Shape Deformation and Recovery of Multilayer Microcapsules after Being Squeezed through a Microchannel

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ABSTRACT: The deformation and recovery behaviors of multilayer microcapsules were investigated after being forced to flow through a microchannel. The microchannel device with a constriction (5.7 μm in depth) in the middle was designed, and the multilayer microcapsules with different size and layer thickness (and thereby different mechanical strength) were used. Deformation in the microchannel was observed for all the capsules with a size larger than the constriction height, and its extent was mainly governed by the difference between capsule size and constriction height. The squeezed microcapsules could recover their original spherical shape when the deformation extent was smaller than 16%, whereas permanent physical deformation took place when the deformation extent was larger than 34%. The capsules filled with polyelectrolytes could greatly enhance their shape recovery ability due to the higher osmotic pressure in the capsule interior and could well maintain the preloaded low-molecular-weight dyes regardless of the squeezing.

INTRODUCTION

The advanced drug-delivery systems can deliver drugs to desired sites and smartly release under specific stimuli. So far, a variety of polymeric drug carriers have been developed, including micro- and nanocapsules,1 microspheres,2 hydrogels,3 nanoparticles,4 and vesicles.5 Among all the exploited polymeric carriers, microcapsules obtained via layer by layer (LBL) assembly6 attract much attention due to their overwhelming advantages such as tailored structures and mechanical properties,7 large loading capacity, and smart responsiveness to environmental stimuli.8

The studies about multilayer capsules as drug delivery systems are focused on the loading and release of diverse substances, such as low-molecular-weight drugs,9 proteins,10 DNAs,11 and small peptides.12 Recent achievements include their interactions with diverse cells12 and delivery of drugs13 or peptides1b into living cells. Generally, the size of multilayer microcapsules is pretty big and is comparable to that of human red blood cell (RBC, about 7 μm). A fascinating characteristic of RBC is their extreme reversible deformability under physiological flow; thus, they can easily pass through the smallest blood capillary vessel (~3 μm). It is conceivable that the microcapsules have to face the same challenge of passing through the blood capillary vessel as the RBCs do, if they similarly circulate in the bloodstream. Therefore, their deformability and recovery after passing through a thin capillary channel are of practical importance and highly deserved to explore.

The deformability of polymeric microparticles (mainly hydrogel microparticles) with different shapes and sizes has been studied under flow conditions. For example, Mitragotri et al. fabricated 7 μm red blood cell-mimicking particles, which were flexible enough to flow through narrow glass capillaries (5 μm inner diameter) and able to recover to discoidal shape.14 Yogo et al. fabricated 3.5 μm biconcave disk-shaped particles by electrospraying of cellulose derivative ethylhydroxyethylcellulose (EHEC), which could maintain RBC-like shape after filtrated through a membrane with a pore size of 1 μm.15

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et al. synthesized poly(ethylene glycol) (PEG) hydrogel particles with different shapes including disks, rings, crosses, and S-shapes and demonstrated the modes of particles’ passage through poly(dimethylsiloxane) (PDMS) channels.\textsuperscript{16} Very recently, the mechanical properties and flow behaviors of large capsules (tens of micrometers) made of cross-linked ovalbumin are investigated. For example, the Leclerc group inferred an estimation of the elastic properties by flowing the capsules inside a cylindrical channel and a square-section microchannel.\textsuperscript{17} They also investigated the transient behaviors by flowing the capsules through a convergent–divergent microchannel made of PDMS.\textsuperscript{18} However, for the multilayer capsules with a size comparable to that of human red blood cell, their deformation behaviors under flow in a microchannel with a smaller size have not been studied, although the static deformation behaviors have been systematically studied under the press of a colloidal probe\textsuperscript{19} or osmotic pressure.\textsuperscript{20}

Herein, a first step toward the multilayer microcapsules’ deformability under flow in a confined microchannel is attempted by using the spherical poly(allylamine hydrochloride) (PAH)/poly(styrene sulfonate) (PSS) microcapsules either prefilled with PSS or not. The deformation and recovery are observed on line by confocal laser scanning microscopy (CLSM). Influences of capsule size, mechanical strength (controlled by wall thickness), and the preloaded polyelectrolytes on their deformation and shape recovery will be systematically investigated.

