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EDITORIAL

Fiber-based platforms for bioanalytics

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Materials with dimensions on the nanoscale (nanomaterials) are increasingly being integrated within analytical systems to allow the detection of low concentrations of analytes without complicated amplification processes. In addition to their small size, allowing direct molecular interactions, their rapid mass transfer characteristics make them attractive analytical tools. Nanoparticles such as gold, fluorescently doped silica, and upconverting nanoparticles, quantum dots, and magnetic nanoparticles are typically used for signal enhancement strategies in analytical processes. The latter are additionally used as immobilization and separation means, especially as microparticles. Nanofibers and microfibers provide additional interesting characteristics that make them very promising and successful components of an analytical process. Bearing the same advantages because of their nano and micro size, they can, however, span macro dimensions as a fibrous mat. Furthermore, they demonstrate interesting surface chemistries (both native and through straightforward modifications), great mechanical strength, and immense surface-to-volume ratios.

The first articles on nanofibers used in analytical assays were published in 2001, and about 500 articles can now be found for nanofiber and analytical approaches in the Web of Science. The first concepts for nanofiber-enhanced biosensors were suggested at the same time, but the first publications came out only in 2005, with more than 250 publications since then and more than 1800 citations. The possibilities of application seem infinite and range from filtration in air to mixing in microfluidic channels, from immobilization of biorecognition elements to drug delivery in enzymatic assays. Here, their application transitions seamlessly into tissue engineering research. Microfibers have been used for significantly longer in separation processes, the first concepts having been described in the 1960s. However, only recently have they emerged as essential components within analytical assays and for exploring intricate surface structuring of the microfibers themselves.

In the Baeumner research group, electrospun nanofibers have been studied since 2005 in collaboration with Margaret Frey from the Department of Fiber Science and Apparel Design at Cornell University with special emphasis on their use for bioanalytical applications. The research focuses on nanofibers integrated into lateral-flow assays and into microfluidic total analysis systems as an immobilization matrix, a separation component, or transduction material. The combination of new surface chemistries with an immense surface area provides ample room for interesting and novel studies improving the performance of bioanalytical systems for on-site detection.

The Marcus research group uses melt-extruded polymer fibers tens of micrometers in diameter with channels along the fiber axis, so-called capillary-channeled polymer (C-CP) fibers for macromolecule separations. When C-CP fibers are packed into a microbore column structure, the walls of the channels interdigitate to form thousands of parallel channels with a size of 1–5 μm. Transport down these columns occurs with high permeability, under highly effective convective diffusion conditions toward surfaces that are virtually nonporous with regard to protein molecules. As such, the fibers have found use in analytical protein chromatography and solid-

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phase extraction applications, as well as in the protein downstream processing arena.

This topical collection provides a collective insight into the abundance of possibilities of nanofiber and microfiber research in analytical chemistry. It comes on the heels of a successful symposium that we organized at the 2014 Pittsburgh Conference and Exhibition, which has really opened our eyes to the diversity of applications afforded by these interesting materials. The fine collection of articles presented here starts off with a review article by Tamer Uyar and his colleagues discussing the use of nanofibrous materials for the probably most studied biosensor concept in the literature. Taking advantage of the well-known glucose biosensor concept, they compare the performance of electrospun nanofibers for a typical and yet very important bioanalytical concept and demonstrate that the available immense surface area can indeed improve long-term stability of enzymatic biosensors.

Gregory Rutledge and his colleagues critically review recent developments in electrospun carbon nanofibers. As a low-cost and biocompatible material offering good electron transfer kinetics, electrospun carbon fibers can easily be modified by processing and posttreatment. Their review focuses on modification strategies and the identification of key components that provide the nanofibers with their desirable electroanalytical capabilities. They also discuss future challenges to advance fundamental understanding of the underlying electrochemical principles and realize their application in sensing devices.

