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Coaxial Electrospinning and Release Characteristics of Cellulose Acetate–Gelatin Blend Encapsulating a Model Drug

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ABSTRACT: In order to minimize the degradation of encapsulated compounds in the harsh environment of release medium and to minimize bursting release, a model drug was encapsulated in a kernel of ultrafine cellulose acetate (CA) and gelatin (GL) blend fibers via coaxial electrospinning. The effects of the GL ratio on the properties of the shell solution were investigated, along with the core-to-shell ratio. Transmission electron microscopy images showed that core–shell coaxial fibers were fabricated successfully. Scanning electron microscopy images showed that the average diameter of the fibers was 913 ± 180 nm. As the GL ratio was increased, the viscosity of the shell solution decreased. In addition, more pronounced shear thinning occurred, which resulted in coaxial fibers with thinner shells. Release characteristics of the encapsulated amoxicillin in pepsin-containing simulated gastric fluid (SGF) with a pH of 1.2 were also investigated. It showed that the release of amoxicillin occurs owing to Fickian diffusion mechanism, with the release half-time being approximately 5 h. Bursting release was not observed, and fibers exposed to the SGF remained intact even after 24 h. These core–shell fibers should be suitable for applications requiring the sustained release of compounds in the gastrointestinal tract. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40167.

KEYWORDS: sustained release; fibers; electrospinning

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INTRODUCTION

Delivery of active compounds in the gastrointestinal (GI) tract is a very important issue because the functional properties of these compounds, which are usually encapsulated in another material, must be preserved until they are delivered to the target site. As such, bursting release must be avoided, and the delivery vehicle should be designed to allow for controllable release. Unfortunately, several active compounds degrade in the GI tract because of the strong acidity of the gastric fluid and the presence of a number of proteases in the stomach.[1–3] Therefore, several encapsulating materials and delivery systems for active compounds have been developed either to prevent or delay the degradation.[1–3] In particular, nanofibers have recently been reported as potential carriers and delivery vehicles for active compounds. This is because of their high surface-to-volume and surface-to-weight ratios.[1,2,4,5] In addition, ultrafine, nanoscale fibers have been reported to have properties that make them suitable for minimizing the bursting release of the encapsulated compound in the GI tract.[2,4] However, this type of release is also affected by the type of polymer used as well as the environmental conditions (e.g., the pH, ionic strength, and concentration of the fluids encountered). Although the ultrafine or nanoscale fibers are recognized as an excellent candidate material for use as a delivery vehicle of active compounds, the compounds embedded at the fiber surface are significantly degraded by harsh condition of the release medium. From this viewpoint, a core–shell structure is, thus, far more effective for encapsulation than typical structures.[2,4,6,7] The effectiveness provides in terms of degradation protection capability and/or sustained release property. In a previous study,[2] we had fabricated ultrafine fibers that encapsulated a model protein in the fiber kernels. This was accomplished using the coaxial electrospinning technique. The fibers were electrospun from all-food-grade substances, including cellulose acetate (CA), which was used as the polymer for forming the fiber shell layer, and acetic acid, which was used as the solvent during electrospinning. The coaxial

Additional Supporting Information may be found in the online version of this article.

Table I. Preparation of Electrospinning Core and Shell Solutions

Sample solution	Components	Component ratio (g)
PEG solution (Solution A)	PEG	1.53
	85% acetic acid	7.47
Amoxicillin solution (Solution B)	Amoxicillin	0.17
	85% acetic acid	0.83
Core solution (Amoxicillin dispersing in PEG)	Solution A	9.00
	Solution B	1.00
	Soybean oil	0.22
CA solution (Solution C)	CA powder	1.19
	85% acetic acid	5.81
GL solution (Solution D)	GL powder	0.51
	85% acetic acid	2.49
Shell solution (CA–GL blend solution)	Solution C	7.00
	Solution D	3.00
	Tween®40	0.17

fibers remained intact even after exposure to buffer solutions with pH values of 1.2 and 7.4. The release profile of the coaxial fibers exhibited a near-zero order. In addition, the release rate was extremely low (~5 days). Further, the release was not of the bursting type. However, such a low release rate may not be appropriate for the administration of some types of bioactive compounds in the GI tract.

In this study, we attempted to improve the release properties of CA fibers containing a model core compound by modifying the fiber surface (shell layer matrix). In particular, gelatin (GL), a natural protein widely used in foods and pharmaceuticals, was added to the CA matrix. It was hypothesized that the GL matrix would be removed from the CA–GL composite when the fibers were exposed to gastric fluid and that this would result in the formation of a more porous structure that would increase the rate of release of the encapsulated core compound. Amoxicillin, a broad-spectrum antibiotic drug, was used as a model bioactive core compound. Normally, amoxicillin undergoes significant degradation by the gastric fluid in the stomach[8]; this results in poor treatment efficacy. In this study, amoxicillin dispersed in poly(ethylene glycol) (PEG) was encapsulated within kernels of the CA–GL composite fibers using coaxial electrospinning technique. The effects of the GL blending ratio on fiber morphology as well as the optimal coaxial electrospinning conditions and release characteristics of amoxicillin in pepsin-containing simulated gastric fluid (SGF) at 37°C were also investigated.

