug delivery of mesoporous SiO₂ by manipulating the mesoporous structure, i.e. the pore size, as well as certain surface modifications [11–14]. Despite these advances, there still remains room to improve both the bioactivity and controlled drug delivery by mesoporous SiO₂.

It is known that strontium is an important trace element in human bone and strontium ranelate has been used for treatment of osteoporosis. Sr²⁺ was found to induce osteoblast activity by stimulating bone formation and reducing bone resorption [15–17]. It has a great affinity for bone tissue and is incorporated into the bone matrix by two mechanisms: (i) surface exchange involving the incorporation of Sr²⁺ into the crystal lattice of the bone mineral; and (ii) ionic substitution whereby Sr²⁺ is taken up by ionic exchange with Ca²⁺ [18]. For this reason, Sr²⁺ has been incorporated into bioactive ceramics and traditional bioactive non-mesoporous glass to further improve their bioactivity [19–23]. However, to
the best of our knowledge, there are no previous reports describing the incorporation of Sr\(^{2+}\) into mesoporous SiO\(_2\). We hypothesized that Sr-doped mesoporous SiO\(_2\) glass could deliver controlled doses of Sr\(^{2+}\) into the biological medium, thereby enhancing bone cell activity. An earlier study shows that the dissolution of drug carriers is one of the most important factors influencing the rate of drug release [24]. We therefore hypothesized that the incorporation of Sr\(^{2+}\) into mesoporous SiO\(_2\) would also modify its structure and rate of dissolution, thus enhancing the controlled drug delivery. The aim of this study was therefore to incorporate Sr\(^{2+}\) into mesoporous SiO\(_2\) in order to develop a bioactive mesoporous Sr–Si glass with an improved drug delivery profile and therefore better suited for bone repair applications; here we describe the effects of Sr\(^{2+}\) on mesoporous structure, physiochemistry, drug delivery and biological properties.

2. Materials and methods

2.1. Preparation and characterization of mesoporous SrO–SiO\(_2\) glasses powders

A series of four mesoporous SrO–SiO\(_2\) glass species, with different chemical compositions (molar compositions: 0SrO–100SiO\(_2\), 2.5SrO–100SiO\(_2\), 5SrO–100SiO\(_2\) and 10SrO–100SiO\(_2\), labeled as 100Si, 2.5Sr–100Si, 5Sr–100Si and 10Sr–100Si, respectively), were prepared by a modified template-induced and self-assembling method, using nonionic block copolymer EO\(_{20}\)PO\(_{70}\)EO\(_{20}\) (P123) [9]. In a typical reaction of 10Sr–100Si, 3.34 g of Sr(NO\(_3\))\(_2\) (Sigma–Aldrich) was dissolved in 30 ml of ddH\(_2\)O to obtain a Sr\(^{2+}\) containing slurry. Twenty grams of P123 (\(M_w = 5800\); Sigma–Aldrich) was dissolved in 300 ml of ethanol under stirring for 1 h, after which 33.5 g of tetraethyl orthosilicate (TEOS, 98%; Sigma–Aldrich), the aqueous Sr(NO\(_3\))\(_2\) solution and 5.0 g of 0.5 M HCl were added to the P123–ethanol solution and stirred in a sealed beaker at room temperature for 24 h. The resulting solution was introduced into eight Petri dishes for an evaporation-induced self-assembly process, and the dry gel calcined at 700 °C for 5 h, resulting in the 10Sr–100Si powders. Other Sr–Si materials (100Si, 2.5Sr–100Si and 5Sr–100Si) were prepared by the same method but with differ-
ent amounts of Sr(NO$_3$)$_2$ dissolved in 30 ml of ddH$_2$O. After calcination, the Sr–Si glass was ground and sieved to 300 meshes for further testing. The particle sizes of the glass powders thus produced were less than 45 µm (see the inset image of Fig. 7a).