\section*{EXPERIMENTAL SECTION}

\textbf{Materials.} Sodium poly(styrenesulfonate) (PSS, $M_w$ 70 kDa), poly(allylamine hydrochloride) (PAH, $M_w$ 56 kDa), and Rhodamine 6G (RD6G) were obtained from Sigma-Aldrich. Manganese sulfate ($\text{MnSO}_4$) was obtained from Shanghai Meixing Chemical Factory Co., Ltd. Ammonium hydrocarbonate (NH$_4$HCO$_3$) and disodium ethylenediaminetetraacetate dihydrate (EDTA) were purchased from Guangdong Guanghua Chemical Factory Co., Ltd. All chemicals were used as received except that PSS was dialyzed using a dialysis bag with a cutoff molecular weight of 14 kDa. The water used in all experiments was prepared in a Millipore Milli-Q Reference purification system.

\textbf{Spherical MnCO$_3$ microcapsules with three different sizes were synthesized by mixing MnSO$_4$ and NH$_4$HCO$_3$ solutions according to ref 21.}

\textbf{Fabrication of Hollow Microcapsules.} Sequential adsorption of PAH and PSS (2 mg mL$^{-1}$) onto the MnCO$_3$ microparticles ($\sim$3% w/w in suspension) was conducted in 0.5 M NaCl solution for 10 min followed by 3 washings in 0.5 M NaCl solution. The excess polyelectrolytes were removed by centrifugation at 1000 rpm for 1 min. After desired number of layers was assembled, the coated particles were incubated in 0.05 M EDTA solution (pH 7.0, adjusted by NaOH solution) for 30 min under shaking. The resultant capsules were washed with fresh EDTA solution thrice and finally washed thrice with water. The fluorescein isothiocyanate (FITC) labeled PAH (fabricated according to ref 22) was used as the last PAH layer for the visualization by confocal laser scanning microscopy (CLSM).

\textbf{Fabrication of (PAH/PSS)$_1$ (PSS) microcapsules.} (PAH/PSS)$_1$ (PSS) microcapsules loaded with PSS were fabricated according to a method reported previously by using CaCO$_3$ particles doped with PSS (CaCO$_3$(PSS)) as template.\textsuperscript{23} 2 mg/mL PSS was dissolved in 0.05 M calcium nitrate solution, into which equal volume of 0.05 M sodium carbonate solution was rapidly poured under mechanical agitation (700 rpm) for 40 s. The particles were then collected by centrifugation and washed by Milli-Q water thrice. The (PAH/PSS), multilayer was assembled onto the CaCO$_3$(PSS) particles as described above. Finally, the cores were removed by 0.02 M EDTA solution thrice, and the preloaded PSS was liberated to obtain the (PAH/PSS)$_1$ (PSS) capsules, which were washed 3 times with water before use.

\textbf{Fabrication of Microchannel Device.} The microchannel (Figure 1a–d) was made in a configuration similar to the blood vessel. The microchannel was gradually decreased in size, forming a capillary constriction in the middle (Figure 1b). The microchannel was fabricated via the photolithographic and wet chemical etching methods described previously.\textsuperscript{24} Briefly, the photomask with a star-shaped slit of 25 $\mu$m in width (see in Figure 1a) was transferred onto the photoreist layer on a glass slide, which was then etched via a two-step method. First, the light exposed area (unprotected) was etched with 1 M HF and 1 M NH$_4$F solution for 3 min to form a shallow groove. Next, a 250 $\mu$m width bracer was taped onto the groove middle, and the other unprotected groove was further etched for 17 min. The remnant etchant was washed away by water flow after each etching. The geometry of the groove (Figure S1a) was characterized by laser scanning microscopy (Keyence, VK-9710) with a 20x objective. Access holes were drilled at each terminal of the groove with a 1.2 mm diameter diamond-tipped drill bit. Then a thin coverslip was permanently covered onto the glass slide by a thermal bonding procedure.\textsuperscript{25} On the back side of the glass slide, a pipet tip head was glued to each terminal, which is functioned as a small cell for the sample supply and collection.

