

Milan Šonka  
Ioannis A. Kakadiaris  
Jan Kybic (Eds.)

LNCS 3117

# Computer Vision and Mathematical Methods in Medical and Biomedical Image Analysis

ECCV 2004 Workshops CVAMIA and MMBIA  
Prague, Czech Republic, May 2004  
Revised Selected Papers

R445-53  
C738  
2004

Milan Šonka Ioannis A. Kakadiaris  
Jan Kybic (Eds.)

# Computer Vision and Mathematical Methods in Medical and Biomedical Image Analysis

ECCV 2004 Workshops CVAMIA and MMBIA  
Prague, Czech Republic, May 15, 2004  
Revised Selected Papers



E200404691



Springer

## Volume Editors

Milan Šonka

University of Iowa, Department of Electrical and Computer Engineering

Iowa City IA 52242, USA

E-mail: milan-sonka@uiowa.edu

Ioannis A. Kakadiaris

University of Houston, Department of Computer Science and ECE

Visual Computing Lab, MS CSC 3010

Houston, TX 77204-3010, USA

E-mail: ioannisk@uh.edu

Jan Kybic

Czech Technical University, Faculty of Electrical Engineering

Department of Cybernetics

Technick 2, Praha 6, 166 27, Czech Republic

E-mail: kybic@fel.cvut.cz

Library of Congress Control Number: 2004111941

CR Subject Classification (1998): I.4, I.2.10, I.3.5, I.5, J.3

ISSN 0302-9743

ISBN 3-540-22675-3 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, re-use of illustrations, recitation, broadcasting, reproduction on microfilms or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media

springeronline.com

© Springer-Verlag Berlin Heidelberg 2004

Printed in Germany

Typesetting: Camera-ready by author, data conversion by Boller Mediendesign

Printed on acid-free paper SPIN: 11301004 06/3142 5 4 3 2 1 0

*Commenced Publication in 1973*

Founding and Former Series Editors:

Gerhard Goos, Juris Hartmanis, and Jan van Leeuwen

## Editorial Board

David Hutchison

*Lancaster University, UK*

Takeo Kanade

*Carnegie Mellon University, Pittsburgh, PA, USA*

Josef Kittler

*University of Surrey, Guildford, UK*

Jon M. Kleinberg

*Cornell University, Ithaca, NY, USA*

Friedemann Mattern

*ETH Zurich, Switzerland*

John C. Mitchell

*Stanford University, CA, USA*

Moni Naor

*Weizmann Institute of Science, Rehovot, Israel*

Oscar Nierstrasz

*University of Bern, Switzerland*

C. Pandu Rangan

*Indian Institute of Technology, Madras, India*

Bernhard Steffen

*University of Dortmund, Germany*

Madhu Sudan

*Massachusetts Institute of Technology, MA, USA*

Demetri Terzopoulos

*New York University, NY, USA*

Doug Tygar

*University of California, Berkeley, CA, USA*

Moshe Y. Vardi

*Rice University, Houston, TX, USA*

Gerhard Weikum

*Max-Planck Institute of Computer Science, Saarbruecken, Germany*

# Preface

Medical imaging and medical image analysis are rapidly developing. While medical imaging has already become a standard of modern medical care, medical image analysis is still mostly performed visually and qualitatively. The ever-increasing volume of acquired data makes it impossible to utilize them in full. Equally important, the visual approaches to medical image analysis are known to suffer from a lack of reproducibility. A significant research effort is devoted to developing algorithms for processing the wealth of data available and extracting the relevant information in a computerized and quantitative fashion.

Medical imaging and image analysis are interdisciplinary areas combining electrical, computer, and biomedical engineering; computer science; mathematics; physics; statistics; biology; medicine; and other fields. Medical imaging and computer vision, interestingly enough, have developed and continue developing somewhat independently. Nevertheless, bringing them together promises to benefit both of these fields. We were enthusiastic when the organizers of the 2004 European Conference on Computer Vision (ECCV) allowed us to organize a satellite workshop devoted to medical image analysis.

