BIOMEDICAL MATHEMATICS:

Promising Directions in Imaging, Therapy Planning, and Inverse Problems

BIOMEDICAL MATHEMATICS:

Promising Directions in Imaging, Therapy Planning, and Inverse Problems

Yair Censor, Ming Jiang, Ge Wang Editors

The Huangguoshu International Interdisciplinary Conference on Biomedical Mathematics

The Huangguoshu National Park of China Guizhou, China

November 3–9, 2008

MEDICAL PHYSICS PUBLISHING Madison, Wisconsin Notice: Information in this book is provided for instructional use only. The editors have taken care that the information and recommendations contained herein are accurate and compatible with the standards generally accepted at the time of publication. Nevertheless, it is difficult to ensure that all the information given is entirely accurate for all circumstances. The editors, contributing authors, and publisher cannot assume responsibility for the validity of all materials or for any damage or harm incurred as a result of the use of this information.

Copyright © 2010 by Yair Censor, Ming Jiang, and Ge Wang

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission from the publisher.

Library of Congress Control Number: 2010921431

ISBN: 978-1-930524-48-4

Medical Physics Publishing 4513 Vernon Boulevard Madison, WI 53705-4964 Phone: 1-800-442-5778, 608-262-4021 Fax: 608-265-2121 Web: www.medicalphysics.org

Printed in the United States of America

Contents

	Preface	ix
	Contributing Authors	xi
1	Planning and Optimizing Treatment Plans for Actively Scanned Proton Therapy Francesca Albertini, Sylvain Gaignat, Matthias Bosshardt, Antony J. Lomax [*]	1
2	Identification and Characterization of Transcriptome-based Biomarkers in Arthritis and Cancer for Personalized Medicine by Translational Genomics Ashok R. Amin [*] and Ge Wang	19
3	Approximate Stability Estimates in Inverse Transport Theory Guillaume Bal [*] and Alexandre Jollivet	33
4	General Resolvents for Monotone Operators: Characterization and Extension Heinz H. Bauschke [*] , Xianfu Wang, and Liangjin Yao	57
5	Clustering, Classification, and Contour Approximation of Data Adi Ben-Israel [*] and Cem Iyigun	75
6	Multi-Slice CT: Optimizing the Use of Intravenous Contrast Material	.01
7	Statistical Iterative Reconstruction for X-Ray Computed Tomography	.13
8	On the Estimation of Motion-Induced Temporal Dose Variations in Intensity Modulated Radiotherapy Treatment Fields	141

^{*}Corresponding author.

Contents

9	A Class of Iterative Methods: Semi-convergence, Stopping Rules, Inconsistency, and Constraining <i>Tommy Elfving[*]</i> , <i>Touraj Nikazad, and Constantin Popa</i>	157
10	Radiation Therapy Planning with a Given Set of Binary Matrices <i>Çigdem Güler and Horst W. Hamacher</i> [*]	185
11	Mathematical Theory for X-Ray Phase-Contrast Imaging with 2D Grating Interferometry <i>Ming Jiang[*] and Ge Wang</i>	201
12	An Approach to Motion Compensation in Tomography Alexander Katsevich	221
13	Iterative Algorithms for the Multiple-Sets Split Feasibility Problem Genaro López, Victoria Martín-Márquez, and Hong-Kun Xu [*]	243
14	X-Ray Phase Imaging with Talbot Interferometry Atsushi Momose [*] , Wataru Yashiro, and Yoshihiro Takeda	281
15	Acoustic Imaging in 3D Frank Natterer	321
16	Optimization of Physical and Biological Dose Distributions in Hadron Therapy Uwe Oelfke [*] , Joanne Kang, Daniel Pflugfelder, and Jan Jakob Wilkens	329
17	Block-Iterative and String-Averaging Projection Algorithms in Proton Computed Tomography Image Reconstruction Scott N. Penfold [*] , Reinhard W. Schulte, Yair Censor, Vladimir Bashkirov, Scott McAllister, Keith E. Schubert, and Anatoly B. Rosenfeld	347
18	Advanced Contrast Modalities for X-Ray Radiology: Phase-Contrast and Dark-Field Imaging Using a Grating Interferometer Franz Pfeiffer [*] , Martin Bech, Torben Jensen, Oliver Bunk, Tilman Donath, Christian David, Timm Weitkamp, Geraldine Le Duc, Alberto Bravin, and Peter Cloetens	369

^{*}Corresponding author.

