

# Advances in Delivery Science and Technology

**Series Editor:**

Michael J. Rathbone

For further volumes:

<http://www.springer.com/series/8875>



Juergen Siepmann • Ronald A. Siegel  
Michael J. Rathbone  
Editors

# Fundamentals and Applications of Controlled Release Drug Delivery

 Springer

*Editors*

Juergen Siepmann  
College of Pharmacy  
University Lille Nord de France  
Lille, France  
juergen.siepmann@univ-lille2.fr

Ronald A. Siegel  
Departments of Pharmaceutics  
and Biomedical Engineering  
University of Minnesota  
Minneapolis, MN, USA  
siege017@umn.edu

Michael J. Rathbone  
School of Pharmacy  
Griffith University  
Southport, QLD, Australia  
m.rathbone@griffith.edu.au

ISSN 2192-6204 e-ISSN 2192-6212  
ISBN 978-1-4614-0880-2 e-ISBN 978-1-4614-0881-9  
DOI 10.1007/978-1-4614-0881-9  
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011939206

© Controlled Release Society 2012

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Forward

Controlled Release Systems impact the health and well being of tens of millions of people every year. And yet, it is a relatively new field built both on solid fundamentals of chemistry and mass transport, as well as new discoveries in materials science and biology. It is also an interdisciplinary field and involves the convergence of a broad range of engineering, scientific, and medical disciplines. Ron Siegel, Juergen Siepmann, and Mike Rathbone have put together a book that explains and discusses the fundamentals of this field.

*Fundamentals and Applications of Controlled Release Drug Delivery* examines various aspects of fundamentals of drug delivery from why and when controlled release is needed to the different mechanisms and processes involved, including aspects of mathematically modeling these systems. This work also covers biodegradable polymers, hydrogels, hydrophobic polymers, and other materials of significance. A significant portion of this volume is devoted to delivering drugs over both the right time period and to the right place in the body. Mechanisms of release for achieving appropriately timed drug release such as diffusion, swelling, osmosis, and polymer degradation are discussed. For accomplishing targeting to the right place in the body, approaches such as nanosystems, liposomes, and receptor targeted release are examined. Finally, various selected applications of drug delivery are evaluated. These include cancer, heart disease, vaccines, and tissue repair. The need for sophisticated drug delivery systems which take into account circadian and other physiological rhythms is also explored.

As the twenty-first century emerges, there is little question that drug delivery will play a major role in health care. This book will clearly help those who want to design and utilize these important systems.

Cambridge, MA, USA

Robert Langer, Sc.D.



# Preface

This volume provides an overview of fundamental principles relating to the science and technology of drug delivery. It approaches the subject from a mechanistic perspective using language that is understandable to those entering the field and who are not familiar with its common phrases or complex terms. It provides a simple encapsulation of concepts and then expands on them as the reader progresses through the book. Once the concepts are laid out, applications to various disease states are described in detail.

Drug delivery is an interdisciplinary field concerned with the proper administration of bioactive compounds to achieve a desired clinical response in humans or animals. Drug delivery is beneficial to billions of people (and animals) worldwide and is achieved by designing and developing technologies that modify the temporal and spatial drug release profile, resulting in enhanced product safety and improved patient convenience and compliance. Rational design of a drug delivery technology requires the convergence of many fields of science and engineering.

Technologies have been developed for delivery of bioactives via many routes of administration including the oral, topical (e.g., skin), transmucosal (nasal, buccal/sublingual, vaginal, ocular, and rectal), and inhalation routes. A broad range of bioactive compounds are incorporated into delivery technologies, from simple molecules to peptides and proteins, antibodies, vaccines, and gene-based drugs. A well-designed drug delivery technology offers the advantages of reduction in dose frequency, a more uniform effect of the drug over time, reduction of drug side effects, reduced unwanted fluctuations in circulating drug levels, and extension of the commercial value of a drug or formulation. Disadvantages of drug delivery systems include their high cost, and sometimes a decreased ability by the clinician or patient to adjust dosages.