EXPERIMENTAL

Materials

CA (white powder; $M_w = 30$ kDa; acetyl content = 39.7 wt %; degree of acetyl substitution ≈ 2.4) was purchased from Sigma-Aldrich (Switzerland). GL (yellow powder; type B; from alkaline bovine hides) was purchased from SKW Biosystems Ltd. (Thailand). The protein content of the GL was 95% (dry weight basis), as determined using the Kjeldahl analytical method (Association of Official Analytical Chemists; AOAC 2000[9]). PEG powder with $M_w = 35$ kDa was purchased from Merck (Germany). Amoxicillin powder ($M_w = 365.4$ kDa) was purchased from Sigma-Aldrich (Switzerland). Pepsin was purchased from Acros (New Jersey, USA). Glacial acetic acid (Carlo Erba, Italy), hydrochloric acid (Merck, Germany), Tween®40 (Fluka, Germany), sodium chloride (Fluka Chemie GmbH, Buchs, Switzerland), and sodium azide (Carlo Erba, Rodano, Italy) were of analytical grade and were used without further purification.

Preparation of Polymer Solutions for Electrospinning

The shell solution was prepared by dissolving the CA powder in 85% acetic acid and the GL powder in 85% acetic acid and mixing the two solutions. About 5 wt % Tween®40 was added in order to decrease the surface tension of CA. The core solution was prepared by mixing PEG and amoxicillin in a solid PEG/amoxicillin blending ratio (w/w) of 90 : 10; this yielded the proper core-to-shell solution electrical conductivity ratio, as suggested by Sakuldao et al.[2] Next, the amoxicillin–PEG blend solution was homogenized with soybean oil at 8000 rpm using a high-shear-speed homogenizer. The amount of soybean oil added to the amoxicillin–PEG blend was 2.2 wt %. Details of the preparation of the shell and core solutions and the blending ratio are listed in Table I.

Setup of Coaxial Electrospinning Apparatus

The setup of the coaxial electrospinning apparatus and the coaxial spinneret is shown in Figure 1(a,b). The coaxial spinneret unit consists of two main parts: the shell compartment (dotted area) and the core compartment (hatched area). The shell compartment was composed of a solution-feeding capillary (A), a solution-ejection head (B), and a shell capillary holder (C). One side of the shell-feeding capillary (A) was mounted on the shell-solution reservoir, which was clamped on a syringe pump, while the other side was fixed to Component (C). Component (B) was fixed to the holder (C) by screwing. The core compartment was composed of a core-feeding capillary (D) and a capillary holder (E). The core-feeding capillary (D) was connected to the core-solution reservoir, which was clamped on a second syringe pump. Component (D) was inserted into component (E). In the coaxial spinneret setup, the core compartment was attached to the shell compartment by coaxially inserting the long capillary of the core compartment into the extruding capillary of the shell compartment and screwing the two compartments together. A thin slab of Teflon gasket was placed at the interface of the two capillary holders in order to prevent the solution from leaking.

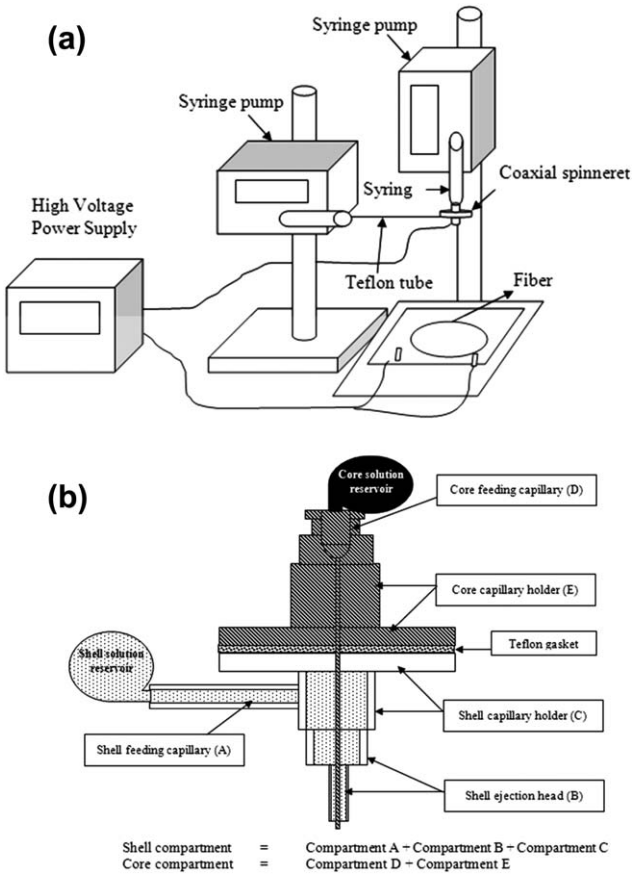

Figure 1. (**a**) Setup of the coaxial electrospinning apparatus for the production of coaxial electrospun fibers and (**b**) schematic figure of coaxial electrospinning spinneret.

Characterization of the Core and Shell Solutions and the Coaxial Electrospun Fibers

Properties of the Core and Shell Solutions. The rheological properties of the core and shell solutions were measured using a rotational rheometer (MCR 150, Physica Paar, Germany) with a CC 17 bob and cup. The measurements were made at 25°C. The results of the steady-shear rheometry measurements (i.e., the shear stress vs. shear rate curves) were fitted to a power-law model [eq. (1)], as described previously:[10]

$$\sigma = K\dot{\gamma}^n \quad (1)$$

where σ is the shear stress, $\dot{\gamma}$ is the shear rate, K is the consistency coefficient, and n is the flow-behavior index, which indicates the solution flow behavior ($n = 1$ if the solution exhibits Newtonian behavior and $n \neq 1$ if the solution exhibits non-Newtonian behavior such as shear thinning or shear thickening).