19	Comparison of Some Reconstruction Schemes for Optical Tomography Martin J. Schweiger and Simon R. Arridge [*]	
20	Seminorm-Induced Oblique Projections for Sparse Nonlinear Convex Feasibility Problems Alexander Segal and Yair Censor [*]	
21	3D Fluorescence Lifetime Imaging in Turbid Inhomogeneous Media by Using Time-Gated Data Acquisition Vadim Y. Soloviev [*] , Cosimo D'Andrea, Gianluca Valentini, Rinaldo Cubeddu, and Simon R. Arridge	
22	Towards a New Paradigm for Radiation Treatment Planning George Starkschall	
23	Towards the Patient-Adaptive Approach to Risk Evaluation, Treatment Planning, and Delivery of Thoracic Radiotherapy Alexei Trofimov [*] , Cornelia Gansemer, Adam D. Yock, Christian Vrancic, Thomas Bortfeld, and Noah C. Choi	457
24	Imaging Biomarkers Michael Vannier	
25	Interior Tomography: Practical Applications Ge Wang [*] , Hengyong Yu, Yangbo Ye	
26	Real-Time Imaging for Radiation Therapy Guidance Rodney D. Wiersma [*] , Nadeem Riaz, and Lei Xing	509
27	Interior Tomography: Mathematical Analysis Yangbo Ye [*] , Hengyong Yu, Ge Wang	543

^{*}Corresponding author.

Preface

This book brings together 27 state-of-the-art, refereed and subsequently revised, research and review papers, by leading experts and practitioners in mathematical methods in biomedical imaging, in intensity-modulated radiation therapy (IMRT) and in optimization and inverse problems. The emphasis is on trying to discover relations and connections between these fields that will enhance progress in each of them. As this volume shows, applicable mathematical work in these fields goes hand-in-hand with real-world applications and the mutual "technology transfers" between them leads to further progress.

The topics covered here include mathematical aspects and practical problems in current major and emerging technologies in diagnostic and therapeutic medicine and biology research. The contributed work signifies the interdisciplinary cooperation between mathematicians and scientists from medical physics, engineering, clinical medicine, and biology that leads to mathematically based better solutions of practical problems in biomedical imaging and IMRT.

The Huangguoshu National Park of China, Guizhou, China, under the leadership of Mr. Degang Yuan, President of the Huangguoshu Tourism Group Company, LTD, recognizing the importance of the field and the need for interaction between theoreticians and practitioners, and desiring to create a high-profile cultural activity at the Huangguoshu National Park, provided us with a special grant to organize the "Huangguoshu International Interdisciplinary Conference on Biomedical Mathematics—Promising Directions in Imaging, Therapy Planning, and Inverse Problems." The Conference took place during November 3–9, 2008, in the breathtaking Huangguoshu National Park of China.

The Conference was conducted under the scientific auspices of the Mathematical Center of the Ministry of Education of China at Peking University (PKU) in Beijing, China; the Center for Computational Mathematics and Scientific Computation (CCMSC) at the University of Haifa, Haifa, Israel; the School of Biomedical Engineering & Sciences at the Virginia Polytechnic Institute and State University, Virginia, USA; and the Guizhou University in Guiyang, Guizhou, China.

Experts from around the world were invited and participated. They came from Australia, Canada, Germany, Israel, Italy, Japan, Korea, P.R. China, Spain, Sweden, Switzerland, the United Kingdom, and the United States of America. Most of the papers in this volume originated from the lectures presented at the Conference, while others were written in the wake of discussions held during the Conference.

