

WOODHEAD PUBLISHING SERIES IN BIOMATERIALS



# Bioresorbable Polymers for Biomedical Applications

From Fundamentals to  
Translational Medicine

Edited by Giuseppe Perale  
and Jöns Hilborn

**WP**  
WOODHEAD  
PUBLISHING

Woodhead Publishing Series in Biomaterials:  
Number 120

# Bioresorbable Polymers for Biomedical Applications

From Fundamentals to Translational  
Medicine

*Edited by*

*Giuseppe Perale and Jöns Hilborn*



AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG  
LONDON • NEW YORK • OXFORD • PARIS • SAN DIEGO  
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO  
Woodhead Publishing is an imprint of Elsevier



Woodhead Publishing is an imprint of Elsevier  
The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom  
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States  
The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

Copyright © 2017 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

### Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

### Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

### British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-08-100262-9 (print)

ISBN: 978-0-08-100266-7 (online)

For information on all Woodhead Publishing publications  
visit our website at <https://www.elsevier.com/>



Working together  
to grow libraries in  
developing countries

[www.elsevier.com](http://www.elsevier.com) • [www.bookaid.org](http://www.bookaid.org)

*Publisher:* Matthew Deans

*Acquisition Editor:* Laura Overend

*Editorial Project Manager:* Lucy Beg

*Production Project Manager:* Poulouse Joseph

*Designer:* Greg Harris

Typeset by TNQ Books and Journals

# **Bioresorbable Polymers for Biomedical Applications**

## **Related titles**

*Modelling Degradation of Polymeric Medical Devices*

(ISBN 978-1-78242-016-3)

*Controlled Drug Delivery*

(ISBN 978-1-907568-45-9)

*Durability and Reliability of Medical Polymers*

(ISBN 978-1-84569-929-1)

*Drug-Device Combination Products*

(ISBN 978-1-84569-470-8)

*To my daughters Matilde and Eleonora, who make  
everything worthwhile.*

Giuseppe Perale

*To my wife, Gunilla, who has  
put up with me for reasons not always obvious.*

Jöns Hilborn



# List of contributors

**M.A. Arriaga** University of Texas Rio Grande Valley, Brownsville, TX, United States

**M. Bassas-Galia** Institute of Life Technologies, University of Applied Sciences and Arts Western Switzerland; HES-SO Valais-Wallis, Switzerland

**M. Belicchi** IRCCS Fondazione Ca' Granda Ospedale Maggiore Policlinico, DePT Università degli Studi di Milano, Milan, Italy; Novastem S.r.l., Milan, Italy

**G. Bellezza** Tensive SRL, Milano, Italy

**S. Berrettini** University of Pisa, Pisa, Italy

**M.J. Blanco-Prieto** University of Navarra, Pamplona, Spain; Instituto de Investigación Sanitaria de Navarra, IdiSNA, Pamplona, Spain

**S. Brianza** Biomech Innovations AG, Nidau, Switzerland

**L. Brizielli** University of Applied Sciences and Arts of Southern Switzerland, SUPSI, Manno, Switzerland

**L. Bruschini** University of Pisa, Pisa, Italy

**T. Casalini** Institute for Chemical and Bioengineering, ETH Zurich, Zürich, Switzerland

**S.A. Chew** University of Texas Rio Grande Valley, Brownsville, TX, United States

**G. Conti** Industrie Biomediche Insubri SA, Mezzovico-Vira, Switzerland; Furatena S.r.l., Brescia, Italy

**D. D'Alessandro** University of Pisa, Pisa, Italy

**S. Danti** University of Pisa, Pisa, Italy

**K.N. Ekdahl** Uppsala University, Uppsala, Sweden; Linnæus University, Kalmar, Sweden

**E.C. Ekwueme** Rutgers University, Piscataway, NJ, United States

**S. Erratico** Novastem S.r.l., Milan, Italy



**M.L. Focarete** Department of Chemistry “G. Ciamician”, University of Bologna, Bologna, Italy; Health Sciences and Technologies, Center for Industrial Research (HST-ICIR), University of Bologna, Bologna, Italy

