Biologie-inspirierte Grenzflächen- und Materialgestaltung

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Im Jahr 2016 konnten am IPF verschiedene neue Facetten Biologie-inspirierter Polymermaterialien erkundet werden. Dabei war es uns ein besonderes Anliegen, translationale Forschungsansätze zu verstärken. So gelang es im Rahmen des Transregio-Sonderforschungsbereichs „Biomaterialien zur Regeneration von Knochen und Haut“ (TR67) Möglichkeiten zur Modulation von entzündungsrelevanten Zytokinen durch Biomaterialien zu erschließen, woraus sich wertvolle Optionen für die bessere Behandlung von chronischen Wunden ergeben (Adv Healthc Mater 5 (2016) 3157-3164). Mit Hilfe makroporöser Cryogele konnte ein neuer Ansatz für die Transplantation von Inselzellen zur Behandlung von Diabetis Type I entwickelt und im Tiermodell als erfolgversprechend bewertet werden (Acta Biomater 44 (2016) 178-187, mit Professor E. Bonifacio, CRTD). Funktionell angepasste Polymernetzwerke dienten auch als Grundlage für die gezielte Steuerung von Organoid-Kulturen, denen für die Untersuchung von biologischen Entwicklungsprozessen, aber auch für pharmazeutische Studien immer größeres Interesse zukommt (Biomaterials doi: 10.1016/j.biomaterials.2016.10.007). Die multifaktorielle Stimulation von humanen Stammzellen des Knochenmarkraums konnte im Rahmen des Sonderforschungsbereichs „Cells into Tissues“ (SFB 655) mit Hilfe von mikrostrukturierten Hydrogelen umfassend modellhaft beschrieben werden (Kooperation mit Professor Tilo Pompe, Leipzig, und Professor Peter Zandstra, Toronto, Scientific Reports 6 (2016) DOI:10.1038/ srep31951). Fortschritte wurden auch bei der Entwicklung von dreidimensionalen in vitro Modellen für das Mikromilieu von Tumorzellen (Acta Biomaterialia 36 (2016) 73-85) und bei der Entwicklung neuer, Heparin-funktionalisierter Mikropartikelsysteme für fokale Krebstherapien erreicht werden (mit IPF-Fellow Professor Philipp Seib, Strathclyde University, Glasgow U.K./ ACS Biomater. Sci. Eng 2016 DOI: 10.1021/ acsbiomaterials.6b00495). Auch beim Einsatz von Glycodendrimeren als Aktivwirkstoffe zur Leukämiebehandlung wurden Erfolge erzielt (mit IPF-Fellow Professor Barbara Klajnert, Lodz, Polen, Anti-Cancer Agents, 2017,17, 102 und Latest Thinking 2016, https://lt.org). Zur in vitro Untersuchung von Aktivierungsprozessen des humanen Blutes durch Implantatmaterialien wurde eine erweiterte Methodik unter Einbeziehung von Gefäßendothelzellen entwickelt und validiert (Zwanzig20 BMBF-Verbund RESPONSE, Biomaterials 104 (2016) 258–268). Ein neues Konzept zur Zwei-Photonen-Zykloaddition von Maleiimiden konnte für die dreidimensionale Strukturierung und molekulare Funktionalisierung von Hydrogelen erschlossen werden (mit dem BMBF-Innovationszentrum für Molekulare Bioingenieurswissenschaft B CUBE an der TU Dresden, Advanced Materials, 2016, DOI: 10.1002/adma. 201603327). Neben den o.a. Themen wurden 2016 verstärkt biomimetische Ansätze zur Kontrolle der mikrobiellen Besiedlung von Oberflächen verfolgt; hierzu geben die nachfolgenden Berichte (S. Schulz et al., R. Helbig et al., L. Renner et al.) näher Auskunft. Es wurden Übersichtsarbeiten zu fundamentalen Konzepten benetzungsresistenter und anti-bioadhäsvier Oberflächen in der Natur und zu Möglichkeiten ihrer synthetischen Imitation (Chemical Society Reviews 45(2016) 323-341) sowie zur Gestaltung Glykosaminoglykan-basierter Hydrogele für biomedizinische Anwendungen (Advanced Materials DOI: 10.1002/adma.201601908) publiziert. In einem Themenheft der Zeitschrift Current Opinion in Colloid and Interface Science (Volume 24 (2016) A1-A2) wurde der aktuelle Stand von Forschungen auf dem Gebiet elektrokinetischer Phänomene zusammengefasst, ein eigener Beitrag befasste sich mit Zusammenhängen zwischen Ladung und Struktur von Polymer-Grenzschichten (Current Opinion in Colloid and Interface Science 24 (2016) 1-12 mit Professor Jerome Duval, Nancy). Elektrokinetische Phänomene werden auch Gegenstand einer Internationalen Konferenz sein, die im September 2017 am IPF stattfinden wird (http://www.elkin2017.org/home/). Auf dem 10th World Biomaterials Congress (19. bis 24.5.2016, Montreal, Kanada), der wichtigsten internationalen Konferenz des Forschungsgebietes mit mehr als 5000 Teilnehmern, war das Institut mit zwei eigenen New Frontier Symposien (“Cell- instructive polymer matrices to direct organogenesis in vitro” und “Glycosaminoglycan-based cell-instructive materials”) sowie 20 eigenen wissenschaftlichen Beiträgen sehr sichtbar vertreten.

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Exploring the impact of surface structures on initial bacterial adhesion

Ralf Helbig, Jens Friedrichs, Carsten Werner

Adhesion, accumulation and growth of micro-organisms on man-made surfaces in contact with aerial or saline environments, designated as biofouling, can have severe negative consequences in various fields including industrial processes (e.g., food processing, textile, pulp and paper manufacturing) [1,2], medicine (e.g., nosocomial infections) [3-5] and seawater contacting equipment (e.g., pipelines, cooling and filtration systems, fishing nets, ship hulls and bridge pillars) [6]. Despite of the vast amount of literature about bacterial surface interactions a conclusive picture of bacterial retention on structured surfaces does currently not exist.
In our study, cells of a gram positive bacterial strain (*Staphylococcus epidermidis*) and a gram negative strain (*Escherichia coli*) were seeded on surfaces with different micron and submicron-sized structures. The compared surfaces were prepared by Laser Interference Patterning (LIP) [7–9] and varied in structure-type and -dimensions, as well as in their wetting properties. We found a strong dependence of bacterial retention on the structure dimensions of the applied substrates. Periodicities in the range of the bacterial size were observed to increase the retention, smaller periodicities decreased the retention, independent of contact time (minutes to hours), hydrophobicity (Fig. 1) and structure type (Fig. 2) [10]. These results may facilitate the future development of non-fouling surfaces.

