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Preparation of Inorganic/Organic Polymer Hybrid Microcapsules with High Encapsulation Efficiency by an Electrospray Technique

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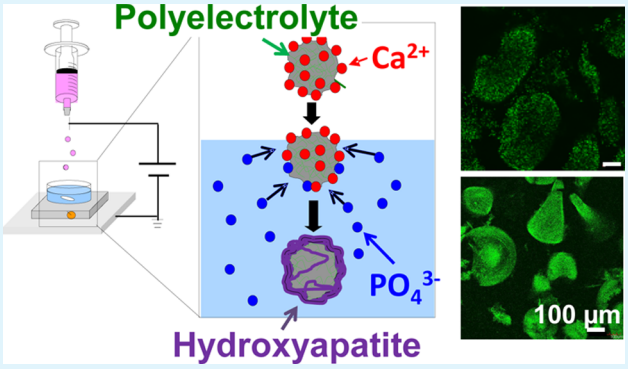
ABSTRACT: Microcapsules composed of calcium phosphate and chitosan were prepared in a single step by electrospraying. An aqueous solution containing calcium chloride and chitosan was electrosprayed into a phosphate solution to form a calcium phosphate shell on the sprayed droplets. The resulting microcapsules were 350 μm in average diameter. Investigation using fluorescently labeled chitosan and XRD measurements revealed that the shells of the microcapsules were composed of calcium phosphate (mainly hydroxyapatite) and chitosan. Instead of chitosan, poly(diallyldimethylammonium chloride) and polyethylene glycol were also available for microcapsule production by electrospraying. Variations in the electrospraying conditions resulted in a variety of microcapsule shapes. Various types of substrates were successfully encapsulated in microcapsules with a high encapsulation efficiency (more than 80%). Finally, we succeeded in the encapsulation of living yeast cells in microcapsules, and observed their growth within these microcapsules.



KEYWORDS: *electrospray, inorganic microcapsule, polyelectrolyte, cell encapsulation*

INTRODUCTION

Microencapsulation techniques are widely used in the cosmetics, agricultural, food, pharmaceutical, and medical fields.[1−3] Although a number of efforts have been devoted to the preparation of various microcapsules, there is still considerable demand for novel preparation methods and novel functional microcapsules. Functional microcapsules often involve precise size-control, novel biocompatible materials, and novel controlled-release properties. While many reports describe the successful formation of microcapsules based on organic polymers, there are limited reports of microcapsules based on inorganic materials. This may be because it is relatively difficult to prepare inorganic microcapsules, or because it is difficult to achieve functional properties with inorganic microcapsules.

To prepare inorganic microcapsules, several methods have been proposed.[4−21] One effective method is template-directed synthesis, in which hard or soft template spheres are used. Using hard templates (e.g., metallic particles or polymer microspheres), inorganic microcapsules with a narrow size-distribution have successfully been achieved.[7,8,22−24] However, this method involves multiple processes and requires the removal of the templates from the inorganic microcapsules, usually under harsh conditions (strong acid, organic solvents, calcination). The removal of the templates results in porosity of the inorganic shell, which becomes permeable to various solutes, and may also limit the microcapsules' ability to encapsulate substrates. Soft templates (e.g., bubbles and emulsions) have also been used to prepare inorganic microcapsules.[12,14,16−18,25] These methods also employ multiple processes to prepare microcapsules, and are often not suitable for the encapsulation of biomolecules or living cells. Recently, several research groups reported the preparation of millimeter-sized inorganic capsules using a hydrogel as a core material, and also reported the successful microencapsulation of enzymes.[20,26−28]

To introduce functional properties to inorganic microcapsules, inorganic/organic hybrid microcapsules have been proposed. The inorganic compounds provide thermal and chemical resistance, and the organic compounds, often organic polymers, provide designable functional properties to the microcapsules. The coexistence of inorganic and organic compounds often aids the successful formation of microcapsules.[26,29−32]

Calcium phosphate and calcium carbonate are abundant in nature, and are biocompatible. Because they can be synthesized in mild conditions, they have been widely studied for biomimetic mineralization.[33,34] However, the reactions between calcium ions and phosphate or carbonate ions are too fast,[35,36] which often makes it difficult to prepare inorganic microcapsules with the designed configuration. Several reports revealed that the control of nucleation and crystal growth are

