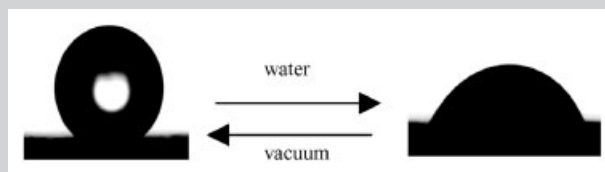


Summary: In this article, we designed and synthesized novel segmented poly(carbonate urethane)s containing both hydrophobic fluorinated alkyl group and hydrophilic phosphatidylcholine polar head groups on the side chain. The contact angle measurement, XPS, together with ATR-IR investigation indicated a reversible overturn of the phosphatidylcholine groups with the movement of the hydrophobic fluorinated alkyl groups when the samples were treated in dry air or water. The change in environment from air to water induced a reorganization of the surface in order to minimize the interfacial free energy, resulting in a macroscopic change of surface wettability. The good environmental responsiveness of such biomembrane-mimicking films may find successful applications as biomaterials.



Environmentally responsive surface using FPCPCU50 as an example; FPCPCU50 coated on aligned carbon nanotube film and dried in vacuum at 50 °C for 7 h and sample c treated in hot water at 80 °C for 1 h.

Novel Biomembrane-Mimicking Polymer Surface with Environmental Responsiveness

Hong Tan,¹ Taolei Sun,² Jiehua Li,¹ Min Guo,¹ Xingyi Xie,¹ Yiping Zhong,¹ Qiang Fu,^{*1} Lei Jiang^{*2}

¹ College of Polymer Science and Engineering, Sichuan University, State key Laboratory of Polymer Materials Engineering, Chengdu 610065, China

Fax: 0086-28-85405402; E-mail: qiangfu@scu.edu.cn

² Institute of Chemistry, Chinese Academy of Science, Beijing 100080, China

E-mail: leijiang@iccas.ac.cn

Received: May 15, 2005; Revised: June 26, 2005; Accepted: June 27, 2005; DOI: 10.1002/marc.200500326

Keywords: environmental responsiveness; fluorinated phosphatidylcholine poly(carbonate urethane); surface behavior

Introduction

Designing of the topmost surface layer with a controlled predictable surface response, or a variable surface response under different conditions has attracted more and more attention for specific applications, such as in biological and biomedical areas. One example is controlling of the response of cells exposed to a biologically active surface containing specific functional unites. Another example is the use of intelligent polymers to change the surface characteristics in response to an environmental stimulus.^[1] Such polymers have been used in tissue culture to detach cells from the surface without the need for trypsin. Moreover, further advances in materials science impose requirements for dual surface properties that frequently are in conflict: a given materials, depending on the conditions under which it is utilized, has to be hydrophobic and hydrophilic, acidic and basic, conductive or non-conductive, adhesive or repellent, and be able to release or adsorb some species. So the surface capable of undergoing reversible changes according

to outside conditions or stimuli is highly demanded. A number of approaches have been employed to reach this goal, including (a) synthesis of functional polymers with specific composition and architecture;^[2–7] One example is a novel type of segmented polyurethanes having both fluorocarbon and polyethylene glycol, which shows a range of hydrophobic and hydrophilic properties in response to the polarity of the contacting medium;^[4] (b) blending of a virgin polymer materials with small amounts of (macro)-molecular additive;^[8–12] (c) surface modification by various chemical/physical treatments.^[13–16] Poly(carbonate urethane)s (PCU) are used as biomedical materials of long-term implants because of their biostability and moderate biocompatibility same as poly(ether urethane)s.^[17] The moderate biocompatibility of PCU is due to the hard segment microdomains at the surface because it would keep protein in native or near-native state on adsorption that has the similar size.^[18] Polyurethanes with phosphatidylcholine polar head groups are desired due to the advantage of better biocompatibility. The key is that the phosphatidyl-