The surface tensions of the core and shell solutions were measured at 25°C using a digital tensiometer (Dataphysics Model DCT11, Germany). A Du Noüy ring ($D = 18.7$ mm) and a sample glass container (6.7 cm) were used for the measurements.

The electrical conductivity of the polymer solution was measured using a digital conductivity meter (Model CG855, Schott, Germany). The meter was calibrated against a NaCl standard solution (1000 ± 10 μS/cm) (Schott, Germany).

All measurements were performed thrice for each sample. The average values of the results are reported as $\overline{X} \pm \mathrm{SD}$, where $\overline{X}$ is the mean and SD is the standard deviation.

Scanning Electron Microscopy. The morphology of the electrospun product (fibers and/or beads) was determined using scanning electron microscopy (SEM) (Model JSM-6400; JEOL, USA). The electrospun products were collected directly on an SEM brass stub that was mounted on the collector plate. After the deposition of the sample, the stub was removed and sputter coated with gold. The average diameter of the fibers was determined using the Image J 1.38 (JEOL, USA) software program. About 200 fibers were analyzed.

Transmission Electron Microscopy. The core–shell structure of the coaxial electrospun fibers was observed using a transmission electron microscopy (TEM) system (Model JEM-1220; JEOL, USA) operated at 100 kV and having a magnification at 100,000×. The samples for TEM were prepared by directly depositing the fine electrospun fiber onto a copper grid. These samples were then dried in a vacuum oven at room temperature before the TEM-based examinations.

Fourier Transform Infrared Spectroscopy. To determine the composition of the coaxial electrospun fibers, the infrared spectra of the fibers were recorded using micro-attenuated total reflectance/Fourier transform infrared spectroscopy (Micro-ATR/FTIR) (Spectrum Spotlight FT-IR Imaging System, Perkin-Elmer, California, USA) for wavenumbers ranging between 4000 and 600 cm^{-1}. Each reported spectrum is an average of 16 scans.

Wide-angle X-ray Diffraction Analysis. The wide-angle X-ray diffraction (WXRD) patterns of the core–shell coaxial electrospun fibers were determined using an X-ray generator (D8 DISCOVER, Bruker AXS, USA) that produced $K\alpha$ radiation. The counted data were accumulated for 0.4 sec at each step. The instrument was operated between initial and final 2θ values of 5° and 60°, respectively, with the values being increased in increments of 0.02°.

Preparation of SGF

The SGF solution, which had a pH of 1.2, was prepared by mixing 7 mL of HCl, 3 g of NaCl, and 3.2 g of pepsin in distilled water. Then, deionized water was added to the resulting solution till the final volume was 1000 mL. Finally, the pH of the SGF was adjusted using 1*M* NaOH.

Release of Amoxicillin from the Ultrafine Coaxial Fibers in SGF

The film of the electrospun fibers, having a thickness of 1.02 ± 0.69 mm, was cut into 2×2 cm pieces. Fourteen pieces of the fibrous film were placed in a nylon net bag, which was immersed into an SGF sample (200 mL) containing pepsin. This experiment was conducted in a water bath at a controlled temperature of $37°C \pm 1°C$ under stirring at a rotational speed of 100 ± 3 rpm.[11,12] Periodically, 3 mL of the release medium was sampled out, and the same amount of fresh SGF was added back into the release medium. The removed sample was then filtered through a 0.8 μm CA membrane filter (Millipore). The amount of amoxicillin released was determined using high-

Table II. Properties of Core and Shell Solutions

Polymer solutions	Apparent viscosity $\eta_{a,204}$ (Pa.s)	Power law consistency coefficient (K)	Power law flow-behavior index (n)	Electrical conductivity (μS/cm)	Surface tension (mN/m)
Shell solution (CA : GL)					
90 : 10	5.01 ± 0.09	7.23 ± 1.68	0.92 ± 0.03	68.5 ± 0.71	29.03 ± 0.22
80 : 20	3.43 ± 0.00	6.80 ± 2.50	0.88 ± 0.08	120 ± 0.71	28.87 ± 0.21
70 : 30	1.93 ± 0.07	5.26 ± 2.07	0.84 ± 0.11	276 ± 2.12	28.68 ± 0.18
Core solution (PEG : amoxicillin)					
90 : 10	0.09 ± 0.01	0.03 ± 0.00	1.03 ± 0.18	255 ± 13	9.02 ± 2.46
Shell solution (CA : GL)	Core solution (PEG : amoxicillin)	Viscosity ratio (η_s/η_c)	Electrical conductivity ratio	Interfacial tension (mN/m)	
90 : 10	90 : 10	55.67	0.27	12.89 ± 2.18	
80 : 20		38.11	0.47	18.07 ± 4.05	
70 : 30		21.44	1.08	18.23 ± 5.20	

performance liquid chromatography (HPLC) on the basis of the method proposed by Douša and Hosmanová[13] and Fontana et al.[14] The stationary phase used was a reverse-phase C18 column (Agela; Unisol, 5 μm, 100 Å, 4.6 × 150 mm) purchased from Bonna-Agela Technologies Inc. (Wilmington, DE). The mobile phase was a phosphate buffer (pH 6.0, 0.01M) containing acetonitrile (96/4 v/v). The flow rate was 1 mL/min, and the retention time was 4.732 min. Amoxicillin was detected at a wavelength of 230 nm.