Sponsor:
Deutsche Forschungsgemeinschaft (DFG)
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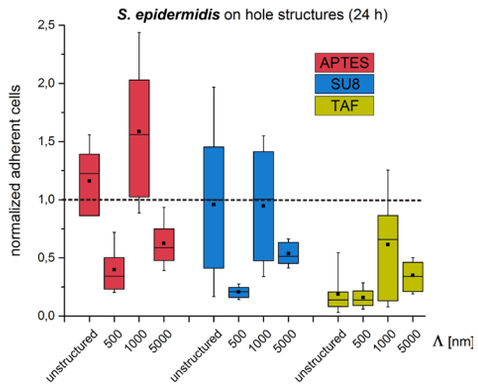
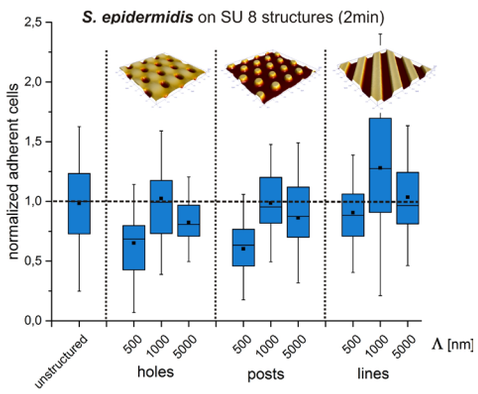
Co-operation:
Prof. A. Lasagni, Fraunhofer Institute for Material and Beam Technology Dresden





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Keywords
initial adhesion
bacterial retention
topography
bio-fouling

Fig. 1:
Bacterial retention on micron- and submicron-scaled structured surfaces of different hydrophobicity. Normalized adherent *S. epidermidis* after 24h. The structure period -Λ- is denoted on the x-axis. Black continuous lines and black rectangles within the boxes mark median and mean, respectively. All values are normalized to the median of unstructured SU8.
APTES - (3-aminopropyl) triethoxysilane; SU8 - Photoresist, TAF - amorphous fluoro polymer

Fig. 2:
Bacterial retention on micron- and sub-micron-scaled hole, post and line structures. Normalized adherent S. epidermidis cells after 2 min of attachment. (Box–whisker details see Fig. 1)

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Keywords
bacteria
morphology
microfabrication

Shape recovery through mechanical strain-sensing in rod-like bacteria

Lars D. Renner

'Endless forms most beautiful': Since the formation of the first membrane compartments encapsulating primitive cellular machinery, ever more complex biological shapes have evolved. The importance of cell shape is reflected in divergent cell morphologies, which are a direct result of environmental adaptation and specialization. The compartmentalization of life into cells is essential for many complex biological processes such as physiology, multicellularity, and motility. Prokaryotic cells display an astounding wide range of diverse shapes [1]. Whether there is an actual evolutionary advantage for one shape over another in specific ecological environments is a matter of debate [2]. One of the central questions in bacterial cell biology is why and how bacterial cells have evolved, established and maintained their cell shape. Despite the obvious importance of cell shape we do not fundamentally understand how cell shape is physically determined in any given cell type. Here, we combine microfabrication tools and mathematical models to analyse cell shape recovery of rod-like *Escherichia coli* cells with intentionally and controlled modification of cell morphology under mechanical stress.
We apply a two-tier strategy, (i) *E. coli* cells are confined into donut-shaped microchambers and grown into filaments under genetic control of SulA (a cell division inhibitor) (Fig. 1) [3,4]. (ii) After deforming rod-shaped cells to curved cells, the cells are released from the chamber. We find that plastically deformed, rod-shaped *E. coli* cells quickly recover their straight morphologies (Fig. 2). Interestingly, the recovery rate is faster than expected from the hypothesis that new cell wall material is inserted infinitely into the growing extending rod. Our results indicate that there is a stress-based feedback mechanism that regulates mechanical deformations. We are now corroborating the molecular components (Fig. 1C) that may be involved in the regulation of stress based cell shape recovery and analyse relationship between macro scale and molecular scale shape regulation. We are working on how external cues are influencing cell wall recovery to develop an overarching biophysical model of rod-shaped maintenance which may enable us to explain cell shape in different domains of life.

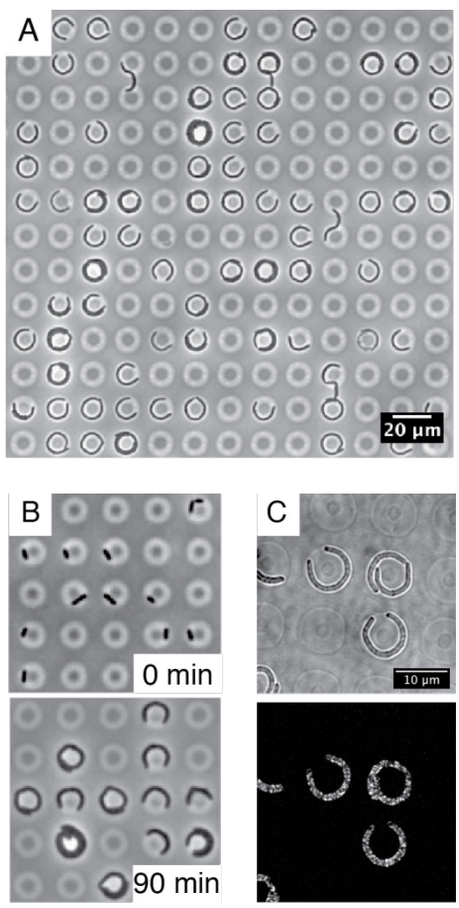

Fig. 1:
(A) Snapshot of a large array of microchamber confined *E. coli* cells in donut-shaped microchambers (design inspired by [5]).
(B) Growth and filamentation of *E. coli* in donut-shaped microchambers after t=0min and t=90min indicates the morphological adaptation of imposed shape.
(C) Brightfield (top panel) and fluorescence image (bottom panel) of confined *E. coli* cells with the prokaryotic actin mreB^{SW}-GFP which is an active regulator of cell shape maintenance.

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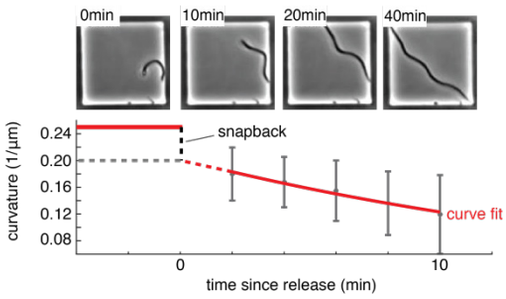

Fig. 2:
The removal of filamentous *E. coli* cells from confinement indicates a fast recovery from donut shape to straight rod-shape (top panel). The analysis of the curvature recovery shows an instant, initial snapback after release and a straightening that is faster than the expected growth rate.