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of great importance for the formation of hierarchal structures and specific assembly.[37−39] Many of the studies mentioned above also involved various approaches to control the rates of nucleation, crystal growth, and assembly of the inorganic particles used to prepare the inorganic or inorganic/organic hybrid microcapsules. An electrospray technique is one of the well-studied approaches to prepare microcapsules and also to encapsulate a wide variety of substrates.[40,41] Our previous studies also reported that an electrospray technique can be utilized for a fast reaction between polyelectrolytes to produce polymeric microcapsules in a single step, and suggested that the formation of droplets by electrospraying has great potential to produce microstructured materials.[42,43] However, to the best of our knowledge, there is no report on the preparation of inorganic/organic polymer hybrid microcapsules that can encapsulate a variety of substrates using an electrospray technique. In the present study, we employed an electrospray technique to produce a core droplet for an inorganic microcapsule, and successfully prepared inorganic/organic hybrid microcapsules using organic polymers. An aqueous solution containing Ca^{2+} and an organic polymer was electrosprayed into a phosphate solution, resulting in the continuous production of inorganic/organic hybrid microcapsules composed of calcium phosphate and organic polymers. The encapsulation of substrates of various sizes (from a dye molecule to a living cell) was also successfully achieved.

EXPERIMENTAL SECTION

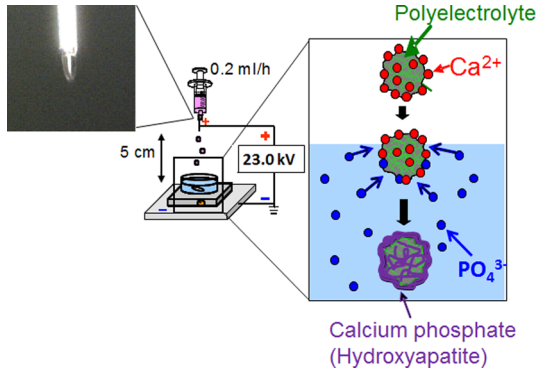
Materials. Calcium chloride, chitosan (commercially chitosan 10, the viscosity of its aqueous solution is less than 20 mPa s when dissolved in 0.5 wt % acetic acid solution at 20 °C), acetic acid, disodium hydrogen-phosphate anhydride, sodium carbonate anhydride, and polyethylene glycol (PEG, MW = 2000) with an amino group at one end, and PEG 20 000 were purchased from Wako Pure Chemical Industries (Osaka, Japan). Albumin−fluorescein isothiocyanate conjugate (albumin−FITC), tetramethylrhodamine isothiocyanate−dextran (TRITC−dextran, MW = ∼2 000 000), poly(diallyldimethylammonium chloride) solution (PDDA, MW = 100 000−200 000, 28 wt % in water), and calcein were purchased from Sigma (St. Louis, MO). Poly(allylamine hydrochloride) (PAH, MW = ∼150 000) was purchased from Nittobo (Tokyo, Japan). Green fluorescent polystyrene microspheres were purchased as a suspension from Duke Scientific (Palo Alto, CA). The microspheres had diameters of 0.5 and 1.9 μm. Tetramethylrhodamine isothiocyanate (TRITC) was purchased from Invitrogen (Carlsbad, CA). Calcein AM (3′,6′-di(*O*-acetyl)-4′,5′-bis[*N*,*N*-bis(carboxymethyl)aminomethyl]-fluorescein, tetraacetoxymethyl ester) was purchased from Dojindo (Kumamoto, Japan).

TRITC-modified chitosan was prepared as follows. TRITC (0.18 mg) was added to an acetate buffer solution (pH 5, 0.1 M) containing chitosan (1 mg/mL). The molar ratio of TRITC/chitosan monomer was 1/300. After reaction for 15 h at room temperature, the reaction solution was dialyzed with an excess amount of an acetate buffer using a dialysis membrane (Spectra/Por7MWCO 50 kDa, Spectrum Laboratories Inc., Rancho Dominguez, CA) three times, followed by freeze-drying.

TRITC-modified PEG was prepared as follows. Amino-terminated PEG (84.5 mg) was dissolved in a triethylamine/acetate buffer (pH 8, 0.1 M, 9 mL), and a DMF solution (1 mL) containing 8.5 mg of TRITC was added to the PEG solution. After 4 h at room temperature, the reaction solution was freeze-dried.