**S. Follonier** Institute of Life Technologies, University of Applied Sciences and Arts Western Switzerland; HES-SO Valais-Wallis, Switzerland

**J.W. Freeman** Rutgers University, Piscataway, NJ, United States

**K. Fromell** Uppsala University, Uppsala, Sweden

**E. Garbayo** University of Navarra, Pamplona, Spain; Instituto de Investigación Sanitaria de Navarra, IdiSNA, Pamplona, Spain

**M. Gerasimov** Department of Clinical and Experimental Medicine (IKE), Linköping University, Linköping, Sweden

**I. Gerges** Tensive SRL, Milano, Italy

**U. Graf-Hausner** Zurich University of Applied Sciences (ZHAW), Wädenswil, Switzerland

**M. Griffith** Integrative Regenerative Medicine Centre and Department of Clinical and Experimental Medicine (IKE), Linköping University, Linköping, Sweden; Ottawa Hospital Research Institute – Vision Programme, Ottawa, Ontario, Canada

**C. Gualandi** Department of Chemistry “G. Ciamician”, University of Bologna, Bologna, Italy; Health Sciences and Technologies, Center for Industrial Research (HST-ICIR), University of Bologna, Bologna, Italy

**J. Hilborn** Uppsala University, Uppsala, Sweden

**V.A. Hinojosa** University of Texas Rio Grande Valley, Brownsville, TX, United States

**A. Koubatis** Altran AG, Zürich, Switzerland

**M. Lattuada** University of Fribourg, Fribourg, Switzerland

**F. Martello** Tensive SRL, Milano, Italy

**E. Mauri** Politecnico di Milano, Milan, Italy

**K. Merrett** Integrative Regenerative Medicine Centre and Department of Clinical and Experimental Medicine (IKE), Linköping University, Linköping, Sweden; Ottawa Hospital Research Institute – Vision Programme, Ottawa, Ontario, Canada

**D. Moscatelli** Politecnico di Milano, Milano, Italy

**C. Mota** Maastricht University, Maastricht, The Netherlands

**M. Müller** ETH Zurich, Zurich, Switzerland

**B. Nilsson** Uppsala University, Uppsala, Sweden

- L. Orlando** Industrie Biomediche Insubri SA, Mezzovico-Vira, Switzerland
- S. Papa** IRCCS Istituto di Ricerche Farmacologiche “Mario Negri”, Milan, Italy
- S. Pascual-Gil** University of Navarra, Pamplona, Spain; Instituto de Investigación Sanitaria de Navarra, IdiSNA, Pamplona, Spain
- J.M. Patel** Rutgers University, Piscataway, NJ, United States
- G. Perale** University of Applied Sciences and Arts of Southern Switzerland, SUPSI, Manno, Switzerland
- G. Pertici** University of Applied Sciences and Arts of Southern Switzerland, SUPSI, Manno, Switzerland; Industrie Biomediche Insubri SA, Mezzovico-Vira, Switzerland
- F. Prosper** University of Navarra, Pamplona, Spain; Instituto de Investigación Sanitaria de Navarra, IdiSNA, Pamplona, Spain
- M. Pusnik** Institute of Life Technologies, University of Applied Sciences and Arts Western Switzerland; HES-SO Valais-Wallis, Switzerland
- F. Redaelli** Politecnico di Milano, Milan, Italy
- M. Rimann** Zurich University of Applied Sciences (ZHAW), Wädenswil, Switzerland
- F. Rossi** Politecnico di Milano, Milan, Italy
- A. Samanta** Integrative Regenerative Medicine Centre and Department of Clinical and Experimental Medicine (IKE), Linköping University, Linköping, Sweden; Ottawa Hospital Research Institute — Vision Programme, Ottawa, Ontario, Canada
- M. Santoro** Rice University, Houston, TX, United States
- M. Sorbona** Politecnico di Milano, Milan, Italy
- M. Sponchioni** Politecnico di Milano, Milano, Italy
- G. Storti** ETH Zurich, Zurich, Switzerland
- E. Sundström** Karolinska Institutet, Care Sciences and Society, Huddinge, Sweden; Stockholms Sjukhem, Stockholm, Sweden
- M. Tamplenizza** Tensive SRL, Milano, Italy
- A. Tocchio** Tensive SRL, Milano, Italy; SEMM, European School of Molecular Medicine, Milano, Italy
- Y. Torrente** IRCCS Fondazione Ca’ Granda Ospedale Maggiore Policlinico, DePT Università degli Studi di Milano, Milan, Italy; Novastem S.r.l., Milan, Italy
- P. Vegliane** IRCCS Istituto di Ricerche Farmacologiche “Mario Negri”, Milan, Italy