The outcomes of recent efforts in the field of drug delivery are rapidly emerging, as is expansion of knowledge of the underlying science. Recent advances include the development of targeted delivery systems in which the drug is only active in a specific area of the body such as cancer tissues, microscopic novel long acting

formulations such as microparticles and nanoparticles in which the drug is released over a period of time in a controlled manner, liposomes, in situ forming implants, and drug polymer conjugates.

This book is divided into six parts. The first part covers the *value of drug delivery*, starting with a chapter written by Wilson on the advantages that drug delivery brings and why drug delivery is needed to treat a specific condition. Terms used in the drug delivery area are defined and controlled release resources are identified. An overview of mechanisms of drug delivery is then provided in a chapter by Siegel and Rathbone. The second part of the book covers *polymeric delivery materials* and includes a description of the synthesis, manufacture, and characterization of polymeric materials used to deliver drugs. Chapters emphasize the need for materials characterization and the need to fully characterize manufacturing processes to avoid process and product failures. Hydrophobic polymers are discussed by Jones et al., hydrogels are reviewed by Omidian and Park, and Burgess and Tsung co-author a chapter on biodegradable polymers. The third part of the book deals with *temporal delivery systems and mechanisms*. Siepmann et al. author two chapters on diffusion and swelling controlled systems, Schwendeman and Wischke provide a summary of degradable polymeric carrier systems, and Siegel presents an overview of porous systems. In the fourth part concerning *spatial delivery systems and mechanisms*, Minko provides a chapter on receptor targeted release, Torchilin reviews liposomes for targeted drug delivery, and Fattal discusses targeted delivery using biodegradable polymeric nanoparticles. The fifth part deals with present and potential future clinical *applications* of controlled drug delivery. This part begins with an extensive review of chronotherapeutics and drug delivery by Smolensky et al., which is followed by chapters on approaches to treatment of cardiovascular disease (Fishbein et al.), cancer (Bardhwaj and Ravi Kumar), and infectious disease (Senel). A final chapter in the fifth part covers controlled release in tissue engineering (Suggs). The sixth, final part is a *future outlook* consisting of a chapter written by Dr. Stephen Perrett surveying the present and future regulatory and commercial landscape for advanced drug delivery systems.

The Editors are indebted to the willingness and expertise of the authoritative contributors who have donated their valuable time to write chapters for this volume. Without them this book would not have become a reality.

Lille, France  
Minneapolis, MN, USA  
Southport, QLD, Australia

Juergen Siepmann  
Ronald A. Siegel  
Michael J. Rathbone



# Contents

## Part I The Value of Drug Delivery

- |                                                             |           |
|-------------------------------------------------------------|-----------|
| <b>1 The Need for Drugs and Drug Delivery Systems .....</b> | <b>3</b>  |
| Clive G. Wilson                                             |           |
| <b>2 Overview of Controlled Release Mechanisms .....</b>    | <b>19</b> |
| Ronald A. Siegel and Michael J. Rathbone                    |           |

## Part II Delivery Materials

- |                                                                   |            |
|-------------------------------------------------------------------|------------|
| <b>3 Hydrophobic Polymers of Pharmaceutical Significance.....</b> | <b>47</b>  |
| Osama A. Abu-Diak, Gavin P. Andrews, and David S. Jones           |            |
| <b>4 Hydrogels .....</b>                                          | <b>75</b>  |
| Hossein Omidian and Kinam Park                                    |            |
| <b>5 Biodegradable Polymers in Drug Delivery Systems .....</b>    | <b>107</b> |
| Jamie Tsung and Diane J. Burgess                                  |            |

## Part III Temporal Delivery Systems and Mechanisms

- |                                                                                      |            |
|--------------------------------------------------------------------------------------|------------|
| <b>6 Diffusion Controlled Drug Delivery Systems.....</b>                             | <b>127</b> |
| Juergen Siepmann, Ronald A. Siegel, and Florence Siepmann                            |            |
| <b>7 Swelling Controlled Drug Delivery Systems .....</b>                             | <b>153</b> |
| Juergen Siepmann and Florence Siepmann                                               |            |
| <b>8 Degradable Polymeric Carriers for Parenteral Controlled Drug Delivery .....</b> | <b>171</b> |
| C. Wischke and S.P. Schwendeman                                                      |            |
| <b>9 Porous Systems .....</b>                                                        | <b>229</b> |
| Ronald A. Siegel                                                                     |            |