choline polar head group is located on the uppermost surface and capable of undergoing reversible changes according to outside conditions. In order to obtain biomedical polyurethanes with excellent biocompatibilities and biostability as well as smart surface behavior, a novel chain extender with long fluorinated side chain phosphatidylcholine and a series of fluorinated phosphatidylcholine (FPC) polyurethanes attached on the hard block have been designed and synthesized recently in our group.^[19] In this article, we will focus our attention on the surface rearrangement of the obtained fluorinated phosphatidylcholine poly(carbonate urethane)s by using contact angle measurement, XPS, and ATR-IR. Interestingly, we have found for the first time a reversible change in the surface property from hydrophobic in dry air to hydrophilic in hot water condition for this material. They show a potential to be used as biomembrane mimicry as in the controlling release of soils and proteins from their surface in both air and water.

Experimental Part

Materials

To obtain fluorinated phosphatidylcholine polyurethanes, a new diol with a long side chain fluorinated alkyl phosphatidylcholine polar headgroup (2-[2-[2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9-hexadecafluoro-10-ethoxy-decyloxy]-*N*-(2-hydroxy-1-hydroxymethyl-1-methyl-ethyl)-acetamide] phosphatidylcholine, HFDAPC) was first synthesized and characterized. Then a series of poly(carbonate urethane)s containing long side chain fluorinated alkyl phosphatidylcholine polar headgroup were synthesized using methylenebis(phenylene isocyanate) (MDI), poly(1,6-hexyl-1,5-pentylcarbonate) diol (PHPCD, $\bar{M}_n = 1058$), 1,4-butanediol (BDO) and HFDAPC as a chain extender. The detailed synthesis route of these fluorinated phosphatidylcholine polyurethanes can be found in reference.^[19] The struc-

tures of these poly(carbonate urethane)s are shown in Figure 1. The ratio of MDI/chain extender/PHPCD, the content of fluorine and phosphorus attached on the hard block can be controlled, as listed in Table 1. The original poly(carbonate urethane) without fluorinated phosphatidylcholine group is designated as PCU and poly(carbonate urethane) with fluorinated phosphatidylcholine group is designated as FPCPCU. The number attached to FPCPCU represents the percentage of the new diol. For example, FPCPCU50 means that 50% of new diol has been used as a chain extender.

Contact Angle Measurements

Contact angles were measured with an OCA20 (Dataphysics Inc) contact angle goniometer. The sample for contact angle measurement was prepared by casting the polymer onto a clean silicon wafer from 5% (w/v) DMAc. The silicon wafers were kept in an oven at 40 °C for 24 h, 50 °C for 12 h, and 60 °C for 3 d under vacuum. Contact angles were measured on 3 μ L of water at 20 °C, and the results reported are the mean values of three replicates.

X-Ray Photoelectron Spectroscopy (XPS)

XPS was carried out on an 220i-XL electron spectrometer (VG Sci., UK). The spectrometer was equipped with a Mg K α achromatic X-ray source (20 KV, 10 mA) and different take-off angles between 5° and 90° were used with X-ray source. Each sample for XPS was prepared by casting the polymer onto a silicon wafer from 5% (w/v) DMAc. The samples were kept in an oven at 40 °C for 24 h, 50 °C for 12 h, and 60 °C for 3 d under vacuum.

ATR-IR

The sample for ATR-IR measurement was prepared in the same way as for the sample for XPS. Infrared data were obtained