**C. Villa** IRCCS Fondazione Ca' Granda Ospedale Maggiore Policlinico, DePT  
Università degli Studi di Milano, Milan, Italy

**T. Villa** Politecnico di Milano, Milano, Italy

**J.L. Walker** Rice University, Houston, TX, United States

**M. Zinn** Institute of Life Technologies, University of Applied Sciences and Arts  
Western Switzerland; HES-SO Valais-Wallis, Switzerland

# Woodhead Publishing Series in Biomaterials

- 1 **Sterilisation of tissues using ionising radiations**  
*Edited by J. F. Kennedy, G. O. Phillips and P. A. Williams*
- 2 **Surfaces and interfaces for biomaterials**  
*Edited by P. Vadgama*
- 3 **Molecular interfacial phenomena of polymers and biopolymers**  
*Edited by C. Chen*
- 4 **Biomaterials, artificial organs and tissue engineering**  
*Edited by L. Hench and J. Jones*
- 5 **Medical modelling**  
*R. Bibb*
- 6 **Artificial cells, cell engineering and therapy**  
*Edited by S. Prakash*
- 7 **Biomedical polymers**  
*Edited by M. Jenkins*
- 8 **Tissue engineering using ceramics and polymers**  
*Edited by A. R. Boccaccini and J. Gough*
- 9 **Bioceramics and their clinical applications**  
*Edited by T. Kokubo*
- 10 **Dental biomaterials**  
*Edited by R. V. Curtis and T. F. Watson*
- 11 **Joint replacement technology**  
*Edited by P. A. Revell*
- 12 **Natural-based polymers for biomedical applications**  
*Edited by R. L. Reiss et al*
- 13 **Degradation rate of bioresorbable materials**  
*Edited by F. J. Buchanan*
- 14 **Orthopaedic bone cements**  
*Edited by S. Deb*
- 15 **Shape memory alloys for biomedical applications**  
*Edited by T. Yoneyama and S. Miyazaki*
- 16 **Cellular response to biomaterials**  
*Edited by L. Di Silvio*
- 17 **Biomaterials for treating skin loss**  
*Edited by D. P. Orgill and C. Blanco*
- 18 **Biomaterials and tissue engineering in urology**  
*Edited by J. Denstedt and A. Atala*