Electrospray. The electrospray (NF-102, MECC Co., Ogori, Japan) experimental equipment consisted of a syringe pump, a stainless steel needle, and a high voltage generator (Scheme 1).[42,43] An aqueous solution containing Ca^{2+} and a polyelectrolyte (or PEG 20 000) was sprayed from the stainless steel needle (cathode) into an aqueous solution containing PO_4^{3-} in a stainless steel dish (anode) to form inorganic/organic microcapsules at room temperature. A polyelectrolyte in a Ca^{2+} solution was used to assist the electrospray to form stable droplets. The aqueous solution was stirred continuously and gently (approximately 100 rpm) in a dish by a magnetic stirrer bar while the electrospraying was performed at room temperature.

Scheme 1. Illustration of the Experimental Setup[a]



[a]The inset is the photo of the Taylor cone formed at the tip of a needle.

Typically, an aqueous solution (pH 4.0) containing calcium chloride (5.0 wt %), chitosan (2.0 wt %), and acetic acid (200 mM) was sprayed into an aqueous solution (receiving solution, 7 mL, pH 8.9) containing disodium hydrogen−phosphate (5.0 wt %) for 3 min. The feed rate of the calcium chloride solution was 0.20 mL/h, and the working voltage was 23.0 kV. The distance from the needle to the collector was 5.0 cm. The inner/outer diameters of the stainless steel needle were 130/310 μm. After electrospraying, microcapsules were separated from the receiving solution by spontaneous precipitation.

To investigate the effects of polyelectrolytes and inorganic salts on microcapsules, microcapsules were prepared using alternative polymers and inorganic salts. PDDA and PAH were used as polyelectrolytes in the feed solution instead of chitosan, and sodium carbonate was used as an inorganic salt instead of phosphate salts.

Encapsulation of Macromolecules, Small Molecules, and Polymeric Microspheres in Microcapsules. To evaluate the encapsulation, fluorescent microspheres, albumin−FITC, TRITC−dextran, TRITC-PEG, calcein, and living cells (*Saccharomyces cerevisiae* Kyokai No.7) were used as core substrates. A calcium chloride (5.0 wt %) aqueous solution containing chitosan (2.0 wt %), acetic acid (200 mM), and the core substrate (10 μL/mL fluorescent microspheres, 10 μg/mL albumin−FITC, 10 μg/mL TRITC−dextran, 10 g/mL TRITC-PEG, or 10 g/mL calcein) was sprayed into an aqueous solution containing 5.0 wt % disodium hydrogen-phosphate under typical conditions. The fluorescent substrate-encapsulated microcapsules were observed using a confocal laser scanning microscope (CLSM) (FV1000-D, Olympus Co., Tokyo, Japan).

After electrospraying, the fluorescence of a supernatant of the receiving solution was measured by a spectrofluorophotometer (FP-8200, JASCO, Tokyo, Japan). An encapsulation efficiency was calculated on the basis of the fluorescence in the supernatant and the sprayed amount of a fluorescence substrate.

The release of encapsulated substrates (calcein and albumin-FITC) was carried out as follows. A microcapsule suspension (7 mL) was left for 3 min to allow precipitation. The supernatant was replaced with a pH-adjusted aqueous buffer (7 mL) and was left for 3 min to allow precipitation. This washing procedure was repeated twice. A pH-adjusted aqueous buffer (7 mL) was added to the precipitate to disperse microcapsules. A HEPES buffer (0.1 M, pH 7.4) and an acetate buffer (0.1 M, pH 5.4) were used as a pH-adjusted buffer. The suspension was gently mixed using a test tube rotator at 25 °C for 48 h in the dark. Supernatant samples (1 mL) were periodically drawn from the suspension and subjected to fluorescence measurements. After each measurement, each sample was returned to the suspension.

Microscopic Observation. An inverted microscope (Olympus, IX71) was employed to observe the microcapsules in an aqueous solution.

Lyophilized microcapsules were observed using a field-emission scanning electron microscope (FE-SEM) (JSM-7500F, JEOL Ltd., Tokyo, Japan) operating at an acceleration voltage of 4 kV. Prior to the observation, the samples were mounted on a carbon-adhesive pad attached to aluminum stubs. After freeze-drying, the samples were sputter-coated with Au/Pd and observed via FE-SEM.