In a short time after the announcement, we received 60 full-length paper submissions, out of which 13 were accepted for oral and 25 for poster presentation after a rigorous peer-review process. The workshop included a keynote lecture and two invited talks. The keynote, entitled *Progress in Quantitative Cardiovascular Imaging*, was presented by Prof. Johan H.C. Reiber from the Leiden University Medical Center, The Netherlands. The first invited talk was given by Prof. Michael Unser from the Swiss Federal Institute of Technology, Lausanne (EPFL), Lausanne, Switzerland – titled *Wavelets, Fractals and Medical Image Analysis*. The second invited talk dealt with *Inverse Consistent Medical Image Registration* and was presented by Prof. Gary E. Christensen from the University of Iowa, Iowa City IA, USA.

The workshop logistics were handled by the organizers of the ECCV 2004, associated with the Centre for Machine Perception of the Czech Technical University in Prague, Czech Republic. We are grateful to all Centre members and students for the smooth organizational support during the entire workshop, as well as for providing a friendly working atmosphere. Finally, we extend our sincere thanks to the program committee members, to the reviewers, and to everyone else who made this workshop possible.

May 2004

Milan Šonka  
Ioannis A. Kakadiaris  
Jan Kybic

# Organization

The 2004 *Computer Vision Approaches to Medical Image Analysis* (CVAMIA) and *Mathematical Methods in Biomedical Image Analysis* (MMBIA) Workshop was held in conjunction with the 8th *European Conference on Computer Vision* (ECCV) in Prague, on May 15, 2004. The ECCV conference was organized by the Centre for Machine Perception, Department of Cybernetics, Faculty of Electrical Engineering, Czech Technical University, Prague, Czech Republic.

## Executive Committee

General Chair

Milan Šonka (University of Iowa)

Program Chair

Ioannis A. Kakadiaris (University of Houston)

Organizing Chair

Jan Kybic (Czech Technical University)

## Program Committee

Amir Amini	Washington University
Nicholas Ayache	INRIA, France
Faisal Beg	Simon Fraser University
Mike Brady	University of Oxford
Gary Christensen	University of Iowa
Christos Davatzikos	University of Pennsylvania
Herve Delingette	INRIA Sophia Antipolis
James Duncan	University of Southern California
Guido Gerig	University of North Carolina at Chapel Hill
Dmitry Goldof	University of South Florida
Tomas Gustavsson	Chalmers University of Technology
Thomas Huang	University of Illinois
Ghassan Hamarneh	Simon Fraser University
Ioannis A. Kakadiaris	University of Houston
Ron Kikinis	Harvard Medical School
Ben Kimia	Brown University
Andrew Laine	Columbia University
Tim McInerney	University of Toronto
Dimitris Metaxas	University of Pennsylvania
Erik Meijering	Biomedical Imaging Group, Rotterdam
Nikos Paragios	École Nationale de Ponts et Chaussées
Steve Pizer	University of North Carolina at Chapel Hill
Joseph Reinhardt	University of Iowa
Gabor Szekely	Computer Vision Laboratory, ETH Zurich
Demetri Terzopoulos	University of Toronto
Michael Unser	Swiss Federal Institute of Technology
Michael Vannier	University of Iowa
Max Viergever	Utrecht University
Andreas Wahle	University of Iowa
James Williams	Siemens
Terry Yoo	National Institutes of Health

# Lecture Notes in Computer Science

For information about Vols. 1–3115

please contact your bookseller or Springer

Vol. 3241: D. Kranzlmüller, P. Kacsuk, J.J. Dongarra (Eds.), *Recent Advances in Parallel Virtual Machine and Message Passing Interface*. XIII, 452 pages. 2004.

Vol. 3240: I. Jonassen, J. Kim (Eds.), *Algorithms in Bioinformatics*. IX, 476 pages. 2004. (Subseries LNBI).

Vol. 3239: G. Nicosia, V. Cutello, P.J. Bentley, J. Timmis (Eds.), *Artificial Immune Systems*. XII, 444 pages. 2004.

Vol. 3232: R. Heery, L. Lyon (Eds.), *Research and Advanced Technology for Digital Libraries*. XV, 528 pages. 2004.

Vol. 3224: E. Jonsson, A. Valdes, M. Almgren (Eds.), *Recent Advances in Intrusion Detection*. XII, 315 pages. 2004.

Vol. 3223: K. Slind, A. Bunker, G. Gopalakrishnan (Eds.), *Theorem Proving in Higher Order Logic*. VIII, 337 pages. 2004.