## Part IV Spatial Delivery Systems and Mechanisms

|                                                                                    |            |
|------------------------------------------------------------------------------------|------------|
| <b>10 Targeted Delivery Using Biodegradable Polymeric Nanoparticles .....</b>      | <b>255</b> |
| Elias Fattal, Hervé Hillaireau, Simona Mura,<br>Julien Nicolas, and Nicolas Tsapis |            |
| <b>11 Liposomes in Drug Delivery .....</b>                                         | <b>289</b> |
| Vladimir Torchilin                                                                 |            |
| <b>12 Receptor Mediated Delivery Systems for Cancer Therapeutics .....</b>         | <b>329</b> |
| Tamara Minko                                                                       |            |

## Part V Applications

|                                                                                                       |            |
|-------------------------------------------------------------------------------------------------------|------------|
| <b>13 Biological Rhythms, Drug Delivery, and Chronotherapeutics .....</b>                             | <b>359</b> |
| Michael H. Smolensky, Ronald A. Siegel, Erhard Haus,<br>Ramon Hermida, and Francesco Portaluppi       |            |
| <b>14 Site Specific Controlled Release for Cardiovascular Disease: Translational Directions .....</b> | <b>445</b> |
| Ilia Fishbein, Michael Chorny, Ivan S. Alferiev,<br>and Robert J. Levy                                |            |
| <b>15 Drug Delivery Systems to Fight Cancer .....</b>                                                 | <b>493</b> |
| Vivekanand Bhardwaj and M.N.V. Ravi Kumar                                                             |            |
| <b>16 Fundamentals of Vaccine Delivery in Infectious Diseases .....</b>                               | <b>517</b> |
| Sevda Şenel                                                                                           |            |
| <b>17 Tissue Engineering in Drug Delivery .....</b>                                                   | <b>533</b> |
| Charles T. Drinnan, Laura R. Geuss, Ge Zhang,<br>and Laura J. Suggs                                   |            |

## Part VI Future Outlook

|                                                                                                                                                             |            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| <b>18 The Shaping of Controlled Release Drug Product Development by Emerging Trends in the Commercial, Regulatory, and Political Macroenvironment .....</b> | <b>571</b> |
| Stephen Perrett and Michael J. Rathbone                                                                                                                     |            |
| <b>Index .....</b>                                                                                                                                          | <b>579</b> |

# Contributors

**Osama A. Abu-Diak** School of Pharmacy, Queen's University of Belfast, Belfast, UK

**Ivan S. Alferiev** Abramson Research Center, The Children's Hospital of Philadelphia, Philadelphia, PA, USA

**Gavin P. Andrews** School of Pharmacy, Queen's University of Belfast, Belfast, UK

**Vivekanand Bhardwaj** Strathclyde Institute of Pharmacy and Biomedical Science, University of Strathclyde, Glasgow, UK

**Diane J. Burgess** Department of Pharmaceutical Sciences, University of Connecticut, Storrs, CT, USA

**Michael Chorny** Abramson Research Center, The Children's Hospital of Philadelphia, Philadelphia, PA, USA

**Charles T. Drinnan** Department of Biomedical Engineering, University of Texas at Austin, Austin, TX, USA

**Elias Fattal** Laboratoire de Physico-Chimie, Pharmacotechnie et Biopharmacie, Faculté de Pharmacie, Université Paris-Sud, Châtenay-Malabry, France

**Ilia Fishbein** Abramson Research Center, The Children's Hospital of Philadelphia, Philadelphia, PA, USA

**Laura R. Geuss** Department of Cellular and Molecular Biology, University of Texas at Austin, Austin, TX, USA

**Erhard Haus** Department of Laboratory Medicine and Pathology, University of Minnesota, Minneapolis, MN, USA  
Health Partners Medical Group, Regions Hospital, St. Paul, MN, USA