Preface

It is our pleasure to heartily thank Mr. Degang Yuan and the team of the Huangguoshu Tourism Group, Peking University, and Virginia Tech for their devoted and efficient work throughout all phases of the preparations for the conference. In particular we thank Dr. Lingyin Zhao, Zongmin (Tracy) Mao, Haifeng (Mountain) Tong, and Gang (Leo) Xie, from the the Huangguoshu Tourism Group; Prof. Tie Zhou, Dr. Caifang Wang, Dr. Xin Jiang, and Yuanzheng Si, Yu Zhou, Shengkun Shi, from Peking University (PKU); and Deepak Bharkhada, from Wake Forest University, for their cooperation and extraordinary support in organizing and conducting the Conference. Many thanks are due to the referees whose work enhanced the final versions of the papers which appear here. Last but not least, we thank the participants of the Conference and the authors who contributed their work to this volume. We gratefully acknowledge the help of Ms. Betsey Phelps, Managing Editor, Medical Physics Publishing, Madison, WI, USA, for her and her team's work on the production of this volume.

We hope that researchers in applied mathematics, medical physics, biomedical imaging, and intensity-modulated radiation therapy will find this book a useful tool in their current research and development efforts.

Yair Censor, Ming Jiang and Ge Wang Haifa, Beijing, and Blacksburg, VA, respectively *January 31, 2010*

Contributing Authors

Numbers in brackets refer to the chapter numbers authored or co-authored by the contributors.

Francesca Albertini Centre for Proton Radiation Therapy Paul Scherrer Institute 5232 Villigen PSI Switzerland	[1]	Heinz H. Bauschke [*] Department of Mathematics Irving K. Barber School UBC Okanagan Kelowna, BC V1V 1V7 Canada	[4]
Ashok R. Amin [*]	[2]	Carlada	
Carilion Clinic	L J	Martin Bech	[18]
101 Elm Avenue, 4 th Floor		Department of Physics (E17)	L]
Roanoke,VA 24013		Technical University of Munich	
and Virginia Tech Biomedical &		85748 Garching	
Engineering Sciences		Germany	
Blacksburg, VA 24061			
		Adi Ben-Israel [*]	[5]
Simon R. Arridge [*]	[19*, 21]	Rutgers Center for Operations Resea	arch
Department of Computer Science		Rutgers University	
University College London		640 Bartholomew Road	
Gower Street		Piscataway, NJ 08854-8003	
London WC1E 6BT			
United Kingdom		Thomas Bortfeld	[23]
		Department of Radiation Oncology	
Guillaume Bal [*]	[3]	Massachusetts General Hospital and	
Department of Applied Physics and		Harvard Medical School	
Applied Mathematics		30 Fruit Street	
Columbia University		Boston, MA 02114	
New York, NY 10027			
		Matthias Bosshardt	[1]
Vladimir Bashkirov	[17]	Centre for Proton Radiation Therapy	7
Department of Radiation Medicine		Paul Scherrer Institute	
Loma Linda University Medical Cen	ter	5232 Villigen PSI	
Loma Linda, CA 92354		Switzerland	

^{*}Corresponding author.