The mechanism of release of amoxicillin from the coaxial electrospun fiber mats was determined by plotting the mass fraction of the amoxicillin released versus the sampling time and fitting the plotted data to a simple power-law model [eq. (2)]:

$$\frac{M_t}{M_\infty} = kt^n \tag{2}$$

where M_t is the mass of the amoxicillin released at time t (μg), M_∞ is the mass of the amoxicillin released at infinite time (μg), k is the release rate constant (min^{-1}), t is the time (min), and n is a variable used to characterize the release mechanism.

RESULTS AND DISCUSSION

Properties of Core and Shell Solutions

The characteristic properties of the core and shell solutions (i.e., their electrical conductivities, viscosities, and surface tensions, as well as the core–shell interfacial tension) used for synthesizing the coaxial electrospun fibers were examined. These are listed in Table II. As the GL ratio was increased, the viscosity of the shell solution decreased, and the solution exhibited flow characteristics similar to shear thinning, which has been found to promote stretching of the electrospinning jet.[9] This stretching is one of the key parameters for obtaining coaxial fibers with thin shell layers. In addition, it was found that the viscosity of the shell solution containing 10 wt % GL was relatively high and that this resulted in fibers with rough surfaces. In addition, the size distribution of the resulting fibers was also high (Figure S1, Supporting Information). The ideal electrical conductivity ratio of the shell-to-core solution for ensuring the successful synthesis of coaxial electrospun fibers has been reported to fall between 1 : 1.09 and 1 : 1.52.[2,12] Therefore, in this study, on the basis of the polymer solution properties listed in Table II, the CA/GL blending ratio was selected to be 70 : 30 for synthesizing the core–shell electrospun fibers.

Coaxial Electrospinning of Ultrafine CA–GL Blend Fibers Containing Amoxicillin

The feed rate of the core solution was varied from 2 to 4 to 8 μL/min by setting the feed rate of the shell solution to be constant at 16 μL/min. This flow rate was determined from a preliminary study on an electrospinning condition used to form CA–GL blend fibers (data not shown). The effect of the core solution feed rate on the morphology of the spun fibers, as observed from SEM images, is shown in Figure 2. All the as-spun fibers exhibited fine morphologies. The average diameters of the fibers produced at core solution feed rates of 2, 4, and 8 μL/min were 858 ± 139, 913 ± 167, and 1035 ± 188 nm, respectively. These results are in keeping with those of previous reports in that increases in the core solution feed rate resulted in increases in the diameters of the coaxial electrospun fibers.[2,6,15–17] To obtain smaller fibers with higher core contents, coaxial fibers were electrospun at core and shell solution feed rates of 4 and 16 μL/min, respectively. The coaxial electrospun fibers were synthesized using a supplied voltage of 24 kV and a tip-to-target distance of 22.5 cm. Figure 3 shows a TEM image of the resulting electrospun fibers; the image shows that the coaxial fibers have sharp core–shell interfaces, and inner and outer fiber diameters of 83 and 134 nm, respectively. On the basis of the TEM image, the core/shell volume ratio was found to be approximately 38%.

