Liposomes, Lipid Bilayers and Model Membranes

From Basic Research to Application

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Preface

I wonder how much it would take to buy a soap bubble, if there were only one in the world.

(Mark Twain, 1835–1910)

Soap bubbles are thin, spherical films of soapy water that only survive for a few seconds, depending on their water content and chemical composition. They are commonly used by children for play, but it is also fascinating how soap bubbles have been used to answer physical problems. In some ways, cell membranes are analogous to soap bubbles, including the importance of water in determining their stability. Cell membranes, however, are much more than soap bubbles. Biological membranes are functional, selectively permeable barriers which surround the various cell organelles (e.g., mitochondria, endoplasmic reticulum, Golgi apparatus, etc.), enabling them to maintain their characteristic differences from the cytosol. Their mimetics—for example, liposomes—are used in a number of scientific and technological applications, some of which are covered in this book. The broad range of such applications can be attributed mostly to Janus-faced properties of amphiphilic molecules that make up these aggregates (lipids, surfactants, polymers), where one side of the molecule prefers to associate with water, while the other associates with oil. These faces can also be "tuned" in a manner whereby aggregates can assume morphologies, ranging from micelles, lamellar and nonlamellar phases, to microemulsions. Importantly, each of these self-assembled morphologies possesses its own unique physical properties, and offers the possibility for scientific insight and/or technological application.

This compilation describes state-of-the-art research and future directions in the dynamic and ever-changing field of membranes, which over the decades has evolved from studies of physicochemical properties of amphiphiles to their application in industry and medicine. Most recently, sophisticated computing techniques have been used to predict the structural and physical properties of these self-organized assemblies to a degree that can rarely be achieved by experiment. Biomimetic membrane research is driven by diverse interests and needs. For example, in order to optimize given processes or to better understand the function of biological membranes (in order to improve or develop new drugs or sensors), different physical and computational experiments are needed. The science described in this book is presented by leading researchers in their fields, and should serve as a useful reference for both the novice and expert. Although the book is organized into two parts, namely, basic and applied research, this differentiation is not strict, and certain chapters could have easily been assigned to either part of the book.

The part on basic research covers a range of topics, beginning with a chapter on soft matter physics of membranes by Harries and Raviv, which is then followed by the chapter by Conn and Seddon, in which they describe nonlamellar phases and their applications. Diat et al. then discuss research involving the extraction of molecules (mainly metal ions) by using the interfacial properties of amphiphilic molecules in an immiscible liquid–liquid (e.g., water–oil). The chapter by Lyman and Patel, as well as that by Ulmschneider, clearly shows the significant developments that have taken place over the last decade in molecular dynamics simulations, starting from lipid-only simulations, to atomistic simulations of proteins embedded in bilayers, to peptides partitioning in membranes.

Subsequent chapters evolve from theory and computational simulations to some of the most up-to-date experimental research. Membrane dynamics, as studied by inelastic neutron scattering, is covered in the chapter by Rheinstädter, while elastic scatterings (neutrons and x-rays) are the topic of discussion by Pan et al. Both works report on recent advances of experimental techniques that enable one to explore the role of lipid diversity in the organization of membranes and the formation of well-defined nanostructures (e.g., lamellae, vesicles, ribbons, and nanodiscs). Lipid diversity leading to lateral heterogeneity in lipid bilayers has received considerable attention, especially in connection to lipid "raft" in living cells. It is widely accepted that rafts play a central role in cellular processes, for example, signal transduction. The aggregate morphology of lipid binary mixtures composed of different chain lengths exhibits a strong dependence on temperature, concentration, and charge. Heberle et al. review a number of current lipid-based models which allow for the study of membrane rafts at a length scale on the order of microns. Baker, Denisov and Sligar introduce the formation of apolipoprotein-associated nanodiscs, which are being used to extract membrane proteins in their native low-curvature environment for biochemical and biophysical studies. Using a different approach, Hayes describes the potential of microemulsions to advance our understanding of model biological systems, including the study of associated biomolecules.