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Co-operation:
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Prof. S. van Teeffelen, Institut Pasteur, France

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Hemocompatibility and antimicrobial properties of antiseptic hydrogels

Sandra Schulz, Manfred Maitz, Stefanie Hänsel, Lars D. Renner, Carsten Werner

Keywords
antiseptic
hydrogel
silver
hemocompatibility

Device-related infections in the application of blood contacting biomaterials motivate research for antimicrobial and hemocompatible materials. Host responses against pathogens on biomaterials can induce excessive inflammatory responses and intravascular coagulation, potentially even resulting in septic shock. Bacterial infections related to indwelling medical devices are one of the leading causes for hospital related fatalities [1]. To reduce bacterial contamination, medical products are frequently functionalized with antiseptic compounds. However, such modifications are often associated with hemocompatibility problems, namely thrombogenicity, of blood contacting devices such as vascular stents or catheters. A biohybrid surface-coating based on starPEG-heparin hydrogels was recently reported to effectively reduce the thrombogenicity of blood contacting biomaterials [2]. The hydrogel was equipped with thrombin-cleavable peptide linkers for adaptive, coagulation-triggered heparin release. Antiseptic functionalization of the hydrogels can be achieved by loading with silver nanoparticles [2, 3].
To test the antiseptic properties of the silver-decorated coatings in a more realistic setting *in vitro*, hydrogel-coated surfaces were exposed to fresh human whole blood and subsequently to bacterial cultures. This novel type of combination experiment enables the analysis of the complex correlations of material-related hemocompatibility and antiseptic properties. Silver functionalized hydrogel surfaces were compared to their corresponding non-loaded equivalent as well as to the reference material polystyrene.
Whole blood incubation experiments showed that the compared antiseptic hydrogel coatings neither induce inflammation nor coagulation. Additionally, it was evaluated if adsorbed proteins and adherent immune cells influence the antiseptic performance of the coatings. Four different bacteria species were seeded onto the compared coatings after blood

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incubation. Gram-negative bacteria were observed to be more sensitive to antiseptic silver. Interestingly, blood exposure was shown to suppress bacterial colonization on any of the compared surfaces. The lowest bacterial count was seen on the antiseptic coating (Fig. 1 and 2). This result indicates that the antimicrobial characteristic of the silver functionalization is maintained after human whole blood contact.

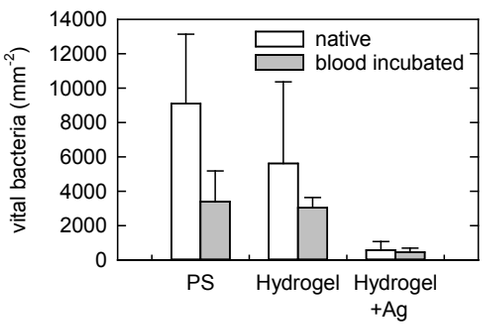

Fig. 1:
Count of live-adherent bacteria (example showing *Staphylococcus epidermidis*) on polystyrene, thrombin-responsive starPEG-heparin hydrogels and silver-loaded thrombin-responsive starPEG-heparin hydrogels, with or without pre-incubation of freshly drawn human whole blood.

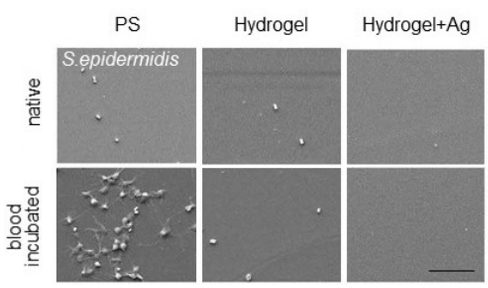

Fig. 2:
Scanning electron microscopy images of *S. epidermidis* on polystyrene, thrombin-responsive starPEG-heparin hydrogels and silver-loaded thrombin-responsive starPEG-heparin hydrogels, with or without pre-incubation of freshly drawn human whole blood.
Scale bar = 20 µm.

In conclusion, the newly established *in vitro* assay combining human whole blood incubation with bacterial culture allows for exploring antiseptic effects and hemocompatibility of biomaterials in more realistic ways. Blood exposure was observed to reduce bacterial settlement on any of the tested surfaces and did not interfere with the antiseptic performance of hydrogel coatings. Based on the obtained data, silver-loaded starPEG-heparin gels are considered advantageous by providing safety in long-term clinical applications.

Sponsor:
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Co-operation:
Universität Rostock

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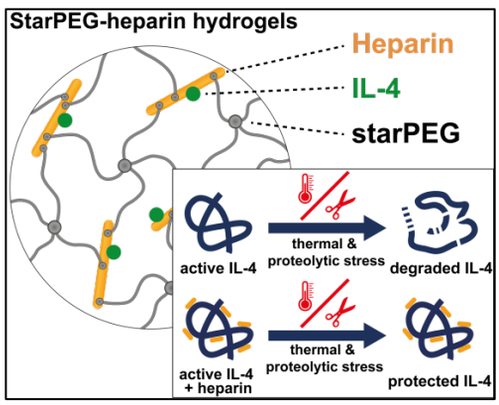
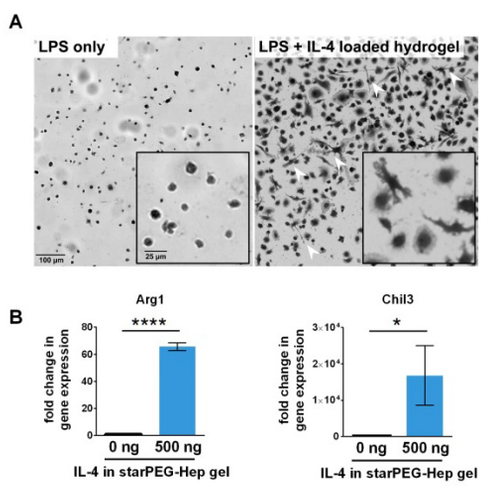
StarPEG-heparin hydrogels to protect and sustainably deliver IL4

Lucas Schirmer, Uwe Freudenberg,
Mikhail V. Tsurkan, Carsten Werner

Clinical therapies targeting signal proteins used in the communication between cells, so called cytokines, offer new treatment modalities for a range of diseases including diabetes mellitus, psoriasis, rheumatic arthritis. While cytokines can effectively trigger tissue regeneration, a major limitation for their therapeutic application is their short half-life time. High levels of proteolytic enzymes found in nearly all tissues can rapidly degrade cytokines As a solution, unphysiologically high amounts of cytokines are applied in current therapeutic applications to generate the desired effects, often resulting in unwanted side effects and increased costs for treatment. Glycosaminoglycans, a class of long unbranched polysaccharides found throughout the human organism, are known to bind and stabilize cytokines *in vivo*. The strong interaction between the cytokine interleukin-4 (IL-4; a key regulator of the inflammatory response) and heparin can be harnessed for the stabilization and sustained delivery of IL-4 through the non-covalent conjugation within heparin-based hydrogel matrices (Fig. 1). Mimicking the situation in the organism, starPEG-heparin hydrogels and starPEG reference gels without heparin were loaded with IL-4 and subsequently exposed to proteolytic enzymes. Heparin-containing gels retained significantly higher amounts of IL-4, exhibiting a significantly higher specific activity than the heparin-free controls. StarPEG-heparin gels were furthermore shown to enable a sustained delivery of the cytokine for time periods of more than two weeks. As a proof-of-function, primary murine macrophages were demonstrated to adopt a wound healing supporting (M2) phenotype when conditioned with IL4 releasing starPEG-heparin hydrogels (Fig. 2). Taken together, our reported results suggest that heparin-based hydrogels offer valuable options for the effective administration of cytokines in protease-rich pro-inflammatory milieus such as chronic wounds of diabetic patients [1].