XRD Measurements. Powder X-ray diffraction (XRD) patterns were obtained on an X-ray diffractometer (Rint-2100, Rigaku, Tokyo, Japan) using Cu Kα radiation (40 kV, 20 mA) at a scan rate of 0.05° (2θ/s). A freeze-dried sample was used for the measurement.

Yeast-Encapsulated Microcapsules. The yeast *Saccharomyces cerevisiae* Kyokai No.7 was grown in a YPD medium (10 g/L yeast extract, 20 g/L glucose, and 20 g/L peptone) at 30 °C overnight. An aqueous solution containing calcium chloride (5.0 wt %), chitosan (2.0 wt %), acetic acid (200 mM), and yeast (OD ≈ 0.5) was electrosprayed into an aqueous solution (receiving solution) containing disodium hydrogen-phosphate (5.0 wt %) under typical conditions. The precipitated microcapsules were collected, and then immersed in a fresh YPD medium, followed by microscopic observation of the yeast growth in microcapsules at 25 °C. Microcapsules encapsulating yeast cells were washed with a fresh YPD medium. The living cells were dyed with 1 μg/mL calcein-AM in PBS solution, followed by fluorescent microscope observation.

RESULTS AND DISCUSSION

A Taylor cone was successfully formed at the tip of a stainless needle when a calcium chloride aqueous solution containing a polyelectrolyte was fed through this needle with an applied electric voltage (see inset of Scheme 1). Small droplets were sprayed from the tip of the Taylor cone into a counter electrode. The sprayed droplets containing Ca^{2+} and a polyelectrolyte (chitosan) fell into a receiving solution containing PO_4^{3-} on the counter electrode. Each droplet immediately formed calcium phosphate, resulting in a microcapsule composed of calcium phosphate and chitosan (Scheme 1).

A microscopic image of the calcium phosphate/chitosan microcapsules is shown in Figure 1a, and SEM images are shown in Figure 1b–e. Figure 1a,b shows that microspheres were successfully prepared, with an average diameter of 350 μm. As shown in Figure 1c, the surface of the microsphere was composed of a dense assembly of submicrometer-sized microspheres. The submicrometer-sized microspheres seemed to be crystalline particles of calcium phosphate. SEM images of microcapsule cross sections are shown in Figure 1d and e. These images show that the inside of the microcapsules had a sponge-like porous structure, indicating that the microcapsules can encapsulate substrates. A fibrous structure, which probably consisted of chitosan and calcium phosphate, was observed in the magnified image of the cross section (Figure 1e). Chitosan is a cationic polyelectrolyte that can form a gel-like complex with multivalent anions (such as phosphate ions).[29] The cross-sectional image suggests that the formation of calcium phosphate occurred not only at the surface of a microcapsule but also within a microcapsule. These microscopic observations indicate that the microcapsule formation might involve the following mechanisms: (i) the chitosan worked as the binder between crystalline particles of calcium phosphate, (ii) chitosan-gel worked as a scaffold for the nucleation and growth of crystalline particles of calcium phosphate, or (iii) chitosan served as nuclei for the formation of crystalline calcium phosphate because the droplet containing chitosan produced chitosan nanoparticles due to its low solubility at neutral pH when contacting the receiving phase.

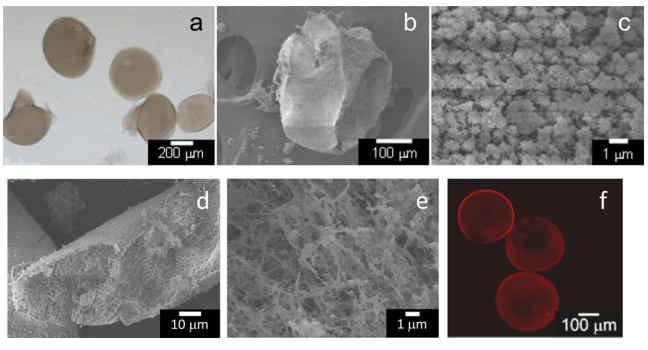


Figure 1. (a) Microscope image of calcium phosphate/chitosan microcapsules. (b) FE-SEM image of a calcium phosphate/chitosan microcapsule. (c) FE-SEM image of the surface of a calcium phosphate/chitosan microcapsule. (d) FE-SEM image of the cross-section of a calcium phosphate/chitosan microcapsule (magnification ratio = 500). (e) FE-SEM image of the cross-section of a calcium phosphate/chitosan microcapsule (magnification ratio = 3000). (f) CLSM image of calcium phosphate/TRITC-chitosan microcapsules.