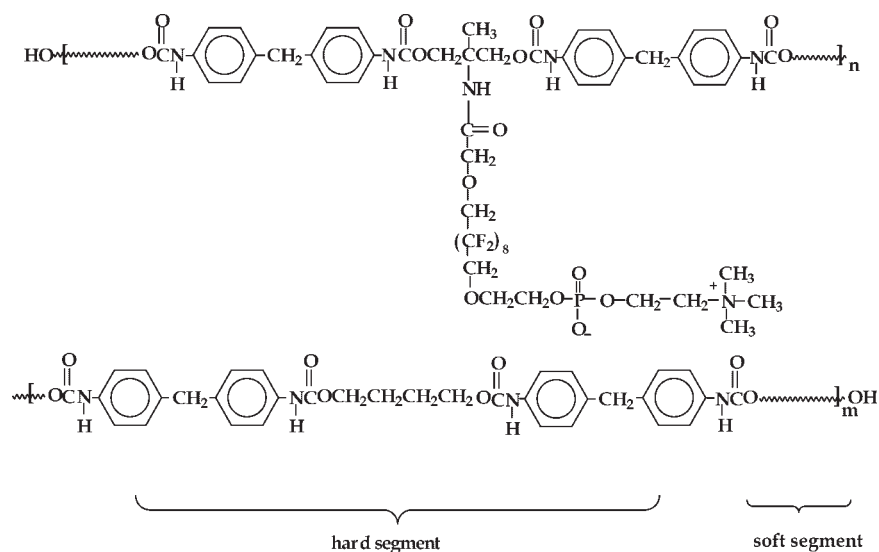


Figure 1. The schematic structure of fluorinated phosphatidylcholine polyurethanes, $n = 1, 2, 3, \dots$; $m = 0, 1, 2, 3, \dots$. Soft segment is PHPCD.

Table 1. Theoretical composition of segmented poly(carbonate urethane)s with various amounts of fluorinated phosphatidylcholine diol chain extender.

Sample	Molar ratio of MDI/chain extender/PHPCD	Chain extender BDO, FPC ^{a)}	Fluorine atom ^{b)}	Phosphorus atom ^{b)}
		mol	%	%
PCU	2:1:1	1.0, 0.0	0.0	0.00
FPCPCU50	2:1:1	0.5, 0.5	5.6	0.35

^{a)} FPC: HFDAPC.

^{b)} The theoretical value F (or P): the total molar quantity of fluorine atom (or phosphorus atom) is divided by the total molar quantity of carbon atom, oxygen atom, nitrogen atom, fluorine atom and phosphorus atom in the FPCPCU50.

with the Nicolet-750 (Thunderdome attachment) spectrophotometer between 4000 and 600 cm^{-1} in the resolution of 4 cm^{-1} .

Results

Water Contact Angle Measurement

Water contact angle measurement is usually used to characterize the surface property of a sample. The water contact angle for FPCPCU is observed much decreased for static, advancing, and receding contact angle compared with that of PCU. For example, the static, advancing, and receding contact angle for PCU are 75°, 77°, and 53°, respectively,^[19] but the corresponding static, advancing, and receding contact angle become 66°, 66°, and 26°, respectively, for FPCPCU50. On the other hand, an obvious increase of hysteresis (which is the difference of advancing angle and receding angle) is seen for FPCPCU compared with that for PCU. Usually a decreased advancing contact angle indicates an increased hydrophilicity, and the increased hysteresis angle indicates a possible rearrangement of surface structure.^[20] Not only the rearrangement, we will show in the following that the surface change is also reversible. To do this, the film of FPCPCU50 was first dried in vacuum at 50 °C for 7 h, then the water contact angle was measured and this is shown in Figure 2(a). One observes an increased hydrophobic surface with a contact angle of 77.7°. Then the same film was treated in hot water at 80 °C for 1 h. After being dried quickly at room temperature by using nitrogen, the water contact angle was measured again and this is shown in Figure 2(b). Expectedly, in this case a hydrophilic surface is observed with a contact angle of 57.5°. This experiment was repeated several times. The change of surface structure was investigated by water contact measurement in each case after being dried in vacuum or treated in hot water. In the air (vacuum)-equilibrated state, lower surface free energy components (hydrophobic fluorinated alkyl groups) are enriched at the air-solid interface, whereas in the water-equilibrated state, higher surface free energy components (hydrophilic phosphatidylcholine polar head groups) are enriched at the water-solid interface. Therefore, the surface change from hydrophobic in dry state to hydrophilic in hydrated state is a reversible process. Since