**Ramon Hermida** Bioengineering & Chronobiology Laboratories,  
University of Vigo, Vigo, Spain

**Hervé Hillaireau** Laboratoire de Physico-Chimie, Pharmacotechnie et  
Biopharmacie, Faculté de Pharmacie, Université Paris-Sud,  
Châtenay-Malabry, France

**David S. Jones** School of Pharmacy, Queen's University of Belfast, Belfast, UK

**Robert Langer** Department of Chemical Engineering, Massachusetts  
Institute of Technology, Cambridge, MA, USA

**Robert J. Levy** Abramson Research Center, The Children's Hospital  
of Philadelphia, Philadelphia, PA, USA

**Tamara Minko** Department of Pharmaceutics, Ernest Mario School  
of Pharmacy, Rutgers, The State University of New Jersey,  
Piscataway, NJ, USA

**Simona Mura** Laboratoire de Physico-Chimie, Pharmacotechnie et  
Biopharmacie Faculté de Pharmacie, Université Paris-Sud,  
Châtenay-Malabry, France

**Julien Nicolas** Laboratoire de Physico-Chimie, Pharmacotechnie et  
Biopharmacie Faculté de Pharmacie, Université Paris-Sud,  
Châtenay-Malabry, France

**Hossein Omidian** Health Professions Division, College of Pharmacy,  
Nova Southeastern University, Fort Lauderdale, FL, USA

**Kinam Park** Departments of Biomedical Engineering and Pharmaceutics, Purdue  
University, West Lafayette, IN, USA

**Stephen Perrett** Portfolio Development, Eurand, Yardley, PA, USA

**Francesco Portaluppi** Department of Clinical and Experimental Medicine,  
Hypertension Center, University Hospital S. Anna, University of Ferrara,  
Ferrara, Italy

**Michael J. Rathbone** School of Pharmacy, Griffith University, Southport,  
QLD, Australia

**M.N.V. Ravi Kumar** Strathclyde Institute of Pharmacy and Biomedical Science,  
University of Strathclyde, Glasgow, UK

**S.P. Schwendeman** Department of Pharmaceutical Sciences, University  
of Michigan, Ann Arbor, MI, USA

**Sevda Şenel** Department of Pharmaceutical Technology, Faculty of Pharmacy,  
Hacettepe University, Ankara, Turkey

**Ronald A. Siegel** Departments of Pharmaceutics and Biomedical Engineering,  
University of Minnesota, Minneapolis, MN, USA

**Florence Siepmann** College of Pharmacy, University Lille Nord de France,  
Lille, France

**Juergen Siepmann** College of Pharmacy, University Lille Nord de France,  
Lille, France

**Michael H. Smolensky** Department of Biomedical Engineering,  
University of Texas at Austin, Austin, TX, USA

**Laura J. Suggs** Department of Biomedical Engineering, University of Texas  
at Austin, Austin, TX, USA

**Vladimir Torchilin** Center for Pharmaceutical Biotechnology and Nanomedicine,  
Northeastern University, Boston, MA, USA

**Nicolas Tsapis** Laboratoire de Physico-Chimie, Pharmacotechnie et Biopharmacie  
Faculté de Pharmacie, Université Paris-Sud, Châtenay-Malabry, France

**Jamie Tsung** Shire HGT, Cambridge, MA, USA

**Clive G. Wilson** Strathclyde Institute of Pharmacy and Biomedical Sciences,  
Glasgow, Scotland, UK

**C. Wischke** Department of Pharmaceutical Sciences,  
University of Michigan, MI, USA

Center for Biomaterial Development, Berlin-Brandenburg Center for  
Regenerative Therapies, Institute of Polymer Research,  
Helmholtz Center Geesthacht, Teltow, Germany

**Ge Zhang** Department of Biomedical Engineering, University of Akron,  
Akron, OH, USA