\textbf{Characterizations.} Confocal Laser Scanning Microscopy (CLSM). Confocal images were taken with Leica TCS SP5 confocal scanning system equipped with a 63x oil immersion objective. To determine the capsule diameter, at least 200...
Table 1. Basic Properties of Microcapsules

<table>
<thead>
<tr>
<th>samples</th>
<th>size [μm]</th>
<th>wall thickness&lt;sup&gt;a&lt;/sup&gt; [nm]</th>
<th>wall thickness in wet [nm]</th>
<th>zeta potential&lt;sup&gt;b&lt;/sup&gt; [mV]</th>
<th>deformation extent (ε)&lt;sup&gt;c&lt;/sup&gt; [%]</th>
<th>critical osmotic pressure&lt;sup&gt;d&lt;/sup&gt; [Pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(PAH/PSS)&lt;sub&gt;5&lt;/sub&gt;-5.1</td>
<td>5.1 ± 0.5</td>
<td>28.6 ± 3.7</td>
<td>40.0</td>
<td>−28.9 ± 4.0</td>
<td>0</td>
<td>2.4</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;5&lt;/sub&gt;-6.8</td>
<td>6.8 ± 0.3</td>
<td>28.3 ± 2.8</td>
<td>40.0</td>
<td>−27.3 ± 0.7</td>
<td>16</td>
<td>1.4</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;9&lt;/sub&gt;-8.6</td>
<td>8.6 ± 0.6</td>
<td>30.8 ± 1.8</td>
<td>43.0</td>
<td>−30.5 ± 5.0</td>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;9&lt;/sub&gt;-6.8</td>
<td>6.8 ± 0.3</td>
<td>49.5 ± 3.2</td>
<td>69.3</td>
<td>−16.7 ± 1.4</td>
<td>16</td>
<td>1.9</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;10&lt;/sub&gt;-6.8</td>
<td>6.8 ± 0.3</td>
<td>59.5 ± 3.6</td>
<td>83.3</td>
<td>−16.2 ± 1.5</td>
<td>16</td>
<td>3.6</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;10&lt;/sub&gt;-8.6</td>
<td>8.6 ± 0.6</td>
<td>42.2 ± 4.2</td>
<td>59.0</td>
<td>−20.1 ± 2.4</td>
<td>34</td>
<td>1.9</td>
</tr>
<tr>
<td>(PAH/PSS)&lt;sub&gt;10&lt;/sub&gt;-8</td>
<td>8.6 ± 0.6</td>
<td>58.4 ± 5.3</td>
<td>82.0</td>
<td>−16.5 ± 0.8</td>
<td>34</td>
<td>3.6</td>
</tr>
</tbody>
</table>

<sup>a</sup>The wall thickness in a dry state was measured by AFM and then converted to the wet state according to ref 25. <sup>b</sup>The capsules’ surface charge was designed as negative so that they are not easily adhered onto the negatively charged glass surface. <sup>c</sup>The deformation extent, ε, is defined as ε = (D<sub>wp</sub> − D<sub>wp</sub>)/D<sub>wp</sub> × 100%, where D<sub>wp</sub> and D<sub>wp</sub> are the capsule diameter and constriction depth, respectively. <sup>d</sup>The critical osmotic pressure, P<sub>c</sub> = 4μ(δ/<R<sup>2</sup>), where μ is the elastic modulus of PAH/PSS multilayers (290 MPa in a wet state),<sup>25</sup> and δ and R are the capsule wall thickness and diameter, respectively. For clarity, here the standard P<sub>c</sub> is designated to (PAH/PSS)<sub>5</sub>-8.6 capsules, and the values of all other capsules are calculated according to their respective δ and R data. A larger P<sub>c</sub> implies a larger force should be exerted to cause the capsule deformation.

Figure 2. Series of Z-scanning images of the (PAH/PSS)<sub>5</sub> microcapsules within (a, c) and after being squeezed through (b, d) the microchannel with a height of 5.7 μm. The images were acquired by CLSM. The sizes of the microcapsules were (a, b) 6.8 μm and (c, d) 8.6 μm. (e) 3D reconstruction of the microcapsule shown in (c). Scale bar: 5 μm.

Capsules were analyzed by Image J software. The microcapsules trapped in microchannel, and those passing through were also scanned by CLSM in a Z series mode, and a series of images were reconstructed by Leica software to demonstrate their 3D topographies.