Alberto Bravin	[18]	Cosimo D'Andrea	[21]
European Synchrotron Radiation Fac	cility	IIT, CNR-INFM, and CNR-IFN	
B.P. 220		Department of Physics	
38043 Grenoble Cedex		Politecnico de Milano	
France		Piazza Leonardo da Vinci 32	
		20133 Milan	
James A. Brink, M.D.	[6]	Italy	
Yale University School of Medicine			
333 Cedar Street		Christian David	[18]
New Haven, CT 06510		Paul Scherrer Institut	
		5232 Villigen PSI	
Oliver Bunk	[18]	Switzerland	
Paul Scherrer Institut			
5232 Villigen PSI		Bruno De Man [*]	[7]
Switzerland		CT and X-ray Systems and Application	ons
		Laboratory	
Yair Censor [*]	$[17, 20^*]$	GE Global Research – KWC1307	
Department of Mathematics		1 Research Circle	
University of Haifa		Niskayuna, NY 12309	
Mt. Carmel, Haifa 31905			
Israel		Tilman Donath	[18]
		Paul Scherrer Institut	
Noah C. Choi	[23]	5232 Villigen PSI	
Department of Radiation Oncology		Switzerland	
Massachusetts General Hospital and			
Harvard Medical School		Eric D. Ehler	[8]
30 Fruit Street		Departments of Human Oncology	
Boston, MA 02114		and Medical Physics	
		University of Wisconsin	
Peter Cloetens	[18]	K4/334-3684 Clinical Science Cente	er
European Synchrotron Radiation Fac	cility	600 Highland Avenue	
B.P. 220		Madison, WI 53792-3684	
38043 Grenoble Cedex			
France		Tommy Elfving [*]	[9]
		Department of Mathematics	
Rinaldo Cubeddu	[21]	Linköping University	
IIT, CNR-INFM, and CNR-IFN		SE-581 83 Linköping	
Department of Physics		Sweden	
Politecnico de Milano			
Piazza Leonardo da Vinci 32		Jeffrey A. Fessler	[7]
20133 Milan		EECS Department	
Italy		University of Michigan	
		1301 Beal Avenue	
		Ann Arbor, MI 48109-2122	

*Corresponding author.

[3]

[16]

[12]

[18]

[13]

[13]

Alexandre Jollivet[3]Department of Applied Physics and Applied MathematicsColumbia University New York, NY 10027
Joanne Kang [16] DKFZ Heidelberg Department of Medical Physics in Radiation Therapy Im Neuenheimer Feld 280 69120 Heidelberg
Alexander Katsevich [12] Department of Mathematics University of Central Florida Orlando, FL 32816-1364
Geraldine Le Duc [18] European Synchrotron Radiation Facility B.P. 220 38043 Grenoble Cedex France
Antony J. Lomax [*] [1] Centre for Proton Radiation Therapy Paul Scherrer Institute 5232 Villigen PSI Switzerland
Genaro López [13] Department of Mathematical Analysis University of Seville Apdo. 1160, 41080-Seville Spain
Victoria Martín-Márquez [13] Department of Mathematical Analysis University of Seville Apdo. 1160, 41080-Seville Spain

^{*}Corresponding author.

Scott McAllister Department of Computer Science and Engineering California State University San Bern San Bernardino, CA 92407	[17] nardino	Franz Pfeiffer [*] Department of Physics (E17) Technical University of Munich 85748 Garching Germany	[18]
Atsushi Momose [*] Department of Advanced Materials Graduate School of Frontier Science The University of Tokyo 5-1-5 Kashiwanoha, Kashiwa Chiba 277-8561 Japan	[14] Science es	Daniel Pflugfelder DKFZ Heidelberg Department of Medical Physics in Radiation Therapy Im Neuenheimer Feld 280 69120 Heidelberg Germany	[16]
Frank Natterer Department of Mathematics and Computer Science University of Münster Münster Germany	[15]	Constantin Popa Faculty of Mathematics and Computer Science Ovidius University Constanta Boulevard Mamaia 124 900527 Constanta	[9]
Touraj Nikazad Demonstructure of Mathematics	[9]	Romania	
Iran University of Science and Techn Narmak, Tehran, 16846-13114 Iran	nology	Nadeem Riaz Department of Radiation Oncology Stanford University School of Medic Stanford, CA 94305	[24] ine
Uwe Oelfke [*] DKFZ Heidelberg Department of Medical Physics in Radiation Therapy Im Neuenheimer Feld 280 69120 Heidelberg Germany	[16]	Anatoly B. Rosenfeld Centre for Medical Radiation Physic University of Wollongong Wollongong, New South Wales, 252 Australia	[17] ss
Scott N. Penfold [*] Centre for Medical Radiation Physi University of Wollongong Wollongong, New South Wales 252 Australia	[17] cs 2	Keith E. Schubert Department of Computer Science and Engineering California State University San Bern San Bernardino, CA 92407	[17] ardino

*Corresponding author.