Sponsor:
Deutsche Forschungsgemeinschaft (DFG)
CRC TR 67 (UF, CW, LS, PA)

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Keywords
biohybrid hydrogel
interleukin-4
cytokine
sustained release
stabilization

Fig. 1:
StarPEG-heparin hydrogel binding interleukin-4 (IL-4) in the polymer network through electrostatic interaction of heparin with the cytokine. The complexation results in the retention and stabilization of IL-4.

Fig. 2:
Effects of IL-4 loaded starPEG-heparin hydrogels on primary bone marrow-derived macrophages. Cells were challenged with LPS and then incubated with hydrogels with or without IL-4 loading for 72 h.
A – Cell morphology of macrophages stained with crystal violet. Cells treated with LPS only show rounded morphology. In contrast, cells treated with IL-4 loaded hydrogel developped spindle-shaped morphology (white arrow heads) indicating pro-regenerative polarization.
B – Gene expression of macrophages. IL-4 loaded hydrogels induced the expression of Arg1 and Chil3. Values are presented as mean values ± SD of macrophages derived from three different animals.

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Keywords
Mammary epithelium
eell-material interaction
organoid morphogenesis
heparin
biomimetic material

Hydrogels for 3D tissue models

Uwe Freudenberg, M. Nowak, Mikhail V. Tsurkan, Kandice R. Levental, Carsten Werner

Three-dimensional (3D) culture systems are gaining interest since they allow to grow cells in native-like environments, paving the way for more powerful diagnostic systems and enabling the replacement of animal experiments. However, matrix preparations currently used in the related approaches are rather ill-defined and poorly reproducible, and lack control over physical parameters. To overcome these drawbacks in here a hydrogel platform based on the glycosaminoglycan heparin, star-shaped poly-(ethylene glycol) (starPEG), and enzymatically (Matrix metalloproteinase (MMP)) cleavable peptide crosslinkers was applied to dissect the biophysical and biochemical signals promoting human mammary epithelial cell (MEC) morphogenesis.
Compliant and enzymatically (MMP) cleavable starPEG-heparin matrices were observed to promote the development of the desired polarized MEC acini (see Fig. 1).
Both, the presence of heparin and enzymatically-cleavable crosslinks were identified to be essential for facilitating MEC morphogenesis. Importantly, the process occurred without supplementation of the media or incorporation of additional matrix derived cues like adhesion ligands. MECs within the hydrogel materials were shown to secrete and organize laminin in basement membrane-like assemblies to promote integrin signaling and drive acinar development.

The easily applicable and versatile hydrogel platform is concluded to allow for the systematic investigation of biophysical and biochemical aspects of mammary gland biology to determine the individual signals that induce or suppress invasion and malignancy in mammary epithelium [1]. Substitution of heparin by other glycosaminoglycans, tethering the matrix with specific extracellular matrix adhesion ligand peptides (e.g. RGD, YIGSR or SIKVAV), or loading of heparin-binding growth factors (e.g. VEGF, TGFb or FGF-2) provide additional options for adjusting the cell-instructive characteristics of the materials and enable its successful application in a variety of different organoid culture studies [2].

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Leibniz Association SAW-2011-IPF-2 68 (CW)
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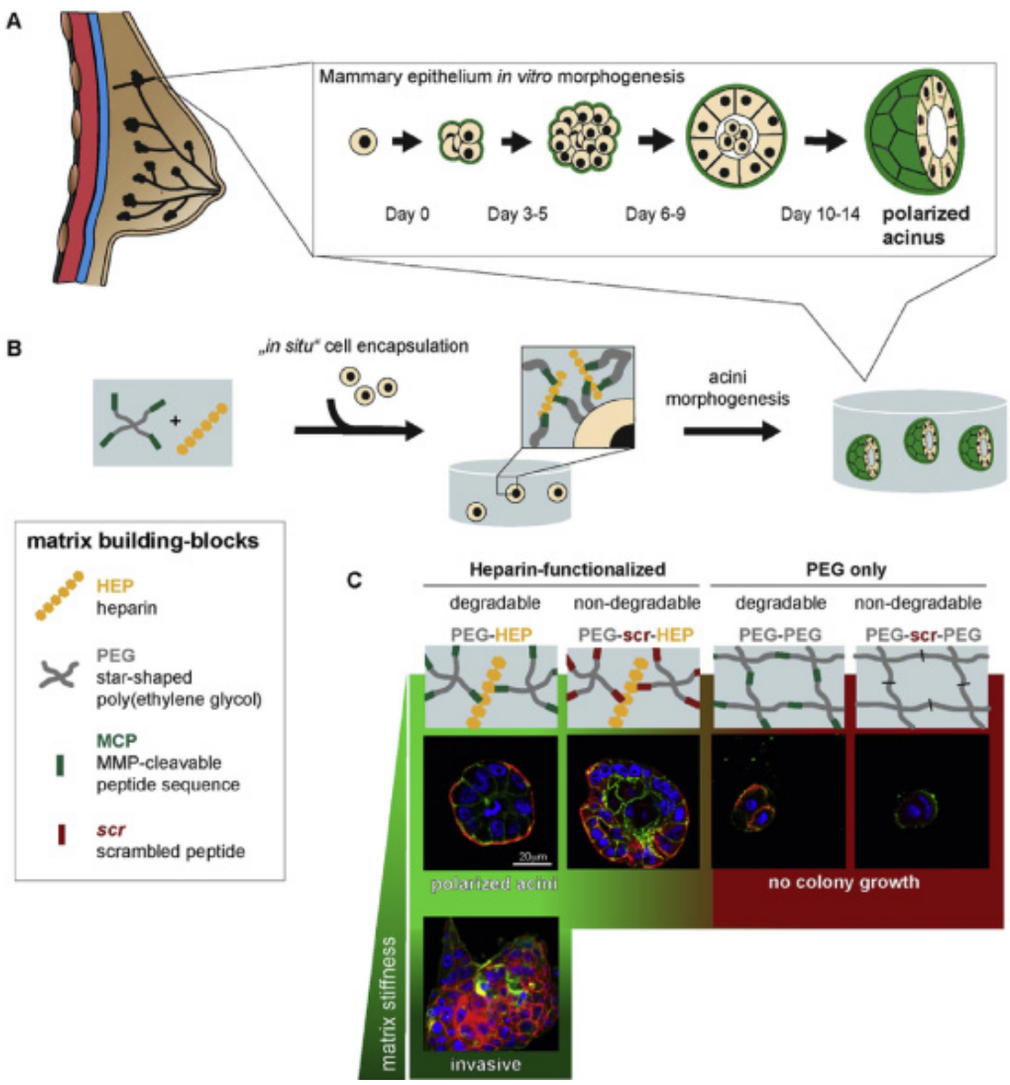

Fig. 1:
Mammary epithelial cell morphogenesis ex vivo in a modular biomimetic hydrogel.
(A) Diagram of in vitro individual mammary epithelial cell (MEC) morphogenesis into polarized acinus displaying a cleared lumen and basement membrane formation (green).
(B) Illustration of the study design to investigate MEC morphogenesis in a hydrogel matrix which contains the following building blocks: glycosaminoglycan (GAG) heparin (yellow), enzymatic (MMP)-cleavable peptide sequence (MCP, green), non-cleavable scrambled peptide sequence (scr, red) and the inert and star-shaped, four-armed PEG (grey) as a structural matrix component.
The versatile and modular chemistry of the biomimetic matrix building blocks facilitates the study of the specific function of the different matrix building blocks and the exogenous biophysical (mechanical) stimuli on mammary epithelial morphogenesis in a systematic fashion. MECs are embedded as single cells with the modular matrix prior to polymerization. Over 14 days in culture, they undergo morphogenesis to form polarized mammary epithelial acini.
(C) Polarized MEC acini formation after 14 days in culture is optimal in soft, enzymatically degradable PEG-HEP hydrogels. In each of the other combinations of modular building blocks (e.g. starPEG, heparin, MMP-cleavability) or matrix stiffness, MEC morphogenesis is perturbed. Scale bar. 20 mm.