the introduction of microstructure in a surface can substantially enhance the wettability of a film, as in the case of vinyltrimethoxysilane and (2-(perfluorooctyl)ethyl)trimethoxysilane modified anisotropic aligned carbon nanotube films,^[21] we carried out the water content measurement on a film located on carbon nanotube to further verify the reversible process. As shown in Figure 2(c) and (d), one observes a highly hydrophobic surface with a contact angle of 153° as treated in vacuum and a hydrophilic surface with a contact angle of 63.5° as treated in hot water. The significant increase in water contact angle in this case is definitely due to the dominant effect of the surface roughness on wettability. This will cause a huge increase of water contact angle as treated in air ($\theta = 153^\circ$ compare to 77.7°) but small as treated in hot water ($\theta = 63.5^\circ$ compare to 57.5°). Our result suggests an possible alternating change of up and down between hydrophobic fluorinated group and hydrophilic phosphatidylcholine group of FPCPCU as change of environment. There may exist another possibility that the surface change is due to temperature difference as treated in vacuum at 50 °C and in hot water at 80 °C. To rule out this possibility, the same experiment was repeated but in hot water at 50 °C. The same result was observed, just a little bit long time was needed in this case, indicating that the treated temperature in our study will not cause an obvious

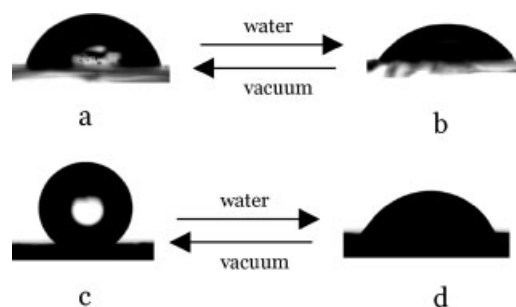


Figure 2. Environmentally responsive surface using FPCPCU50 as an example (a) FPCPCU50 coated on silicon wafer and dried in vacuum at 50 °C for 7 h. (b) Sample a treated in hot water at 80 °C for 1 h, after dried quickly at room temperature by using nitrogen. (c) FPCPCU50 coated on aligned carbon nanotube film and dried in vacuum at 50 °C for 7 h. (d) Sample c treated in hot water at 80 °C for 1 h.

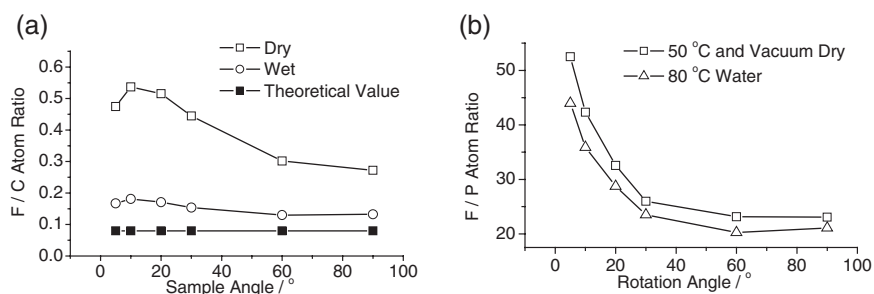


Figure 3. Atomic percentage rate of F/C and F/P on the surface of FPCPCU50 film in 50 °C vacuum dry and 80 °C water condition.

difference of surface structure. But this is truly an environmentally responsive surface.