The phase composition, surface morphology and inner microstructure of the calcined Sr–Si glass were analyzed by wide-angle X-ray diffraction (XRD), small-angle XRD, transmission electron microscopy (TEM), scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS). TEM of the samples was performed using a FEI Tecnai 10 electron microscope (FEI Company, Eindhoven, NL) with an LaB$_6$-source at 100 kV acceleration voltage. Images were recorded with a Tietz slow scan CCD F224HD TVIPS camera (2000 × 2000 pixels, pixel size 24 µm, digitization 16 bit) with an active area of 49 mm × 49 mm. (Tietz Video and Image Processing Systems GmbH, Gauting, Germany). Brunauer–Emmett–Teller and Barret–Joyner–Halenda analyses were used to determine the specific surface area, the nanopore size distribution and the pore volume by N$_2$ adsorption–desorption isotherms.

Fig. 3. Small-angle XRD patterns for the mesoporous Sr–Si glasses powders with different Sr contents. (a) 100Si, (b) 5Sr–100Si and (c) 10Sr–100Si. 10Sr–100Si has most obvious peaks at 2θ = 1.25°. The diffraction peaks are indicated by arrows.

Table 1

<table>
<thead>
<tr>
<th>Materials</th>
<th>Average pore size (nm)</th>
<th>Specific surface (m$^2$ g$^{-1}$)</th>
<th>Total pore volume (cm$^3$ g$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Si</td>
<td>2.8</td>
<td>6.8</td>
<td>0.01</td>
</tr>
<tr>
<td>2.5Sr–100Si</td>
<td>4.0</td>
<td>7.0</td>
<td>0.01</td>
</tr>
<tr>
<td>5.0Sr–100Si</td>
<td>4.8</td>
<td>6.0</td>
<td>0.01</td>
</tr>
<tr>
<td>10Sr–100Si</td>
<td>5.4</td>
<td>209</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Fig. 4. Nitrogen adsorption–desorption isotherm and pore size distribution of 10Sr–100Si mesoporous glass powders.

Fig. 5. Protein (BSA) absorbance for Sr–Si mesoporous glass powders with different Sr contents in BSA-containing SBF.
2.2. Physicochemical properties of mesoporous Sr–Si glass powders in protein-containing simulated body fluids

To evaluate the protein adsorption and the dissolution rates of mesoporous Sr–Si (mSr–Si) glass in a biological environment, simulated body fluids (SBF) were prepared according to Kokubo and Takadama [25]. Bovine serum albumin (BSA) was dissolved in the SBF solution to a final concentration of 1 mg ml\(^{-1}\). mSr–Si glass powders were immersed in the BSA/SBF solution (0.3 g per 200 ml) and incubated at 37°C for 1, 3, 6, 8, 24, 48 and 72 h. Protein adsorption was determined by ultraviolet (UV) spectrophotometry at 280 nm, by the difference in BSA concentration in the SBF before and after soaking (UV min-1240, Shimadzu, Japan). The release of Sr\(^{2+}\) and SiO\(_4^{4-}\) ions from the mSr–Si glass particles into the SBF was determined by atomic emission spectrometry (Perkin–Elmer Optima 7000DV). The pH value of SBF solution was tested by a pH meter and the microstructure of the mSr–Si glass particles after soaking was characterized by SEM (Jeol JSM 6510). All samples were tested in triplicate.

2.3. Rates of drug delivery by the mesoporous Sr–Si glass powders

Dexamethasone (DEX) was selected as the model drug in this study. The DEX was loaded into the mSr–Si glass particles by dissolving DEX in water to a final concentration of 50 \(\mu\)g ml\(^{-1}\). 0.50 g of mSr–Si glass particles was soaked in 50 ml of DEX solution under stirring for 12 h. The DEX-loaded glass particles were collected by centrifugation at 4500g for 15 min, then dried at 60°C for 24 h. To determine the amount of DEX loading in the mSr–Si glass particles, 1.5 g of DEX-loaded and non-loaded glass particles were calcined at 700°C for 1 h at a heating rate of 5 °C min\(^{-1}\). The amount of DEX loaded was calculated by the weight difference tested by a high precision balance between the non-loaded and DEX-loaded Sr–Si glass after heat treatment. The loading efficiency was calculated as the ratio of the loaded DEX and total amount of DEX in the aqueous solution. The assay was performed in triplicate.