Reinhard W. Schulte Department of Radiation Medicine Loma Linda University Medical Cer	[17]	Wolfgang A. Tomé [*] University of Wisconsin School of Medicine and Public Heal	[8]
Loma Linda, CA 92354	ner	Departments of Human Oncology a Medical Physics	nd
Martin J. Schweiger	[19]	K4/314 Clinical Science Center	
Department of Computer Science		600 Highland Avenue	
University College London Gower Street		Madison, WI 53792	
London WC1E 6BT		Alexei Trofimov [*]	[23]
United Kingdom		Department of Radiation Oncology	
		Massachusetts General Hospital and	
Alexander Segal	[20]	Harvard Medical School	
Department of Mathematics		30 Fruit Street	
University of Haifa		Boston, MA 02114	
Mt. Carmel, Haifa 31905			
Israel		Gianluca Valentini	[21]
*		IIT, CNR-INFM, and CNR-IFN	
Vadim Y. Soloviev	[21]	Department of Physics	
Department of Computer Science		Politecnico de Milano	
University College London		Piazza Leonardo da Vinci 32	
Gower Street		20133 Milan	
London WC1E 6BT		Italy	
United Kingdom			[0,4]
	[22]	Michael W. Vannier, M.D.	[24]
George Starkschall	[22]	Department of Radiology	
Department of Radiation Physics		University of Chicago	
The University of Texas M.D. Ander	son	5841 S. Maryland Avenue	
Cancer Center		Chicago, IL 60637	
1515 Holcombe Boulevard			[02]
Houston, IX //030		Christian Vrancic	[23]
Verbilder Televile	[1 4]	Department of Clinical Medicine (N	lannneim)
Yoshiniro Takeda	[14]	Ruprecht-Karls University	
Department of Advanced Materials S	science	Germann	
The Luissensity of Talana	S	Germany	
E 1 E Kashimuraha Kashimu		CoWhee	[2 11 25 27]
Chiba 277, 8561		Ge wang Vinginia Tash Diamadiaal & Engines	[2, 11, 25, 27]
Japan		Sciences	ing
Јаран		1880 Pratt Drive Suite 2000	
		Blacksburg VA 24061	
		Diacksburg, VII 27001	

^{*}Corresponding author.

Contributing Authors

Xianfu Wang Department of Mathematics Irving K. Barber School UBC Okanagan Kelowna, BC V1V 1V7 Canada	[4]	Liangjin Yao Department of Mathematics Irving K. Barber School UBC Okanagan Kelowna, BC V1V 1V7 Canada	[4]
Rodney D. Wiersma [*] Department of Radiation and Cellul Oncology The University of Chicago 5758 S. Maryland Avenue, MC9006 Chicago, IL 60637	[24] lar	Wataru Yashiro Department of Advanced Materials S Graduate School of Frontier Science The University of Tokyo 5-1-5 Kashiwanoha, Kashiwa Chiba 277-8561 Japan	[14] Science s
Timm Weitkamp European Synchrotron Radiation Fa B.P. 220 38043 Grenoble Cedex France	[18] cility	Yangbo Ye [*] Department of Mathematics University of Iowa Iowa City, IA 52242	[25, 27*]
Jan Jakob Wilkens Department of Radiation Oncology Technical University of Munich Klinikum rechts der Isar Ismaninger Strasse 22 81675 Munich	[16]	Adam D. Yock Department of Radiation Oncology Massachusetts General Hospital <i>and</i> Harvard Medical School 30 Fruit Street Boston, MA 02114	[23]
Lei Xing Department of Radiation Oncology Stanford University School of Medic Stanford, CA 94305	[24] cine	Hengyong Yu [*] Biomedical Imaging Division VT-WFU School of Biomedical Engineering and Science Virginia Tech Blacksburg, VA 24061	[25*, 27]
Hong-Kun Xu [*] Department of Applied Mathematics National Sun Yat-sen University Kaohsiung 80424 Taiwan	[13]		

^{*}Corresponding author.