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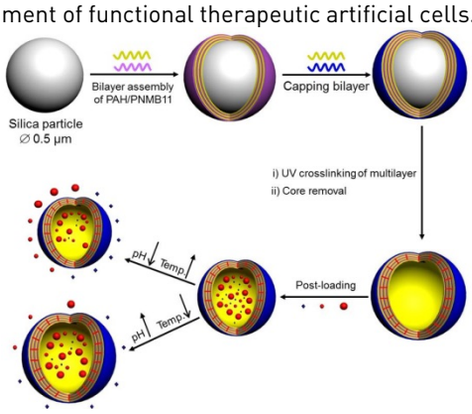
Keywords
hollow capsules
post-encapsulation
pH and temperature
stimulus
controllable release

Mimicking simple cell functions for synthetic biology

Xiaoling Liu, Brigitte Voit, Dietmar Appelhans

Next-generation synthetic biology approaches are expected to rely on the engineering of multifunctional particle compartments that can mimic specific cellular functions. The key features of such particles are the semipermeable nature of the outer membrane to communicate with the external environment for controllable bio-inspired functions and actions [1]. Herein, we report the formation of pH and temperature dual-responsive and photo-crosslinked hollow capsules that can be used for the subsequent post-encapsulation process of protein mimics (∅ ≤ 11 nm) and their controllable release triggered by external stimuli. At first, hybrid polyelectrolyte multilayer systems were fabricated on silica particles of 500 nm in diameter via layer-by-layer (LbL) assembly of the cationic poly(allylamine hydrochloride) (PAH) and the anionic, pH- and thermo-responsive and photo-crosslinkable block copolymer poly(N-isopropylacrylamide)-block-poly[methacrylic acid-co-2-hydroxy-4-(methacryloyloxy) benzophenone] (PNMB), synthesized by RAFT polymerization. After photo-crosslinking the polyelectrolyte multilayers and etching the silica core, temperature and pH dual-responsive hollow polymeric capsules were obtained (Scheme 1) [2]. The morphology and diameters of the capsules were confirmed by TEM, SEM and DLS. They possess membrane thickness of about 30-35 nm in dry state and diameters between 490 and 540 nm [2]. Advantageous post-encapsulation of protein mimics by those hollow capsules can be carried out under physiological conditions at pH 7 and room temperature [2]. Moreover the release of cargo (macro)molecules from hollow capsules is easily tunable by changes in the external stimulus temperature (25, 37 or 45°C) and the internal stimulus pH of the phosphate-containing buffer solution (pH 5.5 or 7.4) and by the degree of photo-crosslinking (Fig. 1) [2]. The advantage of this approach is that all post-encapsulation and retarding release processes of cargos are simultaneously possible, when using those membranes as outer component of complex supramolecular structures in synthetic biology. Thus, first steps are undertaken to subcompartmentalize these photo-crosslinked and dual stimuli-responsive hollow capsules with nanometer-sized polymersomes to form a novel polymeric multicompartment system, presenting new opportunities for the development of functional therapeutic artificial cells.



Scheme 1:
Schematic illustration of the assembly photo-crosslinked hollow capsules and the dual-responsive controlled release characteristics of cargos with different sizes across the membrane of photo-crosslinked hollow capsules

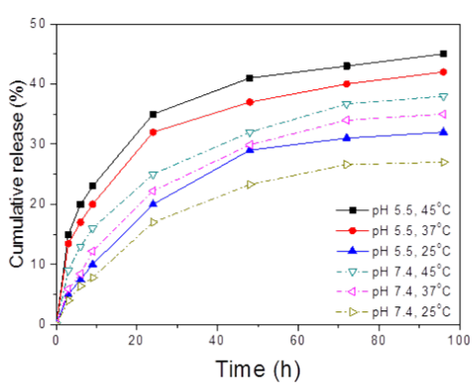


Fig. 1:
Cumulative release profile of rhodamine B labeled PEI-Mal 5 from [PNMB11/PAH]3/PAH/PSS capsules, photo-crosslinked for 30 min, at different temperature and in various pH medium (n=3) [2].

Sponsor:
China Scholarship Council (CSC) from the People's Republic of China

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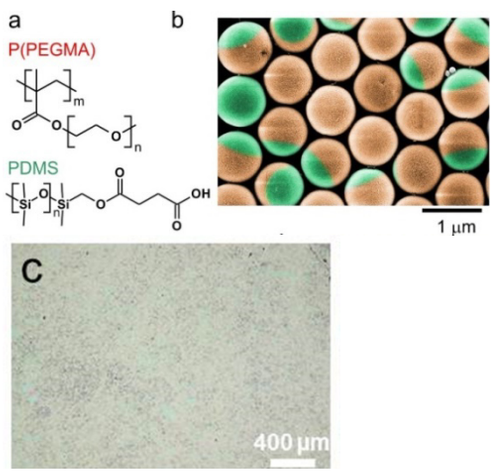
Biologie-inspirierte Grenzflächen- und Materialgestaltung

Biomimetic-inspired design of anti-icing and de-icing surfaces based on hybrid hairy Janus particles

Alla Synytska, Anna Kirillova,
Madeleine Schwarzer

The development of surfaces with reduced icing or easy de-icing is of paramount importance for the wind turbine technology as well as automotive and aircraft industries. Combining of the both properties in one material requires the controlling of several parameters such as ice nucleation, growth and ice adhesion. There are few main strategies for the design of anti-icing coatings. One of them is based on the lowering of the ice adhesion strength. Reduced ice adhesion can be achieved by the fabrication of hydrophobic or superhydrophobic surfaces, as well as the use of hydrophobic lubricants. In the first case, the contact area between the surface and ice is simply reduced. These materials demonstrate good anti-icing properties, however once an ice layer is formed, it can hardly be removed. Moreover, the removal of the ice layer leads to the loss of the superhydrophobic properties. In the case of hydrophobic lubricants, ice can easily be removed because of the hydrophobic lubricant softness. On the other hand, use of oily liquids as anti-icing materials is not favorable due to their insufficient mechanical stability. Another strategy is based on the inhibition of the ice growth. Reduced ice growth can be achieved in two ways. The first way is to utilize the colligative properties of solutions. For example, hydrophilic polymers reduce the freezing point of water, and ice crystals can simply slide off due to the presence of an unfrozen water layer. Nevertheless, the disadvantage of such hydrophilic materials is the very fast growth of ice crystals on their surface.

