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# Bromide-doped polypyrrole microcapsules modified with gold nanoparticles

Krystyna Kijewska [a], Paulina Głowala [a], Katarzyna Wiktorska [b], Marcin Pisarek [c], Jarosław Stolarski [d], Daria Kępińska [a], Marianna Gniadek [a], Maciej Mazur [a,*]

[a] Department of Chemistry, University of Warsaw, Pasteura 1, 02-093 Warsaw, Poland
[b] National Medicines Institute, Chełmska 30/34, 00-725 Warsaw, Poland
[c] Institute of Physical Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw, Poland
[d] Institute of Paleobiology, Polish Academy of Sciences, Twarda 51/55, 00-818 Warsaw, Poland

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ABSTRACT

Micrometer sized polypyrrole capsules were prepared through the photochemical deposition of polymer onto the surface of aqueous droplets dispersed in bromoform. Scanning electron microscopy and transmission electron microscopy analyses demonstrate that the microcapsules are ca. 550 nm in diameter and contain an empty hollow region surrounded by a ca. 40 nm thick polymer shell. The XPS data reveal that the polymeric shell consists of polypyrrole doped with bromide anions, likely originating from the decomposition of bromoform during the photopolymerization reaction. The incorporation of gold nanoparticles inside the capsule allows for the ultrasound-triggered rupture of the structure. This phenomenon was applied to liberate encapsulated Rhodamine 6G to the external solution. This finding is very promising for possible applications in controlled drug delivery.



## 1. Introduction

Hollow polymer microcapsules have received considerable attention in recent years due to their important applications in medicine and chemical analysis. The most exciting feature of these structures is their ability to encapsulate guest materials inside the void regions, which can be released in a controlled manner into the surrounding medium. Polymeric hollow microcapsules have been successfully employed as delivery vehicles that transport drugs through the body to the targeted tissue. The role of the capsule's shell is either to shield the encapsulated material from degradation or to protect the human body from the harmful effects of the drug and restrict the release to only a desired therapeutic volume [1–6]. Hollow microspheres have also been used as micrometer-sized sensors that allow for the determination of the local concentration of analytes under *in situ* conditions. The diffusion of the analyte to the interior of the microcapsule yields an analytical signal that is subsequently detected by a confocal microscope. For example, microsphere-based sensors were used to monitor the pH and virus-specific antibodies [4,6]. The application of microcapsules as transducer layers in all-solid state ion selective electrodes has also been demonstrated [7].

Polymeric microcapsules are prepared from a variety of materials, which include but are not limited to polyelectrolytes [8], polysaccharides [9], proteins and conducting polymers. Although all of these materials have specific advantages, conducting polymers have recently attracted considerable attention due to their unique features [10]. They have been shown to exhibit a pH dependent permeability. In addition, they can be easily oxidized or reduced, which modifies their optical, electronic and mechanical properties [11]. Moreover, they are easily prepared through the chemical or electrochemical polymerization of the corresponding monomer. Recently, photochemical preparation of conducting polymers has attracted considerable attention. One of the most promising examples is photopolymerization of pyrrole which is carried out in chlorinated solvents [12–18]. Even though the detailed mechanism of the reaction is not known, it is believed that the photoexcitation of the monomer results in electron transfer to the solvent molecule. This generates radical cations that couple to produce the polymer. The possible mechanism of pyrrole photopolymerization in chloroform is shown below [19]:

$$Py + CHCl_3 + h\nu \rightarrow Py^{+\cdot} + \cdot CHCl_2 + Cl^-$$

* Corresponding author. Tel.: +4822822021 1x336; fax: +48228225996.
*E-mail address:* mmazur@chem.uw.edu.pl (M. Mazur).

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$Py^{+\cdot} + Py^{+\cdot} \rightarrow (Py)_2 + 2H^+$

We have demonstrated recently that photopolymerization of pyrrole in water–chloroform emulsion yields micrometer-sized capsules [19–21]. The polymer preferentially deposits onto the surface of aqueous droplets resulting in formation of hollow structures. As polypyrrole is a biocompatible material [22–24] such structures are promising as smart drug carriers. Here, the problem of controlled release of the encapsulated material is crucial. There are, in general, two ways to achieve this task: passive or stimulated release. In passive release, the encapsulated species permeate through the capsule's shell due to a chemical potential gradient. For stimulated release, an external stimulus is required to rupture or increase permeability of the capsule's wall. Several stimuli have been demonstrated to be effective to achieve this task, e.g. temperature, light or ultrasound [25]. A key feature of ultrasound from the point of view of medical applications is that this is a non-invasive, safe and painless transmission of energy into the body. Ultrasound can be used to transmit energy at precise locations and thus may be applied to damage the capsule walls. To enhance the ultrasonic effects the incorporation of solid particles into the capsules' walls has been demonstrated. The exact mechanism of nanoparticle-mediated destruction of polymer capsules is not clear, however, it is anticipated that the main effect is due to the fact that the nanoparticle-modified polymer is more rigid thus it is more susceptible to mechanical damage [26–28].