XPS

If the surface change from hydrophobic in dry state to hydrophilic in hydrated state is due to the alternating change of up and down between hydrophobic fluorinated group and hydrophilic phosphatidylcholine group, one should observe a change of atomic percentage ratio of F/C and F/P on the surface of FPCPCU50 film. Thus XPS experiment was carried out. Since the XPS can be only done in high degree of vacuum, in the case of being treated by hot water, the film was immediately dried at room temperature by using nitrogen. Then it was put into sample holder for XPS experiment. It should be noted that the placement of the sample under medium or high vacuum might cause the surface to reconstruct due to rapid removal of the water. This can be neglected in this case since the relative high T_g of PCU will stabilize the surface structure. So it is reasonable to assume that the surface structure being treated in hot water can be preserved during the dry and short time measurement in XPS experiment. The XPS result of FPCPCU50 is shown in Figure 3. As for atomic ratio of F/C [Figure 3(a)], one observes a much higher value for the sample being treated in vacuum than that of treated in hot water at all take off angle investigated. Particularly, at low take-off angle, the difference of atomic ratio of F/C becomes largest. It should also be noted that in both cases, the ratio of F/C has a higher value than the theoretical calculated value. This can be understood as due to the migration of fluorinated group to the surface. For F/P atomic ratio [Figure 3(b)], on the other hand, the value for the sample being treated in vacuum is higher than that of treated in hot water at all take-off angle measured. Again the much higher F/P ratio at low take-off angle is due to the migration of fluorinated group to the surface. The XPS result indicates that the fluorinated group is most likely located at the most up surface after the film is treated in vacuum while the phosphatidylcholine group is most likely located at the most up surface after the film is treated in hot water. XPS result is in good agreement with the water contact angle measurement.

ATR-IR

Though ATR-IR is not surface sensitive because the probing depth extends to a few micrometers into the bulk, we still used this technique to obtain the complementary information near surface, and this is shown in Figure 4. A single stretching band is observed near 1647 cm^{-1} corresponding to the hydrogen-bonded amide. The stretching bands at $\approx 1064\text{ cm}^{-1}$, $\approx 791\text{ cm}^{-1}$, $\approx 768\text{ cm}^{-1}$ are due to the absorption of P-OCH₂, OCO, and -O-C=O, respectively. In dry air, the very weakened single stretching band at 1647 cm^{-1} indicates that the fluorinated group is mostly located on the near surface and phosphatidylcholine group is hidden underneath. However, in hydrated environment (after treated in hot water), one observes a huge peak at 3358 cm^{-1} corresponding to the -OH of free water. Meanwhile, an enhanced stretching band at $\approx 1649\text{ cm}^{-1}$ is seen, and the stretching bands between 1100 and 700 cm^{-1} are markedly changed, indicating a rearrangement of surface property with phosphatidylcholine group located on the near surface and biomembrane mimicry formed in

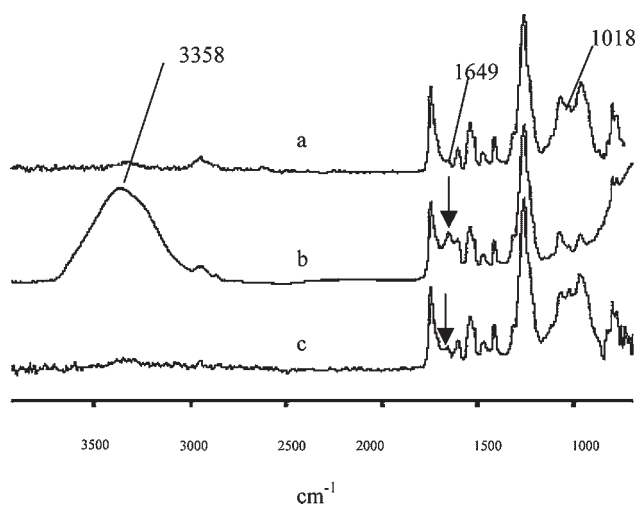


Figure 4. ATR spectra results of FPCPCU50 coated on silicon wafer (a) dried in vacuum at 50 °C for 7 h (D), (b) The sample a treated in hot water at 80 °C for 1 h, and water only adsorbed with filter paper. (c) The sample b dried quickly at room temperature by using nitrogen.

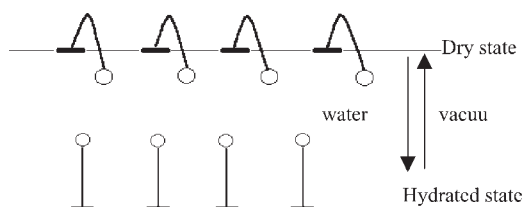


Figure 5. Schematic diagrams of the phosphatidylcholine molecular chain overturn and movement on the polyurethanes surface under hot water condition. ○: PC polar group.

this case. After dried again in air, the ATR-IR spectra returns back nearly to that of original dry state. So the ATR-IR result suggests once again that the surface change from hydrophobic to hydrophilic is a reversible process. The schematic diagram of the reversible surface change in dry air and in hydrated water is shown in Figure 5.