- 
- 19 **Materials science for dentistry**  
*B. W. Darvell*
  - 20 **Bone repair biomaterials**  
*Edited by J. A. Planell, S. M. Best, D. Lacroix and A. Merolli*
  - 21 **Biomedical composites**  
*Edited by L. Ambrosio*
  - 22 **Drug—device combination products**  
*Edited by A. Lewis*
  - 23 **Biomaterials and regenerative medicine in ophthalmology**  
*Edited by T. V. Chirila*
  - 24 **Regenerative medicine and biomaterials for the repair of connective tissues**  
*Edited by C. Archer and J. Ralphs*
  - 25 **Metals for biomedical devices**  
*Edited by M. Niinomi*
  - 26 **Biointegration of medical implant materials: Science and design**  
*Edited by C. P. Sharma*
  - 27 **Biomaterials and devices for the circulatory system**  
*Edited by T. Gourlay and R. Black*
  - 28 **Surface modification of biomaterials: Methods analysis and applications**  
*Edited by R. Williams*
  - 29 **Biomaterials for artificial organs**  
*Edited by M. Lysaght and T. Webster*
  - 30 **Injectable biomaterials: Science and applications**  
*Edited by B. Vernon*
  - 31 **Biomedical hydrogels: Biochemistry, manufacture and medical applications**  
*Edited by S. Rimmer*
  - 32 **Preprosthetic and maxillofacial surgery: Biomaterials, bone grafting and tissue engineering**  
*Edited by J. Ferri and E. Hunziker*
  - 33 **Bioactive materials in medicine: Design and applications**  
*Edited by X. Zhao, J. M. Courtney and H. Qian*
  - 34 **Advanced wound repair therapies**  
*Edited by D. Farrar*
  - 35 **Electrospinning for tissue regeneration**  
*Edited by L. Bosworth and S. Downes*
  - 36 **Bioactive glasses: Materials, properties and applications**  
*Edited by H. O. Ylänen*
  - 37 **Coatings for biomedical applications**  
*Edited by M. Driver*
  - 38 **Progenitor and stem cell technologies and therapies**  
*Edited by A. Atala*
  - 39 **Biomaterials for spinal surgery**  
*Edited by L. Ambrosio and E. Tanner*
  - 40 **Minimized cardiopulmonary bypass techniques and technologies**  
*Edited by T. Gourlay and S. Gunaydin*
  - 41 **Wear of orthopaedic implants and artificial joints**  
*Edited by S. Affatato*
  - 42 **Biomaterials in plastic surgery: Breast implants**  
*Edited by W. Peters, H. Brandon, K. L. Jerina, C. Wolf and V. L. Young*

- 43 **MEMS for biomedical applications**  
*Edited by S. Bhansali and A. Vasudev*
- 44 **Durability and reliability of medical polymers**  
*Edited by M. Jenkins and A. Stamboulis*
- 45 **Biosensors for medical applications**  
*Edited by S. Higson*
- 46 **Sterilisation of biomaterials and medical devices**  
*Edited by S. Lerouge and A. Simmons*
- 47 **The hip resurfacing handbook: A practical guide to the use and management of modern hip resurfacings**  
*Edited by K. De Smet, P. Campbell and C. Van Der Straeten*
- 48 **Developments in tissue engineered and regenerative medicine products**  
*J. Basu and J. W. Ludlow*
- 49 **Nanomedicine: Technologies and applications**  
*Edited by T. J. Webster*
- 50 **Biocompatibility and performance of medical devices**  
*Edited by J-P. Boutrand*
- 51 **Medical robotics: Minimally invasive surgery**  
*Edited by P. Gomes*
- 52 **Implantable sensor systems for medical applications**  
*Edited by A. Inmann and D. Hodgins*
- 53 **Non-metallic biomaterials for tooth repair and replacement**  
*Edited by P. Vallittu*
- 54 **Joining and assembly of medical materials and devices**  
*Edited by Y. (Norman) Zhou and M. D. Breyen*
- 55 **Diamond-based materials for biomedical applications**  
*Edited by R. Narayan*
- 56 **Nanomaterials in tissue engineering: Fabrication and applications**  
*Edited by A. K. Gaharwar, S. Sant, M. J. Hancock and S. A. Hacking*
- 57 **Biomimetic biomaterials: Structure and applications**  
*Edited by A. J. Ruys*
- 58 **Standardisation in cell and tissue engineering: Methods and protocols**  
*Edited by V. Salih*
- 59 **Inhaler devices: Fundamentals, design and drug delivery**  
*Edited by P. Prokopovich*
- 60 **Bio-tribocorrosion in biomaterials and medical implants**  
*Edited by Y. Yan*
- 61 **Microfluidic devices for biomedical applications**  
*Edited by X-J. James Li and Y. Zhou*
- 62 **Decontamination in hospitals and healthcare**  
*Edited by J. T. Walker*
- 63 **Biomedical imaging: Applications and advances**  
*Edited by P. Morris*
- 64 **Characterization of biomaterials**  
*Edited by M. Jaffe, W. Hammond, P. Tolia and T. Arinzeh*
- 65 **Biomaterials and medical tribology**  
*Edited by J. Paolo Davim*
- 66 **Biomaterials for cancer therapeutics: Diagnosis, prevention and therapy**  
*Edited by K. Park*