In the present study, chitosan was used as a polyelectrolyte to help electrospray the feed solution. To investigate the distribution of chitosan in the resulting microcapsules, TRITC-modified chitosan was used to prepare microcapsules. CLSM observation of these microcapsules showed that the TRITC-modified chitosan was distributed throughout the microcapsules (Figure 1f). Interestingly, a relatively strong red fluorescence was observed at the outer surface of the microcapsules and a relatively low fluorescence was observed at the center of some microcapsules, indicating a heterogeneous distribution of the TRITC-modified chitosan and a heterogeneous inner structure. The region with the low fluorescence was likely a void. It should be noted that we observed a variety of shapes (like spherical, elongated, hanging-bell-like, and discotic ones) in the prepared microcapsules. There would be also a variety in the inner structure of the microcapsules. The presence of chitosan inside the microcapsule suggested that a droplet produced by the electrospray was utilized as a gel-like core for the microcapsule.

An XRD spectrum of the microcapsules is shown in Figure 2. The peaks at 26°, 31°, 32°, 33°, and 34° (2θ) indicate the presence of hydroxyapatite.[44] Other peaks suggest other types of calcium phosphate. CLSM observation and XRD measure-

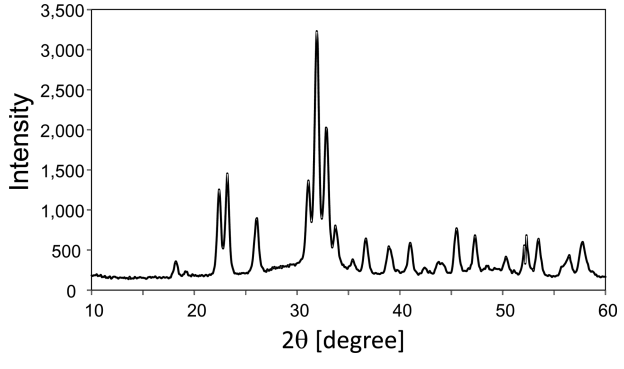


Figure 2. XRD spectrum of calcium phosphate/chitosan microcapsules.

ments revealed that the microcapsules were composed of a mixture of calcium phosphate and chitosan.

The diameters of the microcapsules ranged from 280 to 460 μm, with a relatively narrow diameter distribution (Figure 3),

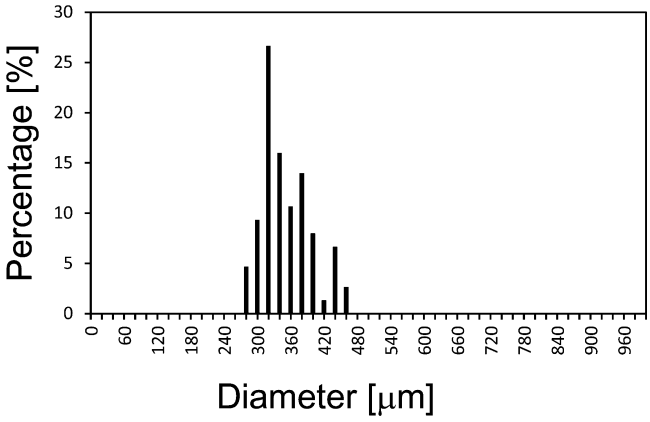


Figure 3. Size distribution of calcium phosphate/chitosan microcapsules.

giving a coefficient of variation (CV) of 12%. Previously, we reported that an electrospray technique produced polyelectrolyte microcapsules and giant vesicles with a relatively narrow size distribution.[42,43] The relatively narrow diameter distribution of the calcium phosphate/chitosan microcapsules agrees with these previous reports. In the preparation of inorganic microspheres and microcapsules, aggregation often occurs. The electrospray technique produced charged droplets, and these charged droplets flew in different directions due to electrostatic repulsion among the charged droplets and dynamic variation in the electric potential between the needle and the collector. When falling into the receiving solution, each droplet formed a calcium phosphate shell, without contacting other droplets because of the rapid formation of this shell. This explains the successful preparation and relatively narrow size distribution of the microcapsules.