To determine the DEX release from the mSr–Si glass particles, 40 mg of DEX-loaded mSr–Si glass was soaked in 4 ml of PBS at 37°C for 1, 3, 6, 8, 10, 24, 72, 168, 336, 504 and 672 h. At each time point, 2 ml PBS solution was taken off to quantify the concentration of released DEX by UV spectrophotometry at 240 nm. The PBS solution was topped up with 2 ml of fresh PBS every time 2 ml was taken off for assaying. Three samples for each material were assayed to calculate mean and standard deviations.

2.4. Cytotoxicity evaluation of the mesoporous Sr–Si glass powders

The bone marrow samples (\(n = 5\)) for isolation of human bone mesenchymal stem cells (BMSCs) were obtained from patients undergoing elective surgery at The Prince Charles Hospital, Brisbane, Australia, after informed consent had been given. BMSC cultures were carried out according to previous publications [26]. The extracts of mSr–Si glass were prepared in culture medium according to International Standard Organization (ISO/EN) 10993-5 [27], by adding mSr–Si glass particles to serum-free DMEM culture medium at a final concentration of 50 mg ml\(^{-1}\). After incubating at 37°C for 24 h, the mixtures were filtered and the supernatants collected. Serial dilutions of extracts (25, 12.5, 6.25 and 3.125 mg ml\(^{-1}\)) were prepared using serum-free DMEM medium (without l-glutamine or ascorbic acid). The diluted extracts were filter sterilized and used for subsequent BMSC cell culture experiments. The ionic concentrations of the extracts were measured by atomic emission spectrometer (Perkin–Elmer Optima 7000DV). BMSCs were seeded at a density of 3 \(\times\) 10^4 cells well\(^{-1}\) into a 96-well plate with regular DMEM medium and incubated for 24 h, after which the medium was removed and replaced by 50 \(\mu\)l of DMEM medium supplemented with 20% FCS and 50 \(\mu\)l of diluted extracts. For a blank control, 100 ml of culture medium supplemented with 10% FCS but without the addition of diluted extracts was used. The corresponding concentrations of SiO\(_4^{4-}\) and Sr\(^{2+}\) ions of the mixture (extract and medium) for cell culture are listed in Table 2. The cells were incubated at 37°C in 5% CO\(_2\) for 7 days.
To assess cell toxicity, an MTT assay was performed by adding 20 µl of 0.5 mg ml⁻¹ of MTT solution (Sigma-Aldrich) to each well and incubated 37 °C to form formazan crystals. After 4 h, the media was removed and the formazan solubilized with 100 µl of dimethyl sulfoxide (DMSO). The absorbance of the formazan-DMSO solution was read at 495 nm on a plate reader. Two separate MTT assays were performed with each sample. Results were expressed as the absorbance reading from each well minus the optical density value of blank wells.

2.5. Alkaline phosphatase activity of BMSCs cultured with mesoporous Sr–Si glass powders

Osteogenic differentiation was assessed by measuring a time course of alkaline phosphatase (ALP) activity of the BMSCs cultured with the extracts from the four mSr–Si glass species. BMSCs were seeded at a density of 5 × 10⁴ cells well⁻¹ into a 24-well plate and incubated for 24 h. The culture medium was then removed and replaced with 500 µl of DMEM medium supplemented with 20% FCS and 500 µl of diluted extracts. Culture medium supplemented with 10% FCS without the addition of diluted extracts was used as a blank control. The cells were incubated at 37 °C in 5% CO₂ for 14 d and the medium changed every 3 days. On day 14 the total protein was harvested by lysing the cells with 0.5 ml of 0.2% Triton X-100. The cell lysates were transferred into 1.5 ml tubes and sonicated, then the samples were clarified by centrifugation for 15 min at 14,000g at 4 °C and the supernatant transferred to fresh tubes. ALP activity in each sample was measured in a 96-well plate using an ALP activity assay kit (BioAssay System Com., Hayward, CA, USA). Optical density (OD) was measured at 405 nm on a plate reader. The ALP activity was expressed as ΔOD₄₀₅nm min⁻¹ µg protein⁻¹.