Herein, we report a facile method for the fabrication of polymer microcapsules through the photochemical polymerization of pyrrole onto the surface of aqueous droplets dispersed in a bromoform solution. Using microscopy techniques, we show that the resulting structures contain a hollow region surrounded by a polymer wall. The encapsulation of guest species within the microcapsules was demonstrated using gold nanoparticles and a Rhodamine 6G (R6G) dye. The release of the encapsulated material was achieved through the nanoparticle-mediated ultrasound rupture of the capsule's shell. Our findings show that polypyrrole-based hollow structures are a promising material that could find medical applications in controlled drug delivery.

## 2. Experimental

### 2.1. Chemicals

All chemicals were of the highest commercially available quality: pyrrole (Aldrich, 98%), bromoform (Aldrich, ≥99%), (mercaptoundecyl)tetra(ethylene glycol) functionalized gold nanoparticles (Aldrich, 2% w/v in water), Rhodamine 6G (Aldrich, 99%), hydrochloric acid (POCh, Poland, reagent grade), and sodium hydroxide (POCh, Poland, reagent grade). Aqueous solutions were prepared using high-purity water (Milli-Q Plus).

### 2.2. Procedures

#### 2.2.1. Preparation of hollow microcapsules

To 5 mL of bromoform (it is crucial to use high purity bromoform in the synthesis), 25 μL of water was added and sonicated for 30 s with an ultrasonic processor (Hielscher UP400S equipped with an S3 micro tip sonotrode). Subsequently, 200 μL of pyrrole was added to the mixture and the resulting emulsion was introduced to a cylindrical quartz container. The container was rotated at 20 rpm, while being exposed to irradiation from a mercury lamp (Polamp-5, Poland, 80 W), placed 10 cm from the reaction vessel, for 6 min. After the reaction was completed, the resulting microcapsules were separated from the supernatant by centrifugation and washed with bromoform. The centrifugation and washing steps were repeated three times.

#### 2.2.2. Re-suspension of microcapsules in water

After centrifugation, the excess solvent (bromoform) was removed with a pipette followed by the addition of 400 μL distilled water to the precipitate. The suspension was then rigorously shaken to uniformly disperse the capsules in the aqueous phase.

#### 2.2.3. Modification of microcapsules with gold nanoparticles

The entrapment of gold nanoparticles was accomplished using an aqueous solution of NPs (2% w/v) in place of water to prepare the polypyrrole microcapsules as described above.

#### 2.2.4. Loading the capsules with Rhodamine 6G

The capsules (neat or modified with gold NPs) were conditioned in a 0.1 mM aqueous solution R6G at pH 2 (the appropriate pH was achieved by addition of 0.1 M NaOH to 0.1 M HCl). After several minutes, the capsules were centrifuged and washed with a pH 6 aqueous solution. The washing and centrifugation were repeated until the supernatant exhibited no residual fluorescence.

#### 2.2.5. Ultrasonic treatment of the microcapsules

A suspension of microcapsules (in the absence and presence of R6G/NPs) in water (ca. 1 mg in 600 μL) was sonicated for 1 min with an ultrasonic processor. The effective power of sonication was 9.3 W as determined by the calorimetric method [29].

### 2.3. Instrumentation

Scanning electron microscopy (Zeiss Merlin field emission SEM) and transmission electron microscopy (Zeiss Libra 120 EFTEM or JEM 1400, JEOL Co.) were used to image the polypyrrole microcapsules.

The chemical composition of the capsules was characterized by X-ray photoelectron spectroscopy (XPS, Microlab 350) using $Al_{K\alpha}$ non-monochromated radiation (1486.6 eV, 300 W) as the excitation source. The pressure during the analysis was $5.0 \times 10^{-9}$ mbar. The binding energy of the target elements (C 1s, O 1s, N 1s, Br 3d, and Si 2p) was determined at a pass energy of 40 eV, with a resolution of 0.83 eV, using the binding energy of carbon (C 1s–285.0 eV) as a reference. A Shirley background subtraction was applied to obtain the XPS signal intensity. The peaks were fit using an asymmetric Gaussian/Lorentzian mixed function.

The XRF (X-ray fluorescence) measurements were performed at the ID 18 X-ray Microscopy beamline at the European Synchrotron Radiation Facility (Grenoble, France). The monochromatic X-ray beam of 14.4 keV energy was used to excite the spectra.

Fourier transform infrared (FTIR) spectroscopy was performed on KBr pellets using a Nicolet 8700 spectrometer. Raman spectra were acquired with a LabRAM HR spectrometer (Horiba Jobin Yvon) coupled to an Olympus BX41 confocal microscope. The excitation source was a LION semiconductor laser (Sacher Lasertechnik) operating at 784.7 nm. The Raman spectrometer was also used for recording the fluorescence spectra of Rhodamine 6G contained in individual polymer microcapsules suspended in the aqueous phase. For this purpose, the 532.3 nm line from the Excelsior-CDRH diode-pumped laser (Spectra Physics) was used to excite the fluorophore. The fluorescence spectra of the solutions were collected with a Fluorolog FL3-2-IHR320 spectrometer (Horiba Jobin Yvon).

Confocal fluorescence images were obtained using an Olympus FV500 confocal laser scanning microscope (CLSM) equipped with 100× oil immersion objective (NA 1.3). An Ar laser (488 nm) was used as an excitation source and the fluorescence was collected