**Fluorescence Microscopy.** Fluorescence images were taken with a Zeiss Axiovert 200 inverted microscope equipped with a 100X oil immersion objective with a numerical aperture (NA) of 1.4 and an Ebo 100 isolated electronic ballast for mercury vapor compressed-arc lamps. (PAH/PSS)<sub>5</sub>(PSS) capsules were all collected after flowing through the microchannel, and fluorescence images were obtained. All parameters were kept constant during the measurements for different samples. The images were analyzed by Image J software by splitting images into three channels (red, green, and blue), and only the gray value of red channel was used to compare the relative fluorescence intensity among different samples.

**Scanning Force Microscopy (SFM).** A drop of sample suspension was applied to freshly cleaved mica and was dried in air. Topographical images were collected using a SPI3800N probe station and a SPA400 SFM unit (Seiko Instruments Inc.) in a dynamic force mode.

**Zeta Potential.** The ζ-potentials of microcapsules were measured by a Delta Nano C particle size and ζ-potential analyzer (Beckman Coulter). The capsules were dispersed in 10 mM NaCl solution. Each value was averaged from 3 parallel measurements.

**Microchannel Device Experiment.** The concentration of microcapsules’ suspension was diluted enough to avoid the collision among capsules and clogging of capillary. 50 μL of microcapsules suspension was added to the access hole at the inlet, and 50 μL of water was added to the two sheath fluid inlets. A negative pressure (0.77P<sub>a</sub>, P<sub>a</sub> is the atmosphere pressure) was applied at the outlet to force the movement of microcapsules in the microchannel. After passing through the microchannel, all the capsules were collected in the small cell at the outlet and used for subsequent characterization. During the experiment, the negative pressure could be released to trap the capsule within the microchannel for in-situ CLSM observation.

### RESULTS AND DISCUSSION

To mimic the flowing behaviors of blood cells through a thin capillary, the key issue is to design and fabricate a microchannel whose size should be smaller than that of the microcapsules in at least one dimension. Only in this case, shape deformation and recovery of the microcapsules may occur when they are squeezed through the microchannel. Indeed, the capillaries of blood vessels, especially the veins through which the drug carriers are injected, are found in a flat tubular structure.

The key geometric features of the typical microchannel used in this study were characterized by laser scanning microscopy before the final bonding procedure. As shown in Figure S1, the microchannel has a depth (size in Z direction) of ~25 μm and a width (size in Y direction) of 75 μm at the both sides of the
constriction region, whose depth and width are about 5.7 and 35 μm (Figure 1c), respectively. The length of the constriction is about 150 μm. By this fabrication method, the depth could be well controlled to match the size of capillary vessel, while the width was determined by the original width of the photomask slit and the diffusion of etchant. Since the constriction width is far larger than the capsule size and does not provide any restriction, the microcapsules shall deform their shape mainly in the Z direction when they are squeezed through. The capsule deformation can be conveniently observed on line by an optical microscope.

The well-studied PAH/PSS microcapsules with variable sizes and wall thicknesses were used for the flowing-in-microchannel study, whose basic properties are summarized in Table 1. They had three different diameters, i.e., 5.1, 6.8, and 8.6 μm, which possess theoretical deformation extents (ε) of 0%, 16%, and 34% in the Z-direction inside the constriction with a depth of 5.7 μm, respectively. By alteration of the assembled bilayer numbers (5, 8, and 10) and the capsule sizes, the relative mechanical strength of the microcapsules was varied from 1 to 6 Pc. Furthermore, all the capsule surfaces are negatively charged so that physical adsorption on the glass microchannel (also negatively charged) can be avoided.

The shape deformation and recovery of the PAH/PSS microcapsules with a constant bilayer number of 5 and variable sizes of 5.1, 6.8, and 8.6 μm were first investigated. The (PAH/PSS)5-5.1 capsules passed through the constriction (5.7 μm in depth, ε = 0) with a very fast rate. No deformation was found, and all the capsules kept their original spherical shape (Figure S2a). As predicated, the (PAH/PSS)5-6.8 capsules could not keep their spherical shape, and deformation did occur inside the constriction (Figure 2a). However, the capsules were invaginated only on their top and bottom areas contacting with the constriction (Figure 2a1,a5), while the middle part was not deformed (Figure 2a3). Moreover, all the capsules could pass through the constriction easily. Characterization of the squeezed capsules by CLSM with different focus planes in the Z direction showed that the invagination disappeared completely without any trace of deformation (Figure 2b1–b5), suggesting the elastic recovery of the capsules. Statistic analysis found a recovery ratio of 93%, and their size (6.7 ± 0.5 μm) was identical to the original one (6.8 ± 0.4 μm). When the capsule size increased to 8.6 μm (ε ~ 34%), the capsules were more seriously deformed in the constriction although they could still easily pass through. As shown in Figure 2c, not only the contacting areas (Figure 2c1,c5) but also the middle part (Figure 2c2–c4) were severely deformed. The 3-D reconstruction of the series images (Figure 2e) of a capsule (shown in Figure 2c) showed more clearly the deformed morphology.