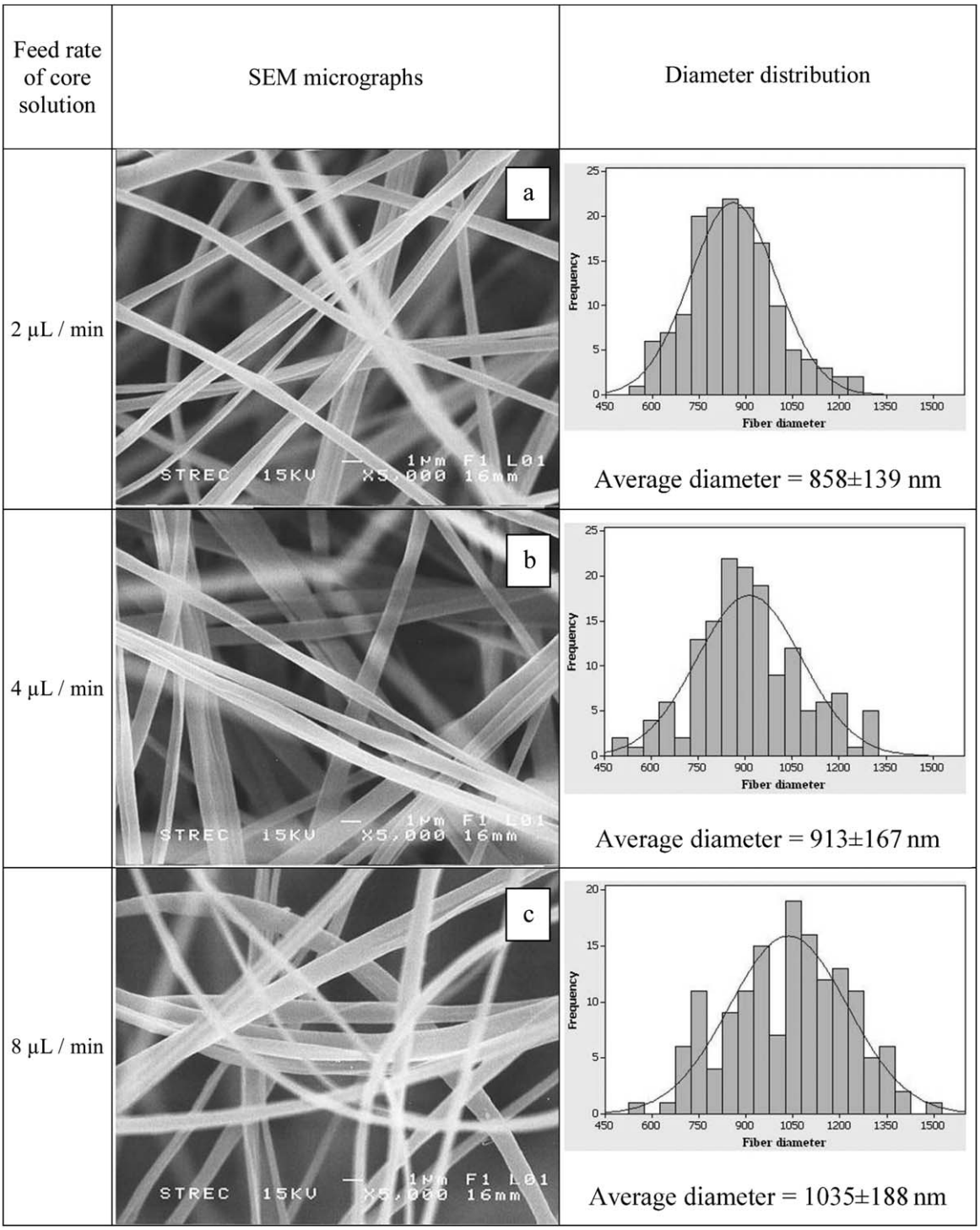

Figure 2. Scanning electron micrographs and size distribution of the amoxicillin–PEG/CA–GL core/shell fiber electrospun at a voltage of 24 kV with a needle tip-to-collector distance of 22.5 cm. The core solution feed rates were (**a**) 2, (**b**) 4, and (**c**) 8 μL/min. The scale bar is 1 μm.

Characterization of Coaxial Electrospun Nanofibers using Fourier Transform Infrared Spectroscopy

The presence of amoxicillin in the coaxial electrospun fibers was confirmed using micro-ATR/FTIR. According to Günzler,[18] in the spectrum shown in Figure 4(a), the characteristic peaks of the coaxial fibers detected at 3444 cm^{-1} (amide NH and phenol OH), 3073 cm^{-1} (benzene ring), 1756 cm^{-1} (beta lactam), 1649 cm^{-1} (amide I), 1535 cm^{-1} (benzene ring; C=C stretch), and 1452 cm^{-1} (NH bend–CN stretch combination band and NH^{3+} symmetric deformation) indicate that amoxicillin was incorporated in the coaxial fibers.[18]

Even though the FTIR result suggested that amoxicillin was incorporated in the fiber matrix, given that amoxicillin was

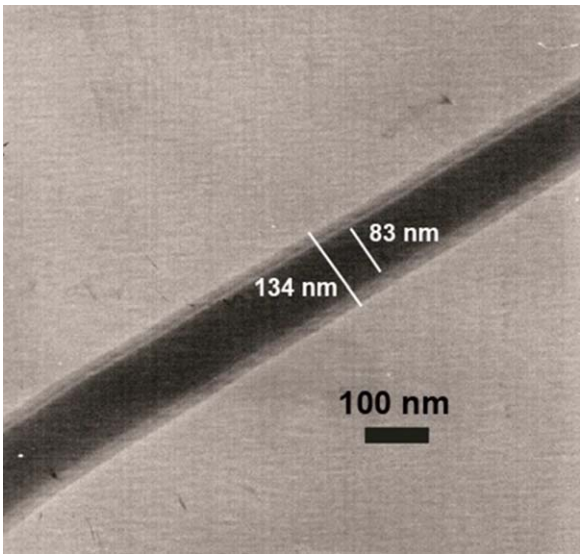

Figure 3. TEM image of core–shell coaxial fibers electrospun from a core solution of amoxicillin–PEG blend (10 : 90) and a shell solution of CA–GL blend (70 : 30). The scale bar was 100 nm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

encapsulated in a small weight ratio (5 wt %), the difference in the absorbance spectra were too insignificant to be noticed with ease. Hence, in order to further confirm the presence of amoxicillin in the coaxial electrospun fibers, the differences in the absorbance spectrum of the core–shell fibers encapsulating amoxicillin and the spectrum of those free from it were obtained by subtracting the absorbance spectrum of the PEG/CA–GL core/shell fibers from that of the amoxicillin–PEG/CA–GL core/shell fibers. The resulting difference spectrum, plotted against the wavenumber, is shown in Figure 4(b). In the spectrum, peaks were detected at wavenumbers of approximately 1776, 1680, 1617, and 1520 cm^{-1}; these corresponded to the characteristic peaks detected in the spectrum of amoxicillin, suggesting that amoxicillin was indeed incorporated in the fiber matrix.

