Geometric bionics: Lotus effect helps polystyrene nanotube films get good blood compatibility

Chun Mao*, Wen-Bo Zhao*, Wen-Ping Luo, Cun-Xia Liang, Xiao-Mei Hou, Xiao-Hua Huang, Hong-Ke Liu, Ying-Hong Xiao, Jian-Chun Bao & Jian Shen

Jiangsu Key Laboratory of Biofunctional Materials, College of Chemistry and Environmental Science, Nanjing Normal University, Nanjing 210097, China

*These authors contributed equally to this work.

Various biomaterials have been widely used for manufacturing biomedical applications including artificial organs, medical devices and disposable clinical apparatus, such as vascular prostheses, blood pumps, artificial kidney, artificial hearts, dialyzers and plasma separators, which could be used in contact with blood[1]. However, the research tasks of improving hemocompatibility of biomaterials have been carrying out with the development of biomedical requirements[2]. Since the interactions that lead to surface-induced thrombosis occurring at the blood–biomaterial interface become a reason of familiar current complications with grafts therapy, improvement of the blood compatibility of artificial polymer surfaces is, therefore a major issue in biomaterials science[3]. After decades of focused research, various approaches of modifying biomaterial surfaces through chemical or biochemical methods to improve their hemocompatibility were obtained[1]. In this article, we report that polystyrene nanotube films with morphology similar to the papilla on lotus leaf can be used as blood-contacted biomaterials by virtue of Lotus effect[4]. Clearly, this idea, resulting from geometric bionics that mimicking the structure design of lotus leaf, is very novel technique for preparation of hemocompatible biomaterials.

When in direct contact with blood, the conventional polymers presently used are still prone to initiate the formation of clots, as platelets and other components of the blood coagulation system are activated. As we known, the interactions between the biological environment and polymers are most likely dominated by the materials' surface properties. So how to improve blood compatibility of polymer surfaces is a major issue in biomaterials science[3]. Most of approaches were obtained by chemical methods including chemical grafting modification, radiation, surface-modifying additives and self-assembly technology in the past time[1]. However, nature always gives us inspirations to fabricate functional materials by mimicking the structure design of natural materials. Further, using nature is best method to solve nature's problem. The concept of biofilm mimetic surfaces was brought forward[5-7]. Based on the premise of achieving hemocompatibility through mimicking the chemical constituents of the biologically inert surface of the inactivated platelet film, considerable attention has been paid to development of the new technologies that get better hemocompatiblity.

We show here, that polystyrene (PS) nanotube films were prepared and used as blood-contacted biomaterials. This idea, resulting from geometric bionics that mimicking the structure design of lotus leaf (Fig. 1), is very novel for preparation of anticoagulated biomaterials. This is first time to report in the world that good blood compatibility of polymer film was obtained just by controlling the geometrical shape of the surface, not changing chemical composition of the surface.

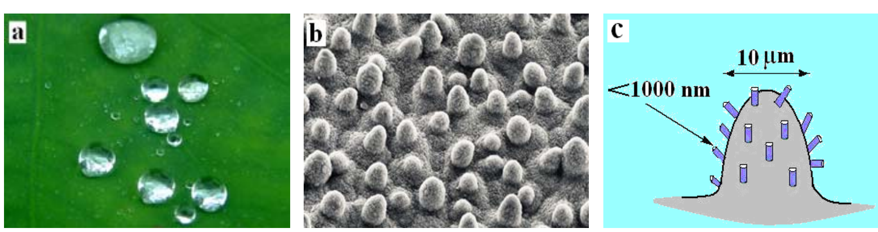

Figure 1 Lotus effect. **a,** Lotus leaf and beads. **b,** SEM image of micropapillae presented the surface of lotus leaf. Reproduced from [4] with perimission from Springer. **c,** Nano- and

microstructure of a single papilla.

Lotus effect, the self-cleaning effect of lotus leaf is of great interest for practical application. The observation of hydrophobicity related to the topology of the surface of a lotus leaf was previously reported by Barthlott and Neinhuis[4,8]. Jiang's group also reported a novel finding of a lotus leaf, *i.e.*, branch-like nanostructures on top of the micropapillae. These structures can induce super-hydrophobic surfaces with large contact angle and low sliding angle[9]. It was believed that this unique property of self-cleaning is based on surface roughness caused by the micrometer-scale papillae and nanometer-scale tomenta (Fig. 1b and 1c).