2.6. Preparation, characterization and drug delivery of mesoporous Sr–Si glass scaffolds

We have found that 10Sr–100Si mesoporous glasses have improved physiochemistry and drug delivery property. Therefore, 10Sr–100Si mesoporous glasses were selected to prepare scaffolds.
100Si (no Sr) scaffolds was prepared for the control material. The scaffolds were prepared using polyurethane template method according to our previous publication [1], in which mesoporous glasses were coated on the polyurethane foam to duplicate the porous structure. The polyurethane foam was then burned out to leave porous mesoporous glass scaffolds. The scaffold morphology and pore structure were observed by optical microscopy and SEM. The porosity of the obtained scaffolds was tested by Archimedean methods.

To investigate the drug delivery of the scaffolds, DEX loading and release from the scaffolds were tested using similar method described in Section 2.3.

2.7. Statistical analysis

The data are expressed as means ± standard deviation for all experiments and were analyzed using a one-way analysis of variance with a post hoc test. A p-value of <0.05 was considered statistically significant.

3. Results

3.1. Characterization of mesoporous Sr–Si glass powders

Wide-angle XRD analysis showed that the four Sr–Si glass species had no sharp diffraction peaks (Fig. 1). The diffraction patterns of 100Si, 2.5Sr–100Si and 5Sr–100Si had a wide SiO2 peak with low intensity, but this peak was not obvious for 10Sr–100Si. Two minor α-SrSiO3 peaks appeared in the pattern of 5Sr–100Si (Fig. 1).

TEM analysis showed that the Sr–Si glass particles had well-ordered mesoporous channel structures (Fig. 2). The 10Sr–100Si (Fig. 2c and d) appeared to have a more mesoporous structure than did the Sr–Si glass particles with lower Sr2+ content and pure SiO2 glasses (Fig. 2a and b). The periodicity of the lattice is approximately

![SEM images for (a) 100Si, (b) 2.5Sr–100Si, (c) 5Sr–100Si and (d) 10Sr–100Si powders after soaking in SBF. Due to the quicker dissolution for 5Sr–100Si and 10Sr–100Si, a number of microparticles are deposited on the surface of 5Sr–100Si and fiber-like particles are deposited on the surface of 10Sr–100Si in SBF (see arrows). EDS shows that there are Ca and P peaks (e) after soaking 10Sr–100Si in SBF indicating that some Ca–P-containing particles are deposited on the surface of 10Sr–100Si glass. The ratio of Ca/P/Sr/Si is 1.87/3.19/0.55/75.92.](image_url)
7 nm (Fig. 2c), with a pore size of approximately 4 nm in the case of lamellar ordering (Fig. 2d).

The small-angle XRD results are listed in Fig. 3. There is a weak peak at 2θ = 2.4° for pure SiO₂ (Fig. 3a). With increasing Sr content, the diffraction peak moves towards a lower angle position (Fig. 3b and c), 10Sr–100Si having a more pronounced diffraction peak at 2θ = 1.25° (Fig. 3c) compared to the other materials. Similarly, with increased Sr content in the composite glass, the average pore size increases, with 10Sr–100Si having a significantly larger surface area and pore volume than the other three species (Table 1).

The results for N₂ adsorption–desorption analysis of 10Sr–100Si showed a type IV isotherm and pore distribution in the 3–5 nm range, typical characteristics of a mesoporous structure (Fig. 4).

3.2. Physiochemical properties of mesoporous Sr–Si glass powders in protein containing SBF

BSA adsorption rates for the mSr–Si glass particles increased with the length of soaking time up to the first 24 h. The 10Sr–100Si glass had the greatest amount of absorbed BSA of the four mSr–Si species (Fig. 5).

Generally, with increasing Sr content, more Sr²⁺ and SiO₄⁴⁻ ions were released from the mSr–Si glass particles (Fig. 6a and b) and the pH value of the SBF increased slightly, maintaining a range of 7.3–7.6 (Fig. 6c). After 3 days of soaking in SBF, the concentration of PO₄³⁻ of SBF for 10Sr–100Si decreased from 31 to 26 ppm.

EDS analysis shows that the rate of Sr/Si in four powders was 0/100, 2.06/100, 4.06/100 and 8.20/100, respectively, which is quite close the theoretical component (Fig. 7).