Characterization of Surfaces of the Coaxial Electrospun Fibers using WXRD Analysis

We also used WXRD analysis to confirm that amoxicillin was encapsulated in the electrospun fibers. In particular, the crystallinities of the amoxicillin crystal powder, CA–GL blend fibers, CA–GL blend fibers containing the PEG core compound, and CA–GL blend fibers containing amoxicillin dispersed in the PEG core compound were examined. As shown in Figure 5(a), the new characteristic peaks as well as the higher intensity peaks (as indicated by the arrows) seen in the XRD pattern of the amoxicillin–PEG/CA–GL coaxial electrospun fibers confirmed that amoxicillin was incorporated in the fibers.

In order to further confirm this finding, the WXRD spectra of amoxicillin and the core/shell fibers with and without amoxicillin were magnified for 2θ of 5°−30° and are shown as Figure 5(b). As can be seen from the figure, peaks characteristic of amoxicillin appear at approximately 17.2°, 19.5°−20.2°, and 25.5°−27° in the spectrum of the core/shell fibers with amoxicillin, indicating that amoxicillin was indeed encapsulated within the amoxicillin–PEG/CA–GL core/shell fibers. On the

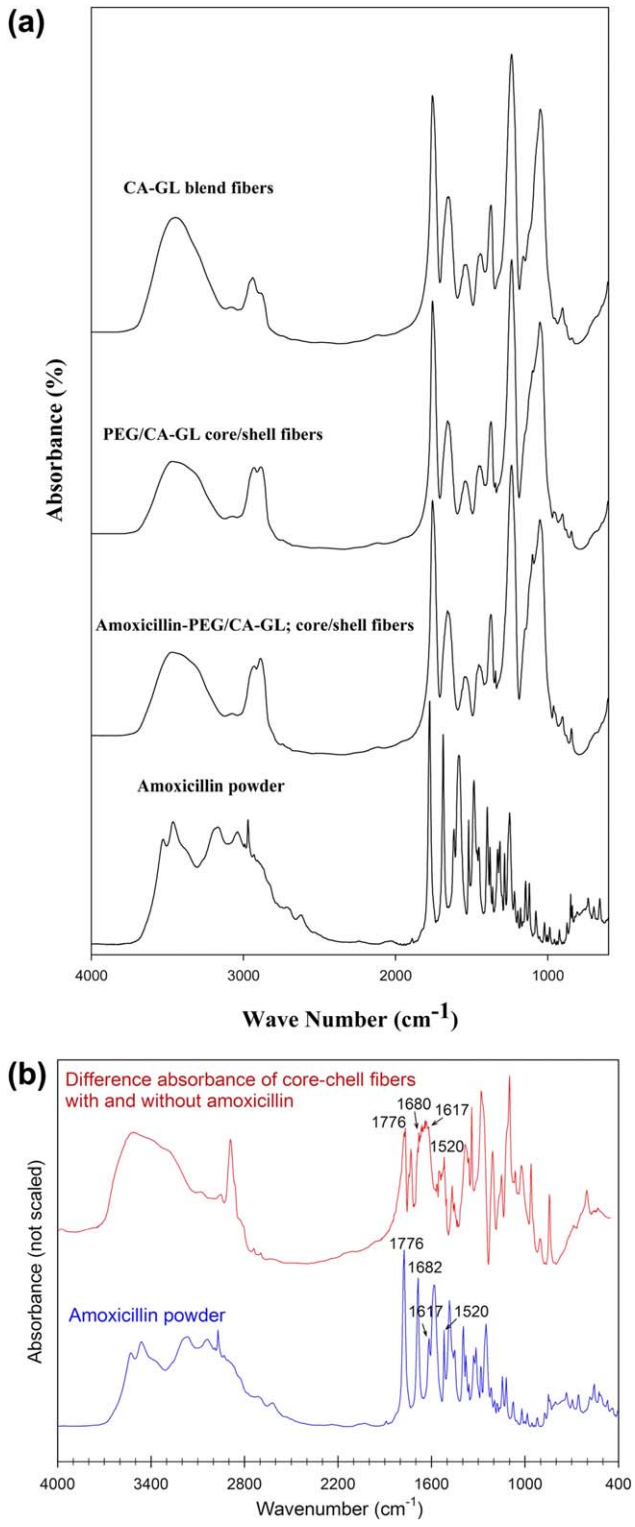

Figure 4. (**a**) FTIR-ATR spectra of the electrospun fibers. (**b**) Difference spectrum of core–shell fibers with and without amoxicillin. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