Conclusion

In summary, we have successfully obtained novel segmented poly(carbonate urethane)s with both long side chain fluorinated alkyl and phosphatidylcholine polar head groups attached to hard block. These poly(carbonate urethane)s show smart surface behavior. In dry air, the fluorinated group is enriched on the uppermost surface and phosphatidylcholine group is hidden underneath, resulting in a hydrophobic surface. In hydrated water, on the other hand, the phosphatidylcholine group is enriched on the uppermost surface and fluorinated group hidden underneath, resulting in a highly hydrophilic surface. Since the excellent biocompatibility of the phosphatidylcholine group and its ability to suppress protein adsorption, this environmentally responsive surface has a potential to be used as biomembrane mimicry.

Acknowledgements: We would like to express our great thanks to the *National Natural Science Foundation of China* (50303014)

and *Young Foundation of Sichuan University* for Financial Support.

- [1] A. S. Hoffman, *Macromol. Symp.* **1995**, 98, 645.
- [2] T. P. Russel, *Science* **2002**, 297, 964.
- [3] R. Mason, C. A. Jalbert, P. A. V. O'Rourke Muisener, J. T. Koberstein, J. F. Elman, T. E. Long, B. Z. Gunesin, *Adv. Colloid Interface.* **2001**, 94, 1.
- [4] A. Vaidya, M. K. Chaudhury, *J. Colloid Interface. Sci.* **2002**, 249, 235.
- [5] Y. Tezuka, S. Nobe, T. Shiomi, *Macromolecules* **1995**, 28, 8251.
- [6] H. Mori, A. Hirao, S. Nakahama, K. Senshu, *Macromolecules* **1994**, 27, 4093.
- [7] Zb. Pientka, H. Oike, Y. Tezuka, *Langmuir* **1999**, 15, 3197.
- [8] C. Forrey, J. T. Koberstein, D. H. Pan, *Interface Sci.* **2003**, 11, 211.
- [9] I. Hopkinson, F. T. Kiff, R. W. Richards, S. Affrossman, M. Hartshorne, R. A. Pethrick, H. Munro, J. R. P. Webster, *Macromolecules* **1995**, 28, 627.
- [10] J. T. Koberstein, "Polymer Surface Properties", in: "Encyclopedia of Polymer Science and Technology", Wiley Publisher, New York 2001.
- [11] S. K. Thanawala, M. K. Chaudhury, *Langmuir* **2000**, 16, 1256.
- [12] A. Hariharan, S. K. Kumar, T. P. Russell, *J. Chem. Phys.* **1993**, 98, 4163.
- [13] D. E. Bergbreiter, B. Walchuk, B. Holtzman, H. N. Gray, *Macromolecules* **1998**, 31, 3417.
- [14] D. E. Bergbreiter, *Prog. Polym. Sci.* **1994**, 19, 529.
- [15] J. Genzer, K. Efimenko, *Science* **2000**, 290, 2130.
- [16] R. A. Lampitt, J. M. Crowther, J. P. S. Badyal, *J. Phys. Chem. B* **2000**, 104, 10329.
- [17] K. Stokes, R. McVenes, J. M. Anderson, *J. Biomater. Appl.* **1995**, 9, 321.
- [18] K. G. Tingey, J. D. Andrade, *Langmuir* **1991**, 7, 2471.
- [19] H. Tan, Ph.D. Thesis, Sichuan University, 2004.
- [20] P. C. Hiemenz, R. Rajagopalan, "Principles of Colloid and Surface Chemistry", 3rd edition, Mercel Dekker, New York 1997.
- [21] T. L. Sun, G. J. Wang, H. Liu, L. Feng, L. Jiang, D. B. Zhu, *J. Am. Chem. Soc.* **2003**, 125, 14996.