Characterization of the squeezed capsules confirmed that the invagination was remained (Figure 2d). The biconcave shape (Figure 2d3,4) is likely caused by the invagination of capsules on their contacting areas with the constriction (corresponding to Figure 2c1,5), and the other perpendicular deformation found in Figure 2d1 represents most possibly the middle invagination (Figure 2c3,4) caused by water flow. Statistical analysis found that ~90% of the capsules kept deformed after passing through the constriction. These results demonstrate that the capsules are hardly recovered when the ε is pretty large, for example, ~34%.

To explore the major controlling factors for the capsule deformation and recovery, next, the ε was fixed at 16% or 34%, but the bilayer numbers (namely the mechanical strength) were changed. It is reasonably assumed that the capsules with a thicker wall should have a stronger ability to resist the impact of water flow and physical deformation. All the 6.8 μm capsules could smoothly pass through the constriction regardless of their bilayer numbers, and the contacting areas to the constriction were invaginated without exception (Figure S3a,c). After being forced to pass through, nearly 100% (PAH/PSS)5-6.8 and 94% (PAH/PSS)10-6.8 capsules recovered to their spherical shape (Figure S3b,d) with a size of 6.8 ± 0.3 and 6.7 ± 0.3 μm, respectively. The deformation and recovery behaviors of (PAH/PSS)5-8.6 and (PAH/PSS)5-10 capsules are similar to that of (PAH/PSS)5-8.6 capsules, except that the deformation in their middle parts disappeared (Figure S3a,c and Figure S3e), leading to only biconcave shape remained in the squeezed capsules (Figure 3b). Again, more than 90% of the (PAH/PSS)5,10-8.6 capsules were in a deformed state after being squeezed through the microchannel.

The above results reveal that it is the deformation extent (ε) but not the mechanical strength that governs the invagination and shape recovery. This is understandable since the capsules are forced to pass through the constriction, and thus deformation must occur if the negative pressure is big enough. With a smaller deformation extent such as 16%, the elastic force of the capsule walls drives the shape recovery suppose the constriction is removed. Previously, the Fery group already observed elastic deformation behavior of 4 bilayers of 4.6 μm poly(diallyldimethylammonium chloride) (PDADMAC)/PSS capsules when their deformation extent was below 18%. However, when the deformation extent is pretty large such as 34%, the invagination degree exceeds the limit that the bending energy can recover, leading to permanent physical deformation. It is worth mentioning that, unlike the PDADMAC/PSS counterpart, the PAH/PSS multilayers are very difficult to be compressed, implying that the overall surface area of the
PAH/PSS capsules should be kept during the deformation and recovery processes. Furthermore, the time required for the capsules to pass through ~100 μm distance in the constriction (schematically shown in the bottom of Figure 1b) was quantitatively measured. As shown in Figure 4 and Figure S4, again it was the deformation extent (ε) but not the mechanical strength that controlled the time required. About 90% of the (PAH/PSS)_6.8 capsules spent less than 500 ms regardless of the wall thickness. The (PAH/PSS)_8.6 capsules generally spent longer time to pass through the same distance, and the softer ones such as (PAH/PSS)_{-8.6} went relatively faster. It was found that the rate-determining step was the entrance of the constriction, where the capsules had to transform their shape to go inside, and thereby larger energy was required. Once inside the constriction, the capsules moved very fast since the main restriction was friction force which is trivial compared with the deformation energy.