Vol. 3221: S. Albers, T. Radzik (Eds.), *Algorithms – ESA 2004*. XVIII, 836 pages. 2004.

Vol. 3220: J.C. Lester, R.M. Vicari, F. Paragauçu (Eds.), *Intelligent Tutoring Systems*. XXI, 920 pages. 2004.

Vol. 3210: J. Marcinkowski, A. Tarlecki (Eds.), *Computer Science Logic*. XI, 520 pages. 2004.

Vol. 3208: H.J. Ohlbach, S. Schaffert (Eds.), *Principles and Practice of Semantic Web Reasoning*. VII, 165 pages. 2004.

Vol. 3207: L.T. Jang, M. Guo, G.R. Gao, N.K. Jha, *Embedded and Ubiquitous Computing*. XX, 1116 pages. 2004.

Vol. 3206: P. Sojka, I. Kopecek, K. Pala (Eds.), *Text, Speech and Dialogue*. XIII, 667 pages. 2004. (Subseries LNAI).

Vol. 3205: N. Davies, E. Mynatt, I. Siio (Eds.), *UbiComp 2004: Ubiquitous Computing*. XVI, 452 pages. 2004.

Vol. 3203: J. Becker, M. Platzner, S. Vernalde (Eds.), *Field Programmable Logic and Application*. XXX, 1198 pages. 2004.

Vol. 3202: J.-F. Boulicaut, F. Esposito, F. Giannotti, D. Pedreschi (Eds.), *Knowledge Discovery in Databases: PKDD 2004*. XIX, 560 pages. 2004. (Subseries LNAI).

Vol. 3201: J.-F. Boulicaut, F. Esposito, F. Giannotti, D. Pedreschi (Eds.), *Machine Learning: ECML 2004*. XVIII, 580 pages. 2004. (Subseries LNAI).

Vol. 3199: H. Schepers (Ed.), *Software and Compilers for Embedded Systems*. X, 259 pages. 2004.

Vol. 3198: G.-J. de Vreede, L.A. Guerrero, G. Marín Raventós (Eds.), *Groupware: Design, Implementation and Use*. XI, 378 pages. 2004.

Vol. 3194: R. Camacho, R. King, A. Srinivasan (Eds.), *Inductive Logic Programming*. XI, 361 pages. 2004. (Subseries LNAI).

Vol. 3193: P. Samarati, P. Ryan, D. Gollmann, R. Molva (Eds.), *Computer Security – ESORICS 2004*. X, 457 pages. 2004.

Vol. 3192: C. Bussler, D. Fensel (Eds.), *Artificial Intelligence: Methodology, Systems, and Applications*. XIII, 522 pages. 2004. (Subseries LNAI).

Vol. 3190: Y. Luo (Ed.), *Cooperative Design, Visualization, and Engineering*. IX, 248 pages. 2004.

Vol. 3189: P.-C. Yew, J. Xue (Eds.), *Advances in Computer Systems Architecture*. XVII, 598 pages. 2004.

Vol. 3186: Z. Bellahsene, T. Milo, M. Rys, D. Suciu, R. Unland (Eds.), *Database and XML Technologies*. X, 235 pages. 2004.

Vol. 3185: M. Bernardo, F. Corradini (Eds.), *Formal Methods for the Design of Real-Time Systems*. VII, 295 pages. 2004.

Vol. 3184: S. Katsikas, J. Lopez, G. Pernul (Eds.), *Trust and Privacy in Digital Business*. XI, 299 pages. 2004.

Vol. 3183: R. Traunmüller (Ed.), *Electronic Government*. XIX, 583 pages. 2004.

Vol. 3182: K. Bauknecht, M. Bichler, B. Pröll (Eds.), *E-Commerce and Web Technologies*. XI, 370 pages. 2004.

Vol. 3181: Y. Kambayashi, M. Mohania, W. Wöb (Eds.), *Data Warehousing and Knowledge Discovery*. XIV, 412 pages. 2004.

Vol. 3180: F. Galindo, M. Takizawa, R. Traunmüller (Eds.), *Database and Expert Systems Applications*. XXI, 972 pages. 2004.

Vol. 3179: F.J. Perales, B.A. Draper (Eds.), *Articulated Motion and Deformable Objects*. XI, 270 pages. 2004.