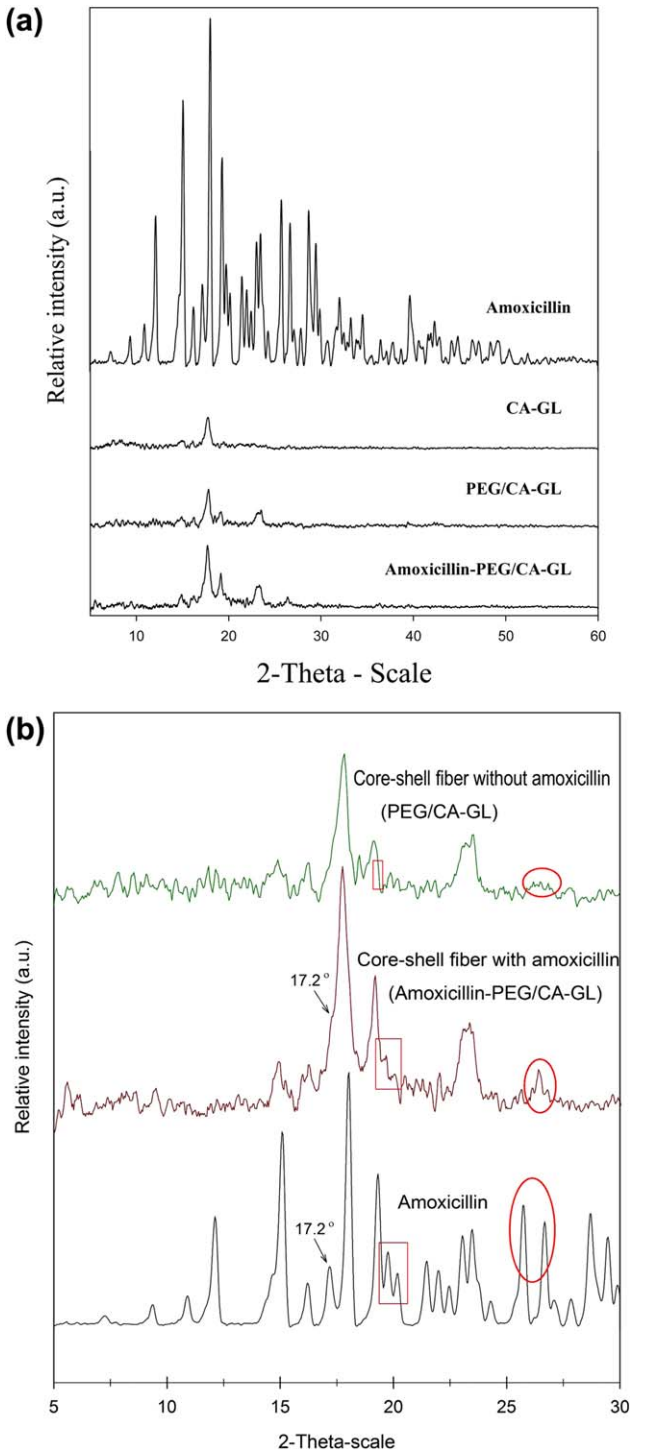

Figure 5. (**a**) WXRD patterns of amoxicillin crystal powder, CA–GL fibers, PEG/CA–GL core/shell fibers, and amoxicillin–PEG/CA–GL core/shell fibers. (**b**) Magnifying WXRD (5°–30°) spectra of core/shell fiber without amoxicillin (PEG/CA–GL core/shell fibers), core/shell fiber with amoxicillin (amoxicillin–PEG/core/shell fibers) and amoxicillin. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

other hand, these peaks were not detected in the spectrum of the core/shell fibers without amoxicillin (i.e., the PEG/CA–GL core/shell fibers).

In Vitro Release Characteristics of Amoxicillin from the Coaxial Electrospun Fiber

The amount of amoxicillin loaded in the fibers was determined using HPLC. Since amoxicillin is degraded in SGF, in order to obtain the exact mass of amoxicillin released from the fibers, we first investigated the degradation of amoxicillin in the SGF sample. The amount of undegraded amoxicillin remaining was found to show as eq. (3). Here, y is the mass of the undegraded amoxicillin (%) and t is time (s). The experimentally determined amounts of amoxicillin released were then corrected according to the equation.

$$y = 100\ exp^{-(2.005\times10^{-5}t)} \quad (3)$$

It was found that the amount of core content loaded in the coaxial fibers was approximately 37 wt %. This value was in good agreement with the result obtained from the TEM image. The profile for the release of amoxicillin from the core/shell fibers at a controlled temperature of 37°C ± 1°C in the pepsin-containing SGF sample having a pH of 1.2 is shown in Figure 6. The release kinetics can be divided into two stages: a higher rate during the initial stage (first 600 min) and a lower rate during the later stage (after 600 min). The high release rate in the first 30 min of the initial stage was believed to be due to the erosion of GL by the pepsin-containing SGF. The release profile was fitted to a simple power-law model [eq. (2)]. As reported by Ritger and Pepas,[19] the power-law constant obtained from the curve fitting is representative of the diffusion mechanism. The release rate constant and diffusion exponent were 4.08 and 0.45, respectively (R^2 ~1.0). For a cylindrical material, a diffusion exponent of 0.45 indicates Fickian diffusion. As can be seen from the SEM images in Figure 7, the fibers were intact even after being exposed to the pepsin-containing SGF for long periods, although their average fiber diameter was reduced from the initial 913 ± 167 nm to 643 ± 146 and 615 ± 127 nm after 12 and 24 h, respectively. It should be noted that acetic acid, which was used as the solvent during the preparation of the core solution, might compromise the functionality of amoxicillin. Hence, a more suitable solvent should be used in next investigation.

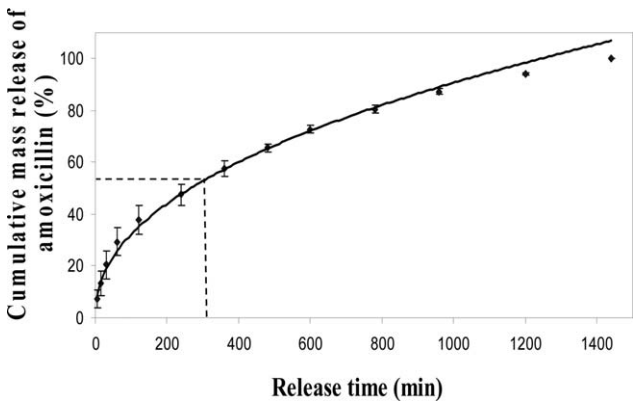

Figure 6. Release profile of amoxicillin encapsulated in a fiber kernel of CA–GL blend electrospun fibers. Release was examined in pH 1.2 SGF at a constant temperature of 37°C ± 1°C.