SEM analyses revealed no significant difference between the surface microstructure of 100Si and 2.5Sr–100Si before and after soaking in SBF (Figs. 7a and b and 8a and b); however, due to the quicker dissolution for 5Sr–100Si and 10Sr–100Si, some microparticles and fiber-like particles are deposited on the surface of materials in SBF (Fig. 8c and d, see arrows). EDS shows that there are Ca and P peaks after soaking 10Sr–100Si in SBF, indicating some Ca–P-containing particles deposited on the surface of 10Sr–100Si glass (Fig. 8e). The ratio of Ca/P/Sr/Si is 1.87/3.19/0.55/75.92.

3.3. Dexamethasone delivery of mesoporous Sr–Si glass powders

The weight differences of DEX-loaded and unloaded particles after heat-treatment were 2.07 ± 0.08, 1.40 ± 0.05, 0.89 ± 0.03 and 2.93 ± 0.13 mg for 100Si, 2.5Sr–100Si, 5Sr–100Si and 10Sr–100Si, respectively. The 10Sr–100Si composite glass had greater DEX loading efficiency (39%) than the other three mSr–Si glass species (100Si = 27.6%; 2.5Sr–100Si = 18.6%, and 5Sr–100Si = 11.8%). All four mSr–Si composites had a sustained DEX-release profile. When the Sr content was less than 5%, the DEX release kinetics increased...
proportionally with the increase of Sr content. The 10Sr–100Si glass particles had the slowest release rate over the full time period (Fig. 9a and b). The relationship of the release rate of DEX in mesoporous Sr–Si glass system over the square root of time is shown in Fig. 9c.

3.4. Cytotoxicity and ALP activity of BMSCs cultured with mesoporous Sr–Si glass powders

The cell viability assays showed there was no discernible cytotoxicity associated with the mSr–Si glass extracts, by the fact that all the experimental groups had values greater than 90% of the controls. The viability of BMSCs cultured with the concentration of mSr–Si glass extracts (ranging from 3.125 to 50 mg ml\(^{-1}\)) was comparable to that of the controls, with the exception of the 10Sr–100Si group at 12.5 and 50 mg ml\(^{-1}\) (Fig. 10a). The ALP activity of the BMSCs cultured with the mSr–Si glass extracts is shown in Fig. 10b. At the highest concentration (50 mg ml\(^{-1}\)), mSr–Si glass clearly has an inhibitory effect on the ALP activity of BMSCs. However, at the lower concentrations (3.125–25 mg ml\(^{-1}\)), ALP activity of BMSCs cultured with the mSr–Si glass extract was comparable to that of the controls. At 12.5 mg ml\(^{-1}\) concentration, ALP activity of BMSCs was enhanced in 10Sr–100Si extract compared to 100Si extract (Fig. 10b). The corresponding ion concentrations of the mixture for cell culture are listed in Table 2, showing SiO\(_4^{2-}\) and Sr\(^{2+}\) ion concentrations ranging from 2.4 to 102 ppm and from 1.7 to 37.5 ppm, respectively.

3.5. Characterization and drug delivery of Sr–Si mesoporous scaffolds

10Sr–100Si and 100Si mesoporous glass scaffolds were successfully prepared. They have similar pore structures, and the large pore size is about 400 μm (Fig. 11a–c). The porosity of the obtained scaffolds is about 90%. Further study has shown that 10Sr–100Si mesoporous glass scaffolds have a slower release of DEX than those of pure 100Si scaffolds (Fig. 11d).

4. Discussion

We have successfully prepared mesoporous SrO–SiO\(_2\) glass particles with a well-ordered structure, and investigated what effects Sr has on mesopore structure, physiochemistry, drug delivery and biological properties. It was found that incorporating Sr\(^{2+}\) into mesoporous SiO\(_2\) glass improved the mesoporous structures (pore size, volume and surface area) and rates of dissolution, as well as protein adsorption. The incorporation of differing amounts of Sr\(^{2+}\) into the mesoporous SiO\(_2\) glass resulted in a more controlled and sustainable drug release profile. These novel mesoporous Sr–Si glass particles had no cytotoxic effects and at certain concentrations of Sr\(^{2+}\) and SiO\(_4^{2-}\) from the mSr–Si glass particles actually enhanced ALP activity in BMSCs. This study indicates that incorporating Sr\(^{2+}\) into mesoporous SiO\(_2\) glass is a feasible method to improve this material’s drug delivery and bioactivity for potential drug carrier and bone tissue repair applications.