We are about to report for the first time the application of anticoagulated biomaterials using a super-hydrophobic nano- and microstructured surface from PS, a kind of conventional polymers by help of geometric bionics.

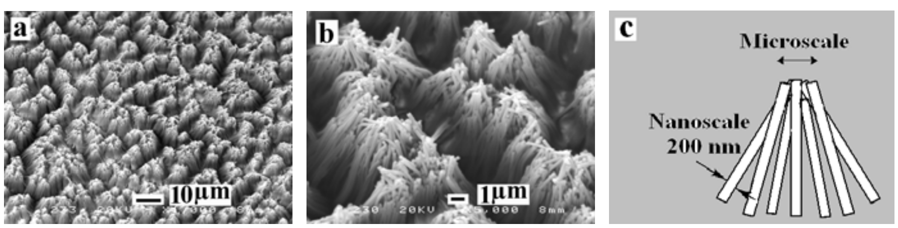

Figure 2 SEM view of PS nanotube film surface. **a,** Blank PS nanotube film surface. **b,** Enlarge view of a few of PS nanotube papillae from (a-1). **c,** Nano- and microstructure of a single PS nanotube papilla.

The method used to fabricate the PS nanotube film is simple. A porous template of commercial alumina films with 200 nm diameter pores (Anodisc 25, Whatman Int. Ltd., England) was brought into contact a PS film under a certainty light load (Vacuum Drying Oven, 170 °C, 0.1 MPa). After 12 h, the template was dissolved away by NaOH solution at room temperature, and an aligned PS nanotube film was obtained.

As shown as Fig. 2, the structure of blank PS nanotube film surface is almost same with that of lotus leaf surface. So we want to know whether hierarchical roughness of PS nanotube films that attributed to Nanoscale PS branches (diameter: about 200 nm) and microscale PS papilla (See Fig. 2b and 2c) is beneficial for superhydrophobic and self-cleaning surfaces when they are used in contact with platelet or blood.

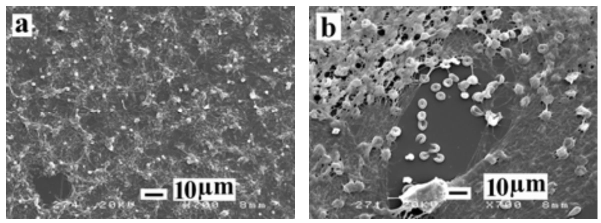

Figure 3 SEM view of blank PS film surface. **a,** After contact with PRP for 90 min. **b,** After contact with huamn whole blood for 90 min.

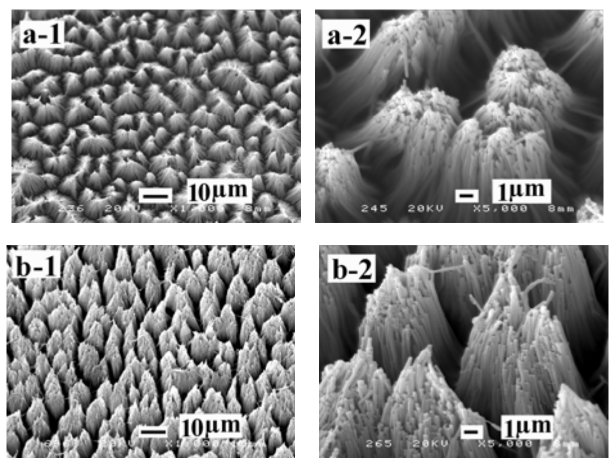

Figure 4 SEM view of PS nanotube film surface. **a-1, A**fter contact with PRP for 90 min. **a-2,** Enlarge view of a few of papillae from (a-1). **b-1,** After contact with human whole blood for 90 min. **b-2,** Enlarge view of a few of papillae from (b-1).