As the potential drug carriers, the microcapsules are expected to recover their original shape after squeezed and maintain the loaded drugs. For this context, the (PAH/PSS)_1(PSS) microcapsules (ϕ 10.7 μm) preloaded with PSS, which possess a so-called “spontaneous deposition” property for loading of diverse drugs and proteins, were forced to flow through the 5.7 μm microchannel. About 83.3% microcapsules showed strong fluorescence emission (Figure S5) after incubation with RD6G, confirming the “spontaneous deposition” effect. These capsules could still pass through the constriction regardless of the largest deformation extent (47%) and similarly invaginated at microchannel-contacting parts (Figure 5a and Figure S6). However, unlike the empty counterparts, 80% of the PSS-filled capsules remained their spherical shape after being squeezed through the microchannel (Figure 5b). This value is very close to that of PSS-loading ratio of capsules (83.3%), suggesting that all the intact capsules (only intact capsules show spontaneous deposition) can recover their original shape. This reversible deformation and recovery can be only attributed to the prefilled PSS, which provides osmotic pressure toward the multilayer wall and thereby can maintain the capsule shape upon release of the physical constriction of the microchannel.

Figure 6 shows that the RD6G content inside the capsules was not changed significantly after the capsules were either squeezed through a smaller microchannel (5.7 μm) or forced to flow through a larger microchannel (20 μm), revealing that the dye molecules are very stably loaded regardless of the water flow and capsule deformation. Our previous studies have proved that the deposited molecules are in a complexed form or closely associated with the preloaded polyelectrolytes. Therefore, the large deformation may mainly squeeze out water but not the RD6G molecules which are associated with PSS. This property is important for future application because the

Figure 4. Statistical velocity of microcapsules with variable sizes and wall thickness during passing through the microchannel. Data are calculated according to the values shown in Figure S4.

Figure 5. Typical series of Z-scanning images of (PAH/PSS)_{1}(PSS) microcapsules (ϕ 10.7 μm) within (a) and after (b) being squeezed through the microchannel with a height of 5.7 μm. Scale bar: 5 μm.

Figure 6. Relative mean fluorescence intensity from the interiors of original (PAH/PSS)_{1}(PSS) capsules, capsules after flowing through 20 μm microchannel and being squeezed through 5.7 μm microchannel. Insets show the corresponding typical fluorescence images; scale bar: 5 μm. The data were averaged from >50 capsules by measuring the gray value of red channel inside the capsules.
drugs can be well preserved when the capsules are squeezed through thin capillaries in organisms.

**CONCLUSION**

Different shape deformation and recovery abilities of spherical multilayer microcapsules were demonstrated after being squeezed through a microchannel. It is the deformation extent but not mechanical strength that governs the recovery ability of capsules. The squeezed hollow microcapsules could recover their original spherical shape when the deformation extent \( e \) was smaller than 16% (reversible deformation), whereas permanent physical deformation took place at a larger \( e \) such as 34%. The 6.8 \( \mu m \) capsules with different mechanical strength did not show apparent difference in their flowing and shape recovery behaviors. However, the 8.6 \( \mu m \) capsules with a thicker wall (or namely stronger mechanical strength) could better resist the water flow-induced deformation with a slower passing through rate. In a sharp contrast, all the intact capsules prefilled with PSS could recover their original shape although the deformation extent was as large as 47%. The spontaneously deposited dyes could be well maintained as well. To the best of our knowledge, it is the first time to disclose the alteration of drug amount in multilayer microcapsules after being squeezed through a constriction. It is for sure that the method developed in this study can be applied to other microcapsules of different compositions, including those composed of biocompatible and biodegradable polymers which are the next focus of our study.

These results are important not only for understanding of capsule properties but also for their practical applications as drug delivery carriers. For example, the capsules for injection application should have a smaller size and soft wall structure, while those for embolization should have a stiff wall which can clog the blood vessels with higher efficiency.

**ASSOCIATED CONTENT**

1. Supporting Information

The groove characterized by laser scanning microscopy before bonding procedure; series of Z-scanning images of (PAH/PSS)\(_n\) microcapsules with variable size and layer numbers within and after passing through the microchannel; the distribution of capsule percentage as a function of consumed time through 100 \( \mu m \) distance of a 5.7 \( \mu m \) microchannel; CLSM image to demonstrate the “spontaneous deposition” of RD6G into (PAH/PSS),(PSS) microcapsules; 3D reconstruction of the (PAH/PSS),(PSS) microcapsule shown in Figure 3a. This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**

The authors declare no competing financial interest.

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