We found that a certain amount of water was required to dissolve Sr(NO\(_3\))\(_2\) in order to obtain a uniform SiO\(_2\) gel with which to prepare mesoporous glass with a well-ordered structure. If water was not used to dissolve the Sr(NO\(_3\))\(_2\), it would become unevenly distributed within the SiO\(_2\) gel. Interestingly, at low concentrations of Sr (0%, 2.5% and 5%), the Sr–Si glasses had fewer mesopores and smaller pore size and volume than those with higher Sr content (10%: 10Sr–100Si). Previous studies have shown that reaction conditions, such as water and inorganic salts, and the crystallinity of the mesoporous materials are important factors that influence the mesopore structure [28–30]. Two causes can best explain the phenomena seen in this study. The first is that adding water to the reaction can cause the condensation degree to decrease, thereby destroying the balance of self-assembly conditions in the low Sr containing mesoporous glass. However, in the 10Sr–100Si mesoporous glass, which had the highest Sr content, the addition of Sr(NO\(_3\))\(_2\) might in fact enhance the cross-linkage of the silica monolith and enhance the self-assembly reaction. This type of phenomenon has previously been reported by Zhong et al. [28]. They found that adding inorganic salts (NaCl, NaNO\(_3\) or Na\(_2\)SO\(_4\)) to silica stimulated the formation of mesopore structures. The second possible cause is that Sr atoms, at high concentration (10Sr–100Si), actually inhibit the crystallization of Sr–Si glass (as seen in Fig. 1), which may benefit the formation of an ordered mesopore structure [30].

Protein adsorption is an important factor when evaluating the potential of biomaterials for tissue repair. Most mammalian cells are anchorage dependent and need a biocompatible, protein-rich surface for attachment, differentiation and migration to form...
new tissue [31]. In the present study, we chose to use BSA as a model protein since it is a stable molecule, and also the most abundant protein in blood, albumin accounting for nearly 60% of the total serum proteins. BSA is also inexpensive and is commonly used in studies to simulate human albumin, given the close structural homology of the two [32]. Our data showed quite convincingly that Sr was an important factor affecting BSA adsorption to mSr–Si glass particles. We attribute this to the capacity of Sr to affect the pore size and volume of the mSr–Si glass, and enhanced protein adsorption ability was especially seen in 10Sr–100Si. We compared the protein adsorption by normalizing to the surface area between 10Sr–100Si (0.047 mg of protein per specific surface) and pure 100Si mesoporous bioglass (0.22 mg of protein per specific surface). It is clear that, for the same surface area, 100Si has greater protein absorption ability than 10Sr–100Si. We therefore reasoned that the greater surface area of 10Sr–100Si is the chief contributor to the improved protein adsorption.

There are two potential reasons to explain the peak value of BSA absorption for 10Sr–100Si. One is that there is a dynamic balance between the protein absorption and desorption to materials; the other is that 10Sr–100Si has a larger specific area and faster dissolution rate than the other three materials. In the early stage, 10Sr–100Si will clearly absorb BSA to reach a maximum value; however, with increasing time, 10Sr–100Si glass will dissolve by releasing of Sr and Si ions (see Fig. 6), which will decrease the BSA absorption.

Moreover, incorporating Sr into the mesoporous glass enhances its dissolution, resulting in a controllable release of bioactive ions ($\text{Sr}^{2+}$ and $\text{SiO}_4^{4-}$). The incorporation of $\text{Sr}^{2+}$ into mesopore $\text{SiO}_2$ glass may produce some defects in the atomic array, such as atomic vacancies or dislocations. These defects will result in the improved dissolution of the materials, which has been described in a previous study [33]. Although the higher solubility led to slightly higher pH values in SBF, in our study the pH stayed within a narrow physiological range (7.3–7.6), which is conducive to cell growth. In addition, our study has shown that the incorporation of Sr into mesoporous $\text{SiO}_2$ glass enhanced the deposition of Ca–P-containing particles, which may indicate improved bioactivity according to previous studies [25,34].