Next, we investigated the effect of organic polymers (polyelectrolytes) on the microcapsules. Calcium phosphate microcapsules were prepared by an electrospray technique using different polymers (PEG, PDDA, and PAH) (Figure 4a–

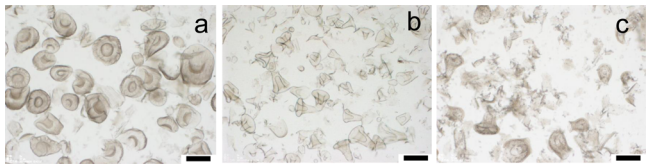


Figure 4. Microscope images of calcium phosphate/polymer microcapsules prepared using different polymers: (a) PEG, (b) PDDA, and (c) PAH. The scale bars represent 200 μm.

c), and calcium phosphate/PEG microcapsules were successfully prepared. These microcapsules had a bowl-like shape. Calcium phosphate/PDDA microcapsules were also successfully prepared, and were shaped like a hanging bell. These microcapsules were slightly smaller than 200 μm. When using PAH, a few microcapsules did seem to be prepared; however, the major portion obtained was a fractured substance. This result suggests the fragility of the calcium phosphate/PAH complex and also the failure in the preparation of the calcium phosphate/PAH microcapsules.

Figure 5a and b shows the effect of polymer concentrations (chitosan and PEG) on the preparation of microcapsules. At low polymer concentrations, microcapsules were not prepared, and only fractured pieces of calcium phosphate were observed. As the polymer concentration increased, the microcapsules became elongated. There have been previous reports in the literature stating that the viscosity of the electrospray solution affects the formation and shape of droplets and fibers.[45,46] The elongated shape of the microcapsules was likely due to the viscosity of the sprayed solution and the rapid formation of calcium phosphate.

As the polymer concentration increased, the number of fractured pieces of microcapsules seemed to decrease. The elongated shape of the microcapsules implies a somewhat higher mechanical strength. Xu and Simon reported that chitosan improved the mechanical strength of calcium phosphate/chitosan hybrid materials.[47] Without an organic polymer, calcium phosphate and calcium carbonate were less elastic and more fragile. In the present study, chitosan was present in the inorganic shell (Figure 1f), indicating a composite of calcium phosphate/chitosan. The polymers used to assist the electrospraying would contribute to an improvement of the mechanical properties of the resulting microcapsules.

Encapsulation of substrates is one important characteristic of a microcapsule. Although there are many reports of hollow inorganic microspheres, the encapsulation of a substrate within a hollow inorganic microsphere remains quite challenging. In particular, template-directed methods have been quite successful in the preparation of hollow inorganic microcapsules, but the encapsulation of substrates using these methods is difficult. We then investigated the encapsulation of particles, macromolecules, and a low molecular weight substrate. Fluorescent microspheres, FITC-dextran, albumin-FITC, TRITC-PEG, and calcein were used as encapsulation substrates. Aqueous calcium chloride/chitosan solutions containing each of these encapsulation substrates were electrosprayed into an aqueous phosphate solution.

CLSM images (Figure 6) revealed that these fluorescent substrates spread over the entire calcium phosphate/chitosan microcapsules, indicating that these substrates were successfully encapsulated in the microcapsules. Fluorescent microspheres (0.5 and 1.9 μm in diameter) were successfully encapsulated, with encapsulation efficiencies of over 95%. The encapsulation efficiencies of FITC-dextran, albumin-FITC, TRITC-PEG, and calcein were 82%, 83%, 90%, and 86%, respectively. FITC-dextran and TRITC-PEG were also encapsulated in the microcapsules with high efficiencies, although dextran and PEG are usually not supposed to have any remarkable interaction with calcium phosphate. The fluorophore-tagged dextran and PEG could have an interaction with calcium phosphate in the present study. Indeed, we observed the adsorption of these fluorophore-tagged dextran and PEG to the empty microcapsules using CLSM (data not shown). Calcein was found mainly in the shells, suggesting a strong interaction of calcein with calcium phosphate due to the five carboxy groups in each calcein molecule. The results demonstrate that the electrospray technique can encapsulate micro- and nanosized substrates in calcium phosphate/chitosan microcapsules with a high encapsulation efficiency.