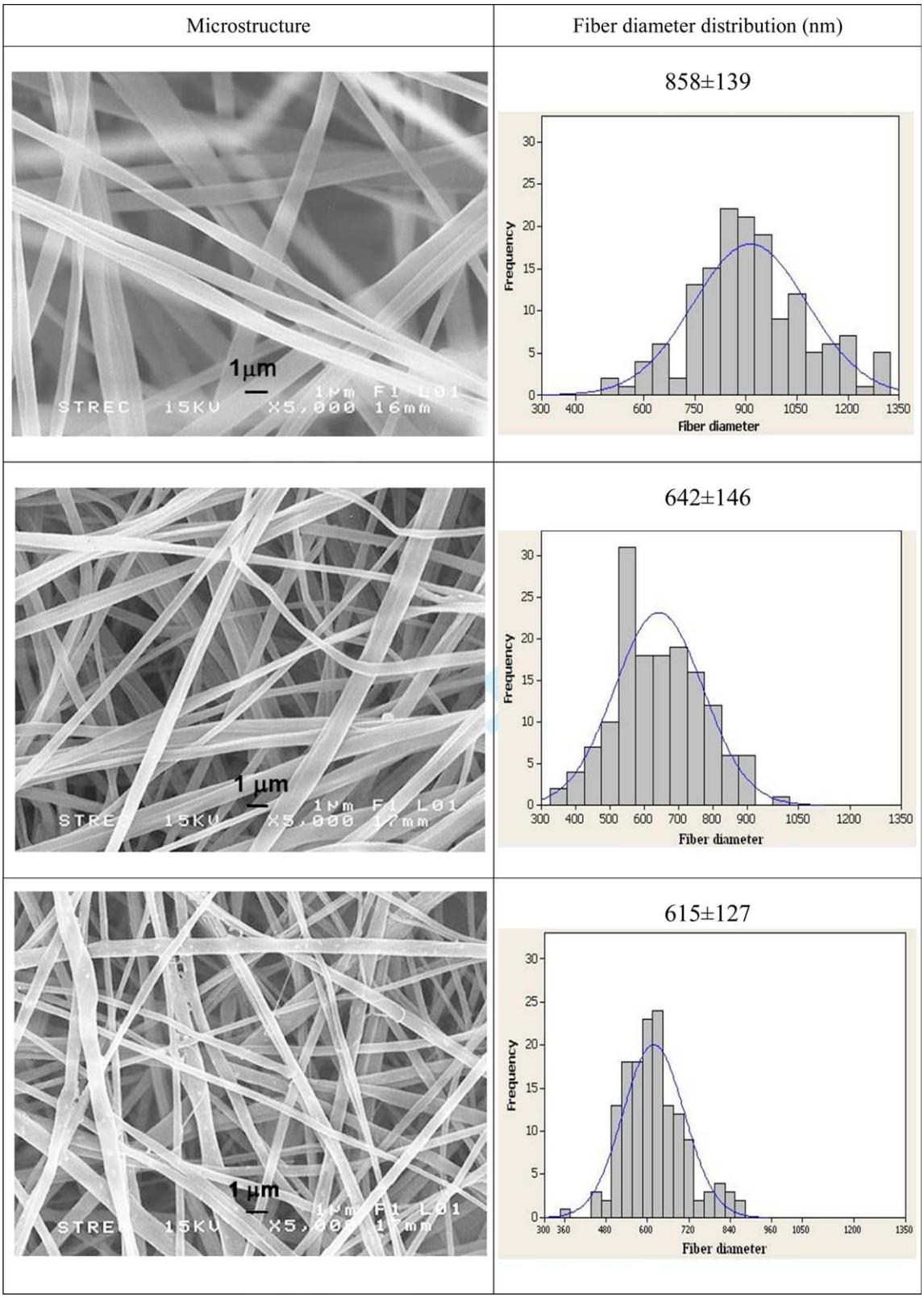

Figure 7. Scanning electron micrographs and size distribution of PEG–amoxicillin/CA–GL core–shell electrospun fiber samples (**a**) before and (**b**, **c**) after immersion in pH 1.2 SGF for (b) 12 h and (c) 24 h. The scale bar is 1 μm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

CONCLUSIONS

In summary, ultrafine fibers consisting of a CA-GL blend as the shell layer and the model drug amoxicillin as an encapsulated core were successfully fabricated using the coaxial electrospinning technique. The diameters of the electrospun fibers were not affected by the blending ratio (CA/GL) of the fiber shell polymers (which ranged from 90 : 10 to 70 : 30). However, increases in the feed rate of the core solution significantly increased the average diameter and also broadened the fiber size distribution. The release of amoxicillin from the fibers was driven by Fickian diffusion, with a half-time for the release being approximately 5 h. The protection potential of these core–shell fibers for the encapsulated drug proved to have sustained release and inhibiting bursting release properties, rather than degradation prevention capability. These CA–GL blend hollow ultrafine fibers should be suitable for applications requiring the controlled release of encapsulated core compounds in the GI tract.

ACKNOWLEDGMENTS

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