- 
- 67 **New functional biomaterials for medicine and healthcare**  
*E.P. Ivanova, K. Bazaka and R. J. Crawford*
- 68 **Porous silicon for biomedical applications**  
*Edited by H. A. Santos*
- 69 **A practical approach to spinal trauma**  
*Edited by H. N. Bajaj and S. Katoch*
- 70 **Rapid prototyping of biomaterials: Principles and applications**  
*Edited by R. Narayan*
- 71 **Cardiac regeneration and repair Volume 1: Pathology and therapies**  
*Edited by R-K. Li and R. D. Weisel*
- 72 **Cardiac regeneration and repair Volume 2: Biomaterials and tissue engineering**  
*Edited by R-K. Li and R. D. Weisel*
- 73 **Semiconducting silicon nanowires for biomedical applications**  
*Edited by J.L. Coffey*
- 74 **Silk biomaterials for tissue engineering and regenerative medicine**  
*Edited by S. Kundu*
- 75 **Biomaterials for bone regeneration: Novel techniques and applications**  
*Edited by P. Dubruel and S. Van Vlierberghe*
- 76 **Biomedical foams for tissue engineering applications**  
*Edited by P. Netti*
- 77 **Precious metals for biomedical applications**  
*Edited by N. Baltzer and T. Copponex*
- 78 **Bone substitute biomaterials**  
*Edited by K. Mallick*
- 79 **Regulatory affairs for biomaterials and medical devices**  
*Edited by S. F. Amato and R. Ezzell*
- 80 **Joint replacement technology Second edition**  
*Edited by P. A. Revell*
- 81 **Computational modelling of biomechanics and biotribology in the musculoskeletal system: Biomaterials and tissues**  
*Edited by Z. Jin*
- 82 **Biophotonics for medical applications**  
*Edited by I. Meglinski*
- 83 **Modelling degradation of bioresorbable polymeric medical devices**  
*Edited by J. Pan*
- 84 **Perspectives in total hip arthroplasty: Advances in biomaterials and their tribological interactions**  
*S. Affatato*
- 85 **Tissue engineering using ceramics and polymers Second edition**  
*Edited by A. R. Boccaccini and P. X. Ma*
- 86 **Biomaterials and medical-device associated infections**  
*Edited by L. Barnes and I. R. Cooper*
- 87 **Surgical techniques in total knee arthroplasty (TKA) and alternative procedures**  
*Edited by S. Affatato*
- 88 **Lanthanide oxide nanoparticles for molecular imaging and therapeutics**  
*G. H. Lee*
- 89 **Surface modification of magnesium and its alloys for biomedical applications Volume 1: Biological interactions, mechanical properties and testing**  
*Edited by T. S. N. Sankara Narayanan, I. S. Park and M. H. Lee*