To confirm preliminary blood compatibility of PS nanotube film, platelet and blood cell adhesion on the PS nanotube film after contact with platelet-rich plasma (PRP) and human whole blood respectively were evaluated by SEM observation (See Supplementary Information A)[10]. Figure 3 shows SEM pictures of the blank PS films after 90-min contact with the PRP or whole blood. The blank PS films showed high platelet adhesion, most of the adhered platelets were distorted with pseudopodia (Fig.

3a). Surprisingly, the surfaces of PS nanotube film have nearly no adhered platelets (Fig. 4a-1 and 4a-2). This tendency was also clear when the films were placed in contact with human whole blood. Many adherent blood cells were observed on the blank PS film after contact with whole blood (Fig. 3b). On the other hand, blood cell adhesion was suppressed on the PS nanotube film (Fig. 4b-1 and 4b-2).

The platelet and blood cells adhesion tests revealed that PS nanotube film show excellent anti-platelet and anti-blood cell adhesion. It is considered that the improved anticoagulation can be attributed to the Lotus effect from nano- and microstructure of PS nanotube film[4,8,9,11,12]. Platelets and blood cells were repelled on the superhydrophobic coating (Water contact angle is about 151º, See Supplementary Information B) formed by using the hierarchical aggregates as the surface building blocks. There were no report on the application of anticoagulated biomaterials by help of geometric bionics. This study might open up new perspectives in the preparation of biomedical materials from various types of conventional materials by the hands of nanotechnology.

1. Mao, C. *et al.* Various approaches to modify biomaterial surfaces for improving hemocompatibility. *Adv. Colloid and Interface Sci.* **110,** 5–17 (2004).
2. Ratner, B. D. The catastrophe revisited: Blood compatibility in the 21st Century. *Biomaterials* **28,** 5144–5147 (2007).
3. Aldenhoff, Y. B. J. *et al.* Photo-immobilization of dipyridamole (Persantin®) at the surface of polyurethane biomaterials: Reduction of in vitro thrombogenicity. *Biomaterials* **18,** 167-172 (1997).

4. Barthlott, W. & Neinhuis, C. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta* **202,** 1-8 (1997).

5. Ishihara, K. *et al.* Modifcation of polysulfone with phospholipid polymer for improvement of the blood compatibility. Part 2. Protein adsorption and platelet adhesion. *Biomaterials* **20,** 1553-1559 (1999).

6. Greisler, H. *et al.* Biointeractive polymers and tissue engineered blood vessels. *Biomaterials* **17,** 329-336 (1996).

7. Salacinski, H. J. *et al.* A Hybrid Compliant Vascular Graft Seeded with Microvascular Endothelial Cells Extracted from Human Omentum. *Artif. Organs* **25,** 947-982 (2001).

8. Neinhuis, C. & Barthlott, W. Characterization and distribution of water-repellent, self-cleaning plant surfaces. *Ann. Bot.* **79,** 667-677 (1997).

9. Feng, L. *et al.* Super-Hydrophobic Surfaces: From Natural to Artifical. *Adv. Mater.* **14,** 1857-1860 (2002).

10. Ishihara, K. *et al.* Improved blood compatibility of segmented polyurethanes by polymeric additives having phospholipid polar groups. I. Molecular design of polymeric additives and their functions. *J. Biomed. Mater. Res.* **32,** 391-399 (1996).

11. Gao, X. F. & Jiang, L. Water-repellent legs of water striders. *Nature* **432,** 36 (2004).

12. Jin, M. H. *et al.* Superhydrophobic Aligned Polystyrene Nanotube Films with High Adhesive Force. *Adv. Mater.* **17,** 1977-1981 (2005).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant No. 20874047) and the Natural Science Key Basic Research Foundation of the Jiangsu Higher Education Institutions of China (Grant No. 08KJA430003). We thank Prof. Yong Qiang Mao (Center of Technology Laboratory, Nanjing Institute of Geology and Palaeontology Academia Sinica, China) for the SEM images.

Author Contributions This work was performed jointly in the Shen's group and Jiangsu Key Laboratory of Biofunctional Materials and with substantial contributions from each.

Author Information Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Jian Shen. (jsklbm@yahoo.com.cn).