The second approach is to employ antifreeze proteins, inspired by nature on the example of Antarctic fish, which kinetically decrease the point of ice crystal formation. The protein molecules adsorb on ice crystal and slow down their growth, which allows reduction of water freezing down to - 60°C but melting point remains unchanged (0°C).
In the present work, we suggested bringing these biomimetic strategies based on hydrophilic and hydrophobic materials together that allows, on one hand, to solve the intrinsic problems of each method and, on the other hand, to combine their advantages and, moreover, to obtain additional benefits such as controlled nucleation of ice [1, 2].



We demonstrated for the first time that rational design of surfaces with effective anti-icing and de-icing capability is possible using amphiphilic hybrid hairy Janus particles as novel building blocks.

Keywords
Janus particles
hybrid hairy Janus particles
anti-icing surfaces
de-icing surfaces
multi-functional coatings

Fig. 1:
Representative layers prepared with P(PEGMA)/ PDMS Janus particles: (a) chemical formulas of the polymers; (b) false color SEM image (orange side - P(PEGMA); green side – PDMS); (c) - optical microscopy images of the P(PEGMA)/ P(PDMS) Janus particle-based surface.

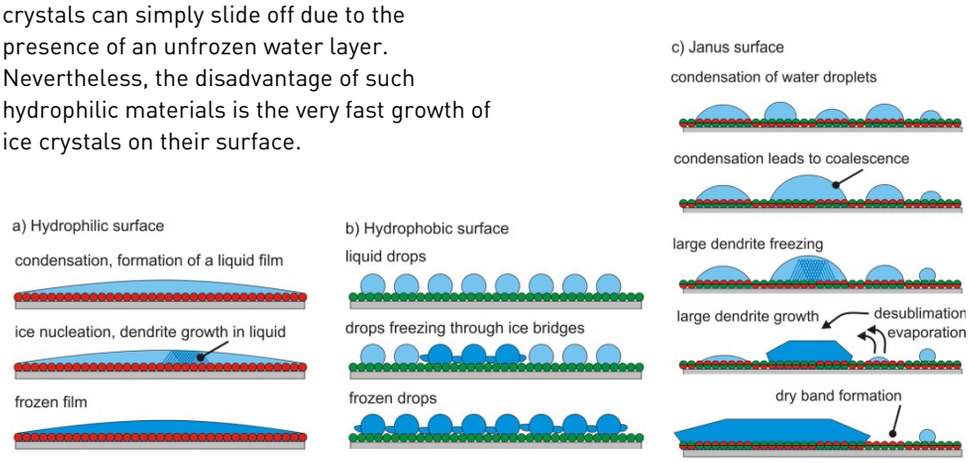


Fig. 3:
Mechanisms of the ice layer formation on rough hydrophilic (a), hydrophobic (b), and Janus surfaces (c)

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The synthesized Janus particles suggested in this work possess core-shell structures having an inorganic core along with hydrophilic and hydrophobic polymeric shells at their opposite sides, thus offering bi-functional building blocks for the design of heterogeneous surfaces with modularity in chemical composition and final surface topography [1-3].
These surfaces exhibit special surface "edge" morphologies due to the Janus particle structure and orientation (Fig. 1).
The experimental results and Monte-Carlo simulations reveal three steps in the formation of ice crystals: (i) water nucleation, which is determined by the size of hydrophilic domains formed by the Janus particles; (ii) spontaneous coalescence and fast spreading of liquid water on the hydrophilic clusters; (iii) solidification of the liquid clusters leading to the appearance of relatively large ice crystals - irregular dendrites (Fig. 2-3). Furthermore, it is observed that the dendrites initially grow extremely quickly along the hydrophilic clusters due to the consumption of not-yet-frozen water droplets from the surface. This evaporation leads to the formation of a dry band around the single crystals. As a result, a considerable part of the surface becomes ice-free (Fig. 2-3).

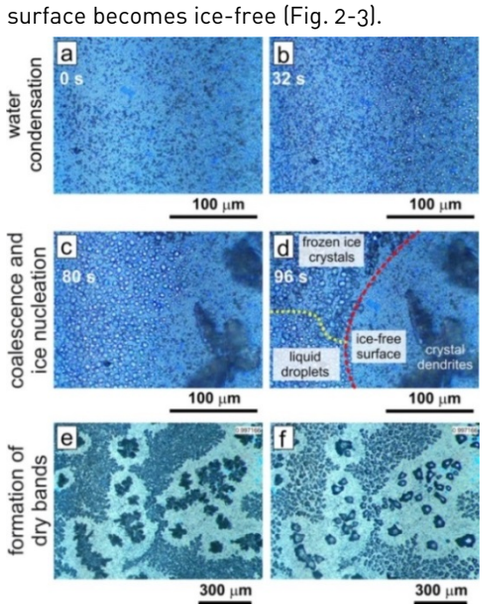
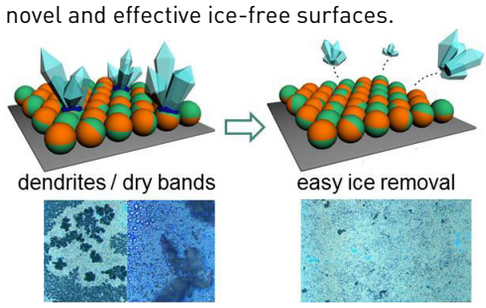


Fig. 2:
Representative optical microscopy images of the P(PEGMA)/P(PDMSMA) Janus particle-based surface during icing:
(a) native surface;
(b) surface after the water droplet condensation;
(c) growth of large liquid clusters and their solidification;
(d, e) freezing of the condensed water droplets (different scales) and formation of dry bands around large crystals/ dendrites;
(f) thawing of ice after finishing of the icing test.

Thus, the synergism of both effects, the area free of ice and the large unstable crystals at the edges of heterogeneities, leads to an extremely low ice adhesion (56kPa) (Scheme 1). Moreover, ice adhesion to the layers of Janus particles is lower than the ice adhesion to the layers made of either hydrophilic or hydrophobic particles.
The great advantage of the Janus particle-based surfaces is that the Janus particles can easily be prepared on a large scale by the recently developed methods, and can be used to cover large surface areas by simple spraying or solvent casting. Furthermore, Janus particles offer heterogeneous structures at different scales between the nano- and micrometer levels depending on the particle size. Additionally, the hybrid Janus particles with inorganic core possess high robustness and long-term stability. No similar effects were found if the mixture of hydrophilic and hydrophobic particles were used for the surface modification. Accordingly, the hybrid Janus particles serve as scalable building blocks and open a new avenue for the design of novel and effective ice-free surfaces.