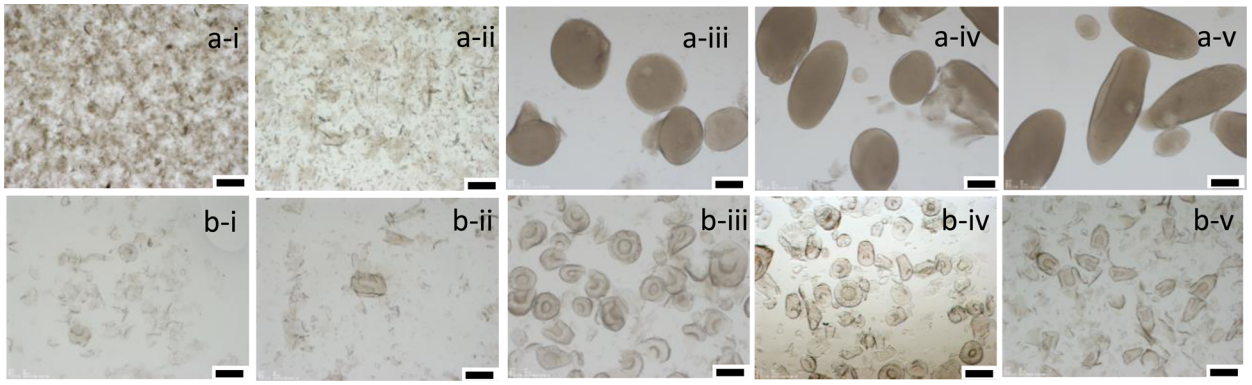


Figure 5. Microscope images of calcium phosphate microcapsules prepared with different polyelectrolyte concentrations. (a) Chitosan and (b) PEG 20 000. The polymer concentrations were 0.5 (i), 1.0 (ii), 2.0 (iii), 3.0 (iv), and 5.0 wt % (v). The scale bars represent 200 μm.

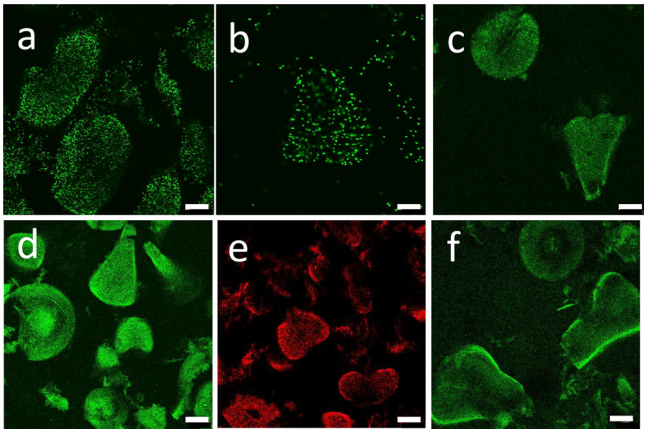


Figure 6. CLSM images of calcium phosphate/chitosan microcapsules containing fluorescent microspheres (0.5 μm) (a), fluorescent microspheres (1.9 μm) (b), albumin-FITC (c), FITC-dextran (d), TRITC-PEG (e), and calcein (f). The scale bars represent 100 μm.

One of the functional properties of microcapsules is to release the encapsulated substrates under certain conditions. We investigated the release of encapsulated substrates from the calcium phosphate/chitosan microcapsules under different pH conditions. Figure 7 shows rapid release of calcein from the microcapsules within a few hours at pH 5.4 and pH 7.4. Because calcein is a small molecule and highly soluble in water, it easily leaked out from a microcapsule. This release and the SEM observation of the microcapsule surface (Figure 1c) indicate that the shell of the microcapsule was permeable for small molecules. The rapid release under an acidic condition (at pH 5.4) would be due to the partial dissolution of calcium phosphate.[48] The release of albumin-FITC was slower than that of calcein, probably because of the large molecular size and a relatively strong interaction between albumin-FITC and calcium phosphate. An acidic condition also accelerated the release of albumin-FITC.