The research article collection considers aspects of nanofibers for separation, for immobilization, as a transduction element, and for biosensing. Antje Baeumner and her colleagues integrate electrospun nanofibers into microfluidic systems to specifically isolate bacterial cells from solution. Lauren Matlock-Colangelo and her colleagues show concepts that are based on mere electrostatic interactions that can be easily adapted to other analytes and or as a preselection component in a suite of separation processes. Utilizing the repelling nature of their nanofibers, they impart bioselectivity through the immobilization of specific antibodies. Blocking of nanofiber surfaces therefore becomes unnecessary. Paul Yager and his group study effective chemical processes to immobilize proteins on nitrocellulose. Because of the importance of nitrocellulose as the main support matrix of lateral-flow assays, an effective immobilization strategy for proteins is mandatory. Carly Holstein systematically investigates different chemical options available and provides a good set of strategies for the immobilization chemistries. Tamer Uyar and his group study the use of nanofibers for ultrasensitive detection of H_2O_2. Anitha Senthamizhan decorates polysulfone nanofibers with gold nanoclusters and demonstrates that localized surface plasmons appeared that lead to a specific and sensitive visible detection of hydrogen peroxide. Along a similar line of thought, Andrea Camposeo and his colleagues use nanofibers and nanofibers modified with gold nanorods for surface-enhanced Raman scattering analysis and investigate how the architecture, composition, and light-scattering properties of the nanofibrous material can influence Raman signals.

The research articles dealing with structures constructed of microfibers concentrate on the ability to efficiently transport, separate, and analyze biomacromolecules, even cellular material. Wei Shen presents the lab-on-a-thread concept, concentrating on yarns of polyester fibers as opposed to typical natural fibers used in that format and in paper-based assays. Very different transport is affected, where red blood cells flow down the thread, resulting in a chromatographic separation that allows assignment of the blood type. Liuwei Jiang and Kenneth Marcus describe the creation of densely aminated surfaces on polyester-based C-CP fibers to affect weak anion exchange separations of proteins at high linear velocities (approximately 70 mm s^{-1}). Amine densities, column permeabilities, and elution characteristics are compared for these polyethylenimine-modified surfaces and native nylon 6 C-CP fibers. Finally, Zheng Ouyang and coworkers describe a modification of what is generally known as paper-spray mass spectrometry, which exploits the favorable solvent and solute mass transport in a paper matrix as a means of feeding biological samples and the sustaining electrolyte into the ambient ionization source. The addition of a capillary emitter improves the overall efficiency of the device in terms of the direct analysis of therapeutic drugs in blood samples.

The commonalities of efficient fluid transport, the ability to affect incredibly diverse surface chemistries, assembly in varied physical structures, and low capital costs hold promise in many fields of bioanalytics. Specifically, it is anticipated that fibrous platforms, including paper, other cellulosic phases, and synthetic polymers, will see increased use in point-of-care applications, proteomics, downstream protein processing, and basic biochemical research.

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Antje J. Baeumner is Professor of Analytical Chemistry and Director of the Institute of Analytical Chemistry, Chemo- and Biosensors at the University of Regensburg, Germany. Before she took up the position in Regensburg, she was Professor of Biological Engineering and Director of Graduate Studies in the Department of Biological and Environmental Engineering at Cornell University in Ithaca, New York, USA. She is on the Board of Directors of the Society of Electroanalytical Chemistry, is a member of the Extended Executive Committee of the International Association of Environmental Analytical Chemistry, was the 2010 Chair of the Gordon Research Conference on Bioanalytical Sensors, and has received numerous honors in recent years, including being a finalist for a Blavatnik Award of the New York Academy of Sciences and a recipient of a Humboldt Research Fellowship and a German National Science Foundation Mercator Guest Professorship. Her research is focused on the development of micro total analysis systems and smart lateral flow assays for detection of pathogens and toxins in food and the environment, and for medical diagnostics. Nanomaterials play an important role in her research, including nanoparticles and nanovesicles for signal amplification, and nanofibers for immobilization and detection as well as mixing.