Scheme 1:
Scheme of the anti-icing surface based on hybrid Janus particles

Sponsor:
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Co-operation:
PD Dr. I. Roismann, Technische Universität Darmstadt, Strömungslehre und Aerodynamik;
Prof. L. Ionov, The University of Georgia, USA

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Biologie-inspirierte Grenzflächen- und Materialgestaltung

Chitosan – Simultane Adsorption von Eisen- und Sulfationen an Biopolymeren

Janek Weißpflog, Simona Schwarz

Für die effektive Abtrennung von Eisen- und Sulfationen aus kontaminierten Grund- und Oberflächengewässern werden hinreichende Untersuchungen mit dem natürlich vorkommenden Biopolymer Chitosan als Sorbens unternommen. Dieses wird aus den Panzerresten von Schalentieren bzw. Pilzen gewonnen und ermöglicht eine erstmalig nachgewiesene Adsorption von sowohl An- als auch Kationen. Als Folgeerscheinung des Bergbaus im Spreegebiet kommt es zur Freilegung sowie anschließender Oxidation von Pyrit (Eisensulfid, FeS_2). Fe^{3+}-Ionen sind die Folge des Oxidationsprozesses von Fe^{2+}-Ionen durch den Kontakt mit Luftsauerstoff und werden als rötlich brauner Schlamm an den Flussufern und Bauwerken als Verockerung sichtbar. Darüber hinaus konnten Beeinträchtigungen der Wasserqualität in Form von außergewöhnlich hohen Konzentrationen an Sulfationen detektiert werden. Sowohl die Sulfationen als auch die Fe^{2+}- und durch Oxidation entstandenen Fe^{3+}-Ionen stellen für Flora und Fauna ein Problem dar. Mit Modellsystemen ($FeSO_4$, Abb. 1) konnte der Adsorptionsprozess von Multikomponenten an Biopolymeren wie Chitosan nachgebildet werden. Die Ergebnisse der Analysen zeigten, dass mit einer Erhöhung der Eisensulfatkonzentration eine zunehmende Färbung des Adsorbermaterials einhergeht. Darüber hinaus konnte die positive Wirkung des Vorhandenseins von Metallionen auf die Adsorption von Sulfationen an Chitosanflocken nachgewiesen werden.

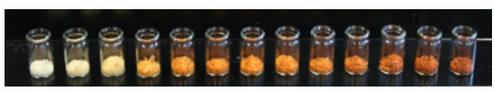


Abb. 1:
Adsorption von $FeSO_4$ an Chitosanflocken mit Zunahme der Eisensulfatkonzentration von links nach rechts.

Das Wesen liegt in der Bildung einer überlagerten Reaktion von Sulfatadsorption und Metall-Komplex-Bindung zum Eisen (Abb. 2). Deshalb ist von Sofortmaßnahmen wie beispielsweise eine Ausfällung von Eisenionen durch Kalkung in betroffenen Gebieten strikt abzusehen.
In Abhängigkeit von der Adsorptionszeit und -konzentration wurden einerseits Batch-Versuche, andererseits Versuche in einer Adsorptionskolonne eingehend charakterisiert. Durch Kolonnenversuche wurde die Adsorption in einer gepackten Säule unter Luftausschluss durchgeführt, wodurch ein wesentliches Problem in Form der Oxidation von Fe^{2+}-zu Fe^{3+}-Ionen durch Luftsauerstoff beseitigt werden konnte.

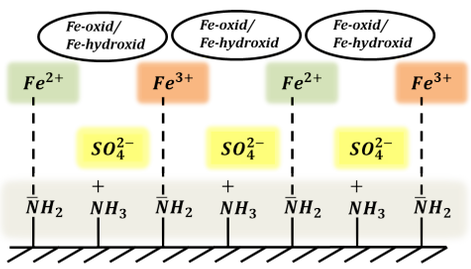
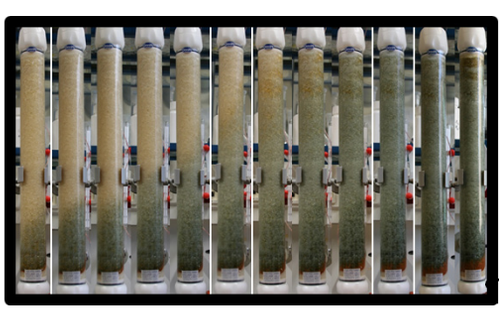


Abb. 2:
Schematische Darstellung des Adsorptionsmechanismus an der Oberfläche von Chitosanflocken.



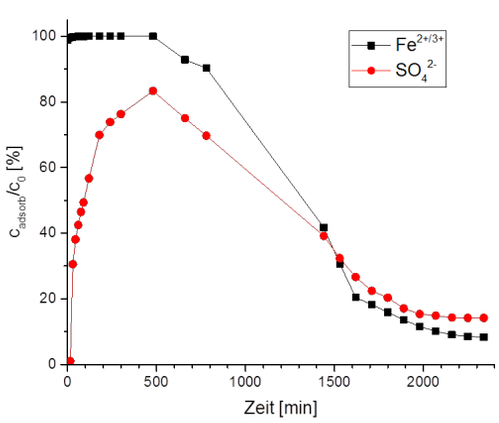


Abb. 3:
Adsorption von Eisensulfat an Chitosanflocken in einer Adsorptionskolonne ($c_0(FeSO_4)$=2500 mg/L, V_{Pumpe}=23 µL/s). Oben: Aufnahmen des Adsorptionsversuchs; Unten: graphische Auswertung.

Förderer:
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Keywords
chitosan
adsorption
sedimentation of iron ochre
simultaneous removal of iron and sulfate ions

Biologie-inspirierte Grenzflächen- und Materialgestaltung

Keywords
embroidery technology
polylactic acid
melt spinning
anterior cruciate ligament
tissue engineering

Kooperation:
Prof. A. Heppe, BioLog Heppe GmbH

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Mechanically adapted embroidered scaffolds based on polylactic acid melt spun multifilaments for ligament tissue engineering

Judith Hahn, Annette Breier, Harald Brünig, Claudia Hinüber, Gert Heinrich

The most common clinically relevant injury of the knee joint is the rupture of the anterior cruciate ligament (ACL) with 200.000 surgeries per year solely in the USA. The ACL consists of three structural zones, ligament, enthesis and bone insertion, each with specific mechanical and cellular characteristics. For reconstruction the current "Gold Standard" is based on the use of autologous grafts from the semitendinosus or the patellar tendon forbearing disadvantages like biomechanical deviations or limited availability. Tissue engineering is considered as an alternative approach based on cell seeded, resorbable three-dimensional (3D) structures (scaffolds). Textile fabrication methods allow the production of mechanical stable scaffolds. Embroidery technology enables the fabrication of structures with adapted mechanical properties based on resorbable thread materials like polylactic acid (PLA) with a defined degradation behavior. The manufacturing process of embroidered scaffolds is described in detail elsewhere [1, 3].
The aim of this work was the development of embroidered triphasic scaffolds representing the three native morphological zones bone insertion, enthesis and ligament made of biocompatible and resorbable thread materials. The embroidery pattern is inspired by the natural collagen structure of the ligament zone and the graded transition to the bone insertion.