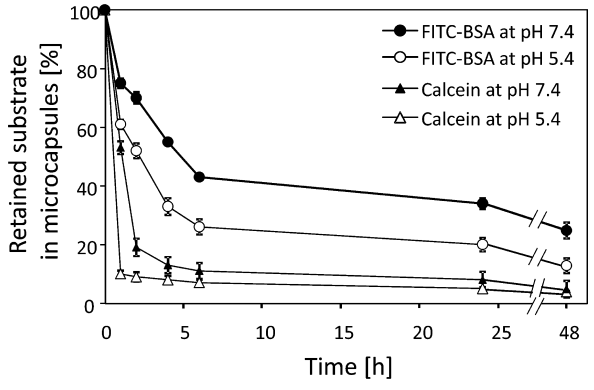


Figure 7. Release of the encapsulated substrates (calcein and albumin-FITC) from the calcium phosphate/chitosan microcapsules under different pH conditions (pH 5.4 and 7.4).

Finally, living yeast cells in an aqueous calcium chloride/chitosan solution were electrosprayed into an aqueous phosphate solution. Figure 8a–d shows phase-contrast microscope images of one microcapsule encapsulating yeast in a YPD medium at different periods after microcapsule preparation. After 6 h, the microcapsule interior was the same as in the initial 0 h image. After 12 h, a bright region emerged at the center of the microcapsule. After 18 h, this bright region became larger. These results indicate growth of yeast within the microcapsule. After 24 h, the microcapsules were washed with a fresh YPD medium. To explore whether the cells in the microcapsules were alive or dead, the cells were dyed with calcein AM that dyes living cells selectively, followed by a fluorescent microscope observation. Bright yellow-green fluorescence, which was derived from calcein AM hydrolyzed in living cells, was observed in the microcapsules, indicating the presence of grown and living yeast (Figure 8e). It should be noted that there was no time-dependent change in the

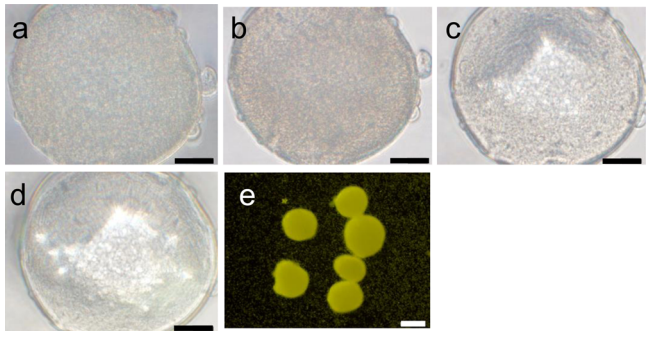


Figure 8. Phase-contrast microscope images (a–d) and a fluorescent microscope image (e) of yeast-encapsulated microcapsules in YPD media at different periods after the preparation of the microcapsules: (a) 0 h, (b) 6 h, (c) 12 h, (d) 18 h, and (e) 24 h. (e) Living yeast cells in the microcapsules were stained with calcein-AM. The scale bars represent 40 μm (a–d) and 200 μm (e).

microscope images of microcapsules without yeast under the same conditions. Furthermore, there was negligible fluorescence in microcapsules without living yeast. These investigations demonstrate that the electrospray technique enables the encapsulation of a physiologically active substrate into inorganic/organic polymer microcapsules without any critical damage to the substrate. Furthermore, the interior of the microcapsules was a suitable environment for the cultivation of the cells.

There are several techniques to encapsulate cells in microspheres. For example, one of the widely used techniques is a calcium/alginate bead. In comparison with the calcium/alginate bead, the present approach can provide the degradable inorganic/organic hybrid microcapsules according to the kinds of polymers. Another approach to prepare inorganic/organic hybrid microcapsules is to put droplets containing phosphate ions into a Ca^{2+} aqueous solution.[28] This method produced the millimeter-sized microcapsules, while the present approach gave micrometer-sized ones.

CONCLUSION

We prepared inorganic/organic polymer hybrid microcapsules based on calcium phosphate using an electrospray technique. The electrospray technique produced calcium phosphate/chitosan microcapsules 350 μm in average diameter. The microcapsules had unique and varied shapes, depending on the electrospraying conditions. The use of an organic polymer played an important role in the electrospraying and in the formation of microcapsules. This technique can encapsulate various substrates (low molecular weight and macromolecular substrates, microspheres, and living cells) in microcapsules with a high encapsulation efficiency and without critical damage to the substrates. The interior of the microcapsules can be used as a miniature incubator for living cells. Because of the moderate conditions and simplicity of the electrospray setup, the electrospray technique provides a practical method for the production of inorganic/organic polymer hybrid microcapsules.

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Notes

The authors declare no competing financial interest.

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