- 90 **Surface modification of magnesium and its alloys for biomedical applications**  
**Volume 2: Modification and coating techniques**  
*Edited by T. S. N. Sankara Narayanan, I. S. Park and M. H. Lee*
- 91 **Medical modelling: the application of advanced design and rapid prototyping techniques in medicine Second Edition**  
*Edited by R. Bibb, D. Eggbeer and A. Paterson*
- 92 **Switchable and responsive surfaces and materials for biomedical applications**  
*Edited by Z. Zhang*
- 93 **Biomedical textiles for orthopaedic and surgical applications: fundamentals, applications and tissue engineering**  
*Edited by T. Blair*
- 94 **Surface coating and modification of metallic biomaterials**  
*Edited by C. Wen*
- 95 **Hydroxyapatite (HAP) for biomedical applications**  
*Edited by M. Mucalo*
- 96 **Implantable neuroprostheses for restoring function**  
*Edited by K. Kilgore*
- 97 **Shape memory polymers for biomedical applications**  
*Edited by L. Yahia*
- 98 **Regenerative engineering of musculoskeletal tissues and interfaces**  
*Edited by S.P. Nukavarapu, J.W. Freeman and C.T. Laurencin*
- 99 **Advanced cardiac imaging**  
*Edited by K. Nieman, O. Gaemperli, P. Lancellotti and S. Plein*
- 100 **Functional Marine Biomaterials: Properties and Applications**  
*Edited by SK. Kim*
- 101 **Shoulder and elbow trauma and its complications: Volume 1: The Shoulder**  
*Edited by R. M. Greiwe*
- 102 **Nanotechnology-enhanced orthopedic materials: Fabrications, applications and future trends**  
*Edited by L. Yang*
- 103 **Medical devices: Regulations, standards and practices**  
*Edited by S. Ramakrishna, L. Tian, C. Wang, S. L. and T. Wee Eong*
- 104 **Biominalisation and biomaterials: fundamentals and applications**  
*Edited by C. Aparicio and M. Ginebra*
- 105 **Shoulder and elbow trauma and its complications: Volume 2: The Elbow**  
*Edited by R. M. Greiwe*
- 106 **Characterisation and design of tissue scaffolds**  
*Edited by P. Tomlins*
- 107 **Biosynthetic polymers for medical applications**  
*Edited by L. Poole-Warren, P. Martens and R.Green*
- 108 **Advances in polyurethane biomaterials**  
*Edited by S. L. Cooper*
- 109 **Nanocomposites for musculoskeletal tissue regeneration**  
*Edited by H. Liu*
- 110 **Thin film coatings for biomaterials and biomedical applications**  
*Edited by H. J. Griesser*
- 111 **Laser surface modification of biomaterials**  
*Edited by R. Vilar*



- 
- 112 **Biomaterials and regenerative medicine in ophthalmology** Second edition  
*Edited by T. V. Chirila and D. Harkin*
- 113 **Extracellular matrix-derived medical implants in clinical medicine**  
*Edited by D. Mooradia*
- 114 **Wound healing biomaterials: Volume 1: Therapies and regeneration**  
*Edited by M. S. Ågren*
- 115 **Wound healing biomaterials: Volume 2: Functional biomaterials**  
*Edited by M. S. Ågren*
- 116 **Materials for the direct restoration of teeth**  
*J. Nicholson and B. Czarnecka*
- 117 **Science and principles of biodegradable and bioresorbable medical polymers**  
*Edited by X. Zhang*
- 118 **Medical Biosensors for point of care (POC) applications**  
*Edited by R. Narayan*
- 119 **Biocompatibility of dental biomaterials**  
*Edited by R. Shelton*
- 120 **Bioresorbable polymers for biomedical applications: From fundamentals to translational medicine**  
*Edited by G. Perale and J. Hilborn*
- 121 **Bioinspired materials for medical applications**  
*Edited by L. Rodrigues and M. Mota*
- 122 **Chitosan based biomaterials Volume 1, Fundamentals**  
*Edited by J. A. Jennings and J. D. Bumgardner*
- 123 **Chitosan based biomaterials Volume 2, Tissue engineering and therapeutics**  
*Edited by J. A. Jennings and J. D. Bumgardner*
- 124 **Material-tissue interfacial phenomena**  
*Edited by P. Spencer*
- 125 **Mechanical testing of orthopaedic implants**  
*Edited by E. Friis*
- 126 **Management of periprosthetic joint infections (PJIs)**  
*Edited by A. J. Arts and J. A. P. Guerts*
- 127 **Bone response to dental implant materials**  
*Edited by A. Piattelli*