Fig. 1:
Scaffold structure with three different embroidery pattern designs,
A) Bone insertion: triaxial pattern with linear reinforcing pattern,
B) Enthesis: partial overlap of triaxial and zig-zag pattern, C) Ligament: zig-zag pattern

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Based on the native tissue formation, three different pattern designs were investigated (Fig. 1). A triaxial pattern for the bone insertion was established before performing an optimal porosity for bone cell ingrowth [1]. The triaxial pattern was reinforced by a linear pattern resulting in a significant increase of the stiffness responding to the higher tensile stress occurring in the application as a ligament replacement. The enthesis was created as transition from rigid to elastic tissue by a partial overlap of triaxial (bone) and zig-zag (ligament) pattern. Furthermore, there is the possibility to integrate a temporary cell barrier made of collagen to separate different cell types in a co-culture system [2]. A zig-zag pattern was used for the ligamental zone with a significant pattern orientation in the direction of loading and an adapted stress-strain behavior (Fig. 2) comparable to that of native ACL tissue [3].

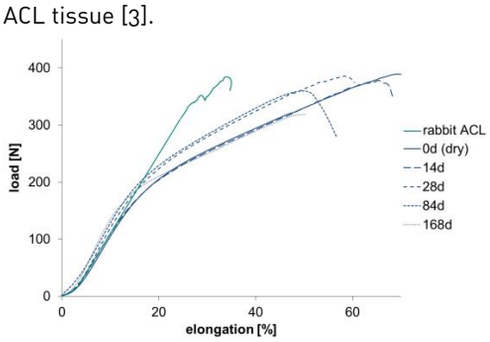

Fig. 2:
Load-elongation behavior of native rabbit ACL and embroidered scaffolds made of PLA fibers

Typical stress-strain curves of ligaments exhibit an S-shape and consist of three parts. The "toe-region" (low stiffness, high elongation) results from the structural deformation of the crimp collagen fibrils in native tissue or in the case of embroidered scaffolds from the zig-zag pattern design. The "high stiffness region" is characterized by an increase of the load compared to the displacement and caused by the material deformation of the straightened collagen fibrils or the thread materials of the embroidered structure. Last part of the curve refers to the "complete rupture" with a proceeding load decrease.

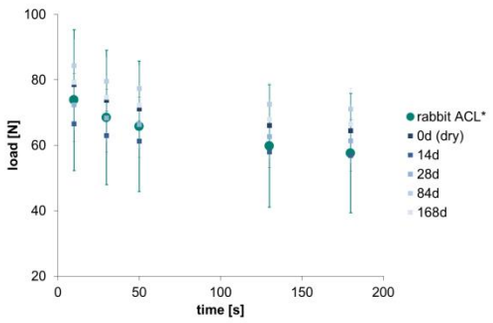

Fig. 3:
Load-time behavior of native rabbit ACL (*data from Panjabi and Courtney 2001) and embroidered scaffolds made of PLA fibers

The viscoelastic behavior was analysed in addition to the stress-strain behavior by measuring the load-time behavior (Fig. 3). Both, the load-elongation and the load-time behavior of the embroidered scaffolds were comparable to that of native ACL tissue at the initial state and after hydrolytic degradation over 168 days. In addition, different in vitro cell culture studies were performed in cooperation with cytologists. Their results allow the conclusion that ACL cells are able to adhere, proliferate and differentiate on the developed scaffolds with a proper collagen surface treatment [4, 5].
In summary, the use of mechanically adapted embroidered scaffolds made of resorbable PLA fibers for the reconstruction of injured ACL tissue could be a promising approach considering the results of further in vivo studies.

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Biologie-inspirierte Grenzflächen- und Materialgestaltung

Keywords
lubrication
polymer brushes

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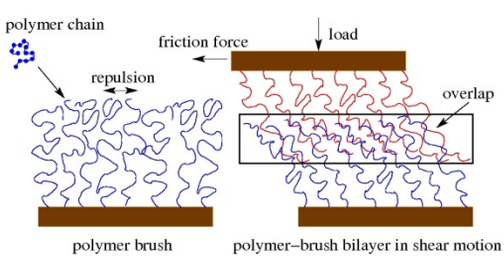
Recent advances in the theory of polymer-brush lubrication

Torsten Kreer

The desire to minimize friction between surfaces is as old as human civilization. While the architects of the Egyptian pyramids used water and sand, modern machine parts typically are lubricated by oil. Nature has found superior solutions. Mammalian joints, such as the human knee or hip, are subject to pressures of up to 50 atmospheres. They are lubricated by polymer brushes, which results in ultra-low friction that allows synovial joints to withstand a lifetime of wear and tear without the joint seizing.
Polymer brushes are comprised of polymer chains that are attached with one end to a surface. A polymer chain is a sequence of connected and repeating monomers, like the pearls of a necklace (Fig. 1). If the amount of polymers on the surface is large enough, the individual chains repel each other. This causes the attached chains to stretch away from the surface.



Schematic plots of a polymer brush and two polymer-brush bearing surfaces pressed against each other (polymer-brush bilayer). The bilayer has two remarkable features: The brushes offer strong resistance against compression (load) and, simultaneously, they display extremely small friction forces due to their ability to reduce their mutual overlap.

A system of two polymer-brush bearing surfaces pressed against each other is called a polymer-brush bilayer and has two remarkable features: The brushes offer strong resistance against compression (load) and, simultaneously, they display extremely small friction forces.

For strong shear motions, the chains can incline, which reduces the overlap between the brushes and thus the friction force. This is why polymer brushes are ideal candidates as lubricants in real and artificial joints. Currently, the lifetime of an artificial knee joint is approximately 15 years. Polymer brushes may extend the durability significantly and increase the life quality for many people.
Our theoretical model allows us to calculate the compressive forces (the load that the device carries) and the friction forces, yielding quantitative predictions for the friction coefficient. The latter is defined as the ratio between the friction and the compressive force and should be minimized to obtain good lubrication. Dry, non-lubricated surfaces typically have a kinetic friction coefficient of 0.1, while oil-lubricated surfaces have a value of approximately 0.01. Surfaces lubricated by polymer brushes can display a kinetic friction coefficient of 0.0001 or lower!
Nature does not use polymer brushes alone in joint lubrication. The synovial fluid contains macromolecular inclusions and charged macromolecules. Our research has found that such inclusions and electrical charge on the brushes (polyelectrolyte brushes) seem not to reduce friction, but rather prevent mechanical instabilities. The latter can occur, for instance, in form of an abrupt increase of the friction force, when the bilayer is subjected to a change of shear direction. This situation is typical for processes inside human knees or hips during walking, where the direction of motion is inverted many times.
As our theoretical understanding increases, we stand at the forefront of many exciting, new developments. For example, methods for switchable friction (changing from a super-lubricant to a strongly adhesive glue) or the usage of polymer brushes as sensors are being explored. In the future, polymer brushes should play an outstanding role in the field of smart materials and (already) find applications in artificial joints, chemical switches and sensors, self-healing surfaces, and so forth.

Sponsor:
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2854/3-1 and 2854/3-2

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