The chapters by Marquardt and Harroun, and Pabst and Lohner describe, respectively, experimental techniques for locating molecules within membranes, and how membrane active compounds couple with the membrane to impart function in systems currently of interest to the medical community. Medical needs are also central for the development of novel gene-transfection systems. Lipoplexes, that is, lipid/DNA aggregates, seem to be promising carriers in addressing the transfer of genetic materials. The interplay between electrostatic and elastic interactions, and the structural variety that these aggregates form are described in the chapter by Uhríková and Pullmannová. The first part of the book concludes with the chapter by Lacoste and Bassereau on lipid vesicles decorated with active proteins. They demonstrate the complex modifications of membrane properties (e.g., elasticity) upon the introduction of proteins, and provide theoretical descriptions.

The second part of the book focuses on the technological applications of amphiphiles. This section begins with the chapter by Fenske and Cullis on liposome-based nanoparticles for drug delivery, in which they describe vesicle formulations and loading characteristics with different drugs. They are followed by Piroyan et al., whose chapter shows how liposomes can be modified with membrane-associated polymers to prolong their in vivo circulation lifetime, and how they can be functionalized for specific medical purposes. These two chapters on drug delivery are followed by the chapter by Yaghmur et al., in which novel drug-delivery systems made up of cubosomes, hexosomes, and micellar cubosomes are discussed; these assemblies hold promise for increased drug loading.

Knoll, Naumann and Nowak, and Martin et al. introduce technology platforms using tethered membranes and reconstituted proteins for bio-sensing applications. They are followed by chapters by Martí et al., describing the use of liposomes in textile dyeing, and by Weiss et al. who describe how lipidic nanoparticles are used by the food industry. The use of lipid-based particles for dyeing materials results in reduced cost and energy, while increasing dye quality in wool. In the case of the food industry, lipidic nanoparticles are used to improve processing times and extend the shelf life of commonly available food products.

We are grateful to all the authors who contributed their time and energy to this book. Without them, this opus would not have been possible. The aim of each chapter is to help the readers understand the different membrane platforms used by basic research laboratories and industry. In the end, we hope that the research presented in this book will inspire many researchers to create better bridges between model systems, biology, healthcare, and industrial applications.

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Editors

Georg Pabst earned his PhD in physics from Graz University of Technology (Austria) and completed his postdoctoral research at the National Research Council (Chalk River, Ontario, Canada). After returning to Austria, he was a senior research officer at the Austrian Academy of Sciences and is presently an assistant professor at the University of Graz. His research is focused on the physics of biological membranes with the aim to understand the functional role of membrane lipids in cellular transport and signaling.

Norbert Kučerka earned his PhD in biophysics from the Faculty of Mathematics, Physics and Informatics at Comenius University in Bratislava (Slovakia). He completed his postdoctoral research at Carnegie Mellon University (Pittsburgh, Pennsylvania), and as a National Science and Engineering Council fellow, at the Canadian Neutron Beam Centre (Chalk River, Ontario, Canada). In 2008, he joined the National Research Council of Canada, and is presently an associate research officer. His research is focused on determining the structure of biological model membranes, and unraveling the structure–function relationships.

Mu-Ping Nieh earned his PhD from the Department of Chemical Engineering at the University of Massachusetts (Amherst, USA). He completed his a postdoctoral research at the National Institute of Standards and Technology, Pennsylvania State University, and the National Research Council (Chalk River, Ontario, Canada). At the National Research Council he was promoted to assistant research officer. He is presently an associate professor at the University of Connecticut (Storrs, USA). His research focuses on the mechanisms behind the spontaneous formation in soft materials, including lipids, polymers, and proteins.

John Katsaras is a senior scientist and distinguished R&D staff at Oak Ridge National Laboratory (ORNL). He earned his PhD in biophysics from the University of Guelph (Ontario, Canada). Prior to joining ORNL, he was principal research officer at the National Research Council of Canada. He is internationally recognized for scientific contributions to the field of membrane biophysics, to materials of biological and medical relevance, and the application of x-ray and neutron scattering techniques to biologically relevant systems.

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