Mesoporous $\text{SiO}_2$ glass has been widely studied as a potential drug delivery system, since its nanochannel structure allows it to maintain a sustained release; however, controlling such drug delivery still remains a challenging issue. Until recently, in most studies the reaction conditions (solvent, surfactant, etc.) and surface modifications to control the pores and surface structure were manipulated in order to better control drug release in mesoporous $\text{SiO}_2$ [12–14]. In our study, DEX was chosen as a model drug since it is already used as an anti-inflammatory agent to treat rheumatoid arthritis [35]. It was found that incorporating $\text{Sr}^{2+}$ into mesoporous $\text{SiO}_2$ yielded a more controllable drug release and the mSr–Si glass particles maintained a sustained release of DEX. At the low end of Sr content (5% and less), the faster dissolution rate of the mSr–Si glass most likely also contributed to the faster rate of DEX release. At the high end of Sr content (10%), 10Sr–100Si, despite having the fastest rate of dissolution, also had a significantly enhanced mesopore structure, which appeared to contribute to its slower DEX release rate. The release rate of DEX in mSr–Si glass system was not a simple linear one, but rather appeared to be a function of the square root of time. This indicates that DEX release in this system is not only affected by diffusion [36], but also by the dissolution of the glass itself.

Sr and Si are both important trace elements in human bone tissues. Previous studies have shown that high concentrations of $\text{Sr}^{2+}$ and $\text{SiO}_4^{4-}$ ions can result in excessive cytotoxicity [21,34]. In our study, $\text{Sr}^{2+}$ and $\text{SiO}_4^{4-}$ ion concentrations from mSr–Si glass reached as high as 34.5 and 102 ppm, respectively. These levels were not cytotoxic to the BMSCs, but there was a slight inhibitory effect on ALP activity (see Fig. 10b and Table 2) when the $\text{Sr}^{2+}$ concentration was greater than 26.5 ppm; below this level ALP activity was comparable to that of the controls. The BMSC ALP activity was greater in cells grown in medium with the 10Sr–100Si extract compared to with the 100Si extract when the extract concentration was 12.5 mg ml$^{-1}$. This could be attributed to Sr somehow
compensating for the negative effect of high concentration of Si2+. Sr2+ and SiO2− 4 ions at optimum concentrations clearly have the ability to enhance the ALP activity of BMSCs by a synergistic effect of the two ions.

Our further study has shown that mesoporous Sr–Si glasses can be prepared as porous scaffolds with a highly porous structure and large pore size, which will benefit cell growth. The incorporation of Sr into mesoporous SiO2 scaffolds maintained a more sustained release, which indicates that the obtained 10Sr–100Si mesoporous glass, in the form of scaffolds, can be used for drug delivery and bone tissue engineering. Further study will be conducted to investigate the effect of controllable DEX release from mesoporous Sr–Si glass scaffolds on the proliferation and differentiation of BMSCs.

5. Conclusion

A novel bioactive SrO–SiO2 glass with a well-ordered mesopore structure has been successfully prepared by the incorporation of Sr2+ into SiO2. At 10% Sr content, mesoporous Sr–Si glass has an improved mesopore structure, dissolution and protein adsorption compared to mesoporous SiO2. The release profile of bioactive Sr2+ ions and a model drug (DEX) can be controlled by altering the Sr content in mesoporous Sr–Si glass particles. No cytotoxicity was associated with these compounds, and the released Sr2+ and SiO2− 4 ions, at an optimum concentration, enhanced the ALP activity of BMSCs. Mesoporous Sr–Si glasses can be prepared as porous scaffolds which show a more sustained drug release. These results indicate that incorporating Sr2+ into mesoporous SiO2 glass may yield a bioactive material with improved drug release properties for potential drug carrier and bone repair application.

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Appendix A. Figures with essential colour discrimination

Certain figures in this article, particularly Figures 1, 5, 6, 9, 10 and 11, are difficult to interpret in black and white. The full colour images can be found in the on-line version, at doi: 10.1016/j.actbio.2010.12.018.

References