Vol. 3178: W. Jonker, M. Petkovic (Eds.), *Secure Data Management*. VIII, 219 pages. 2004.

Vol. 3177: Z.R. Yang, H. Yin, R. Everson (Eds.), *Intelligent Data Engineering and Automated Learning – IDEAL 2004*. XVIII, 852 pages. 2004.

Vol. 3176: O. Bousquet, U. von Luxburg, G. Rätsch (Eds.), *Advanced Lectures on Machine Learning*. VIII, 241 pages. 2004. (Subseries LNAI).

Vol. 3175: C.E. Rasmussen, H.H. Bülthoff, B. Schölkopf, M.A. Giese (Eds.), *Pattern Recognition*. XVIII, 581 pages. 2004.

Vol. 3174: F. Yin, J. Wang, C. Guo (Eds.), *Advances in Neural Networks – ISNN 2004*. XXXV, 1021 pages. 2004.

Vol. 3173: F. Yin, J. Wang, C. Guo (Eds.), *Advances in Neural Networks – ISNN 2004*. XXXV, 1041 pages. 2004.

Vol. 3172: M. Dorigo, M. Birattari, C. Blum, L. M. Gambardella, F. Mondada, T. Stützle (Eds.), *Ant Colony, Optimization and Swarm Intelligence*. XII, 434 pages. 2004.



- Vol. 3170: P. Gardner, N. Yoshida (Eds.), *CONCUR 2004 - Concurrency Theory*. XIII, 529 pages. 2004.
- Vol. 3166: M. Rauterberg (Ed.), *Entertainment Computing - ICEC 2004*. XXIII, 617 pages. 2004.
- Vol. 3163: S. Marinai, A. Dengel (Eds.), *Document Analysis Systems VI*. XII, 564 pages. 2004.
- Vol. 3162: R. Downey, M. Fellows, F. Dehne (Eds.), *Parameterized and Exact Computation*. X, 293 pages. 2004.
- Vol. 3160: S. Brewster, M. Dunlop (Eds.), *Mobile Human-Computer Interaction - MobileHCI 2004*. XVIII, 541 pages. 2004.
- Vol. 3159: U. Visser, *Intelligent Information Integration for the Semantic Web*. XIV, 150 pages. 2004. (Subseries LNAI).
- Vol. 3158: I. Nikolaidis, M. Barbeau, E. Kranakis (Eds.), *Ad-Hoc, Mobile, and Wireless Networks*. IX, 344 pages. 2004.
- Vol. 3157: C. Zhang, H. W. Guesgen, W.K. Yeap (Eds.), *PRICA1 2004: Trends in Artificial Intelligence*. XX, 1023 pages. 2004. (Subseries LNAI).
- Vol. 3156: M. Joye, J.-J. Quisquater (Eds.), *Cryptographic Hardware and Embedded Systems - CHES 2004*. XIII, 455 pages. 2004.
- Vol. 3155: P. Funk, P.A. González Calero (Eds.), *Advances in Case-Based Reasoning*. XIII, 822 pages. 2004. (Subseries LNAI).
- Vol. 3154: R.L. Nord (Ed.), *Software Product Lines*. XIV, 334 pages. 2004.
- Vol. 3153: J. Fiala, V. Koubek, J. Kratochvíl (Eds.), *Mathematical Foundations of Computer Science 2004*. XIV, 902 pages. 2004.
- Vol. 3152: M. Franklin (Ed.), *Advances in Cryptology - CRYPTO 2004*. XI, 579 pages. 2004.
- Vol. 3150: G.-Z. Yang, T. Jiang (Eds.), *Medical Imaging and Augmented Reality*. XII, 378 pages. 2004.
- Vol. 3149: M. Danelutto, M. Vanneschi, D. Laforenza (Eds.), *Euro-Par 2004 Parallel Processing*. XXXIV, 1081 pages. 2004.
- Vol. 3148: R. Giacobazzi (Ed.), *Static Analysis*. XI, 393 pages. 2004.
- Vol. 3146: P. Érdi, A. Esposito, M. Marinaro, S. Scarpetta (Eds.), *Computational Neuroscience: Cortical Dynamics*. XI, 161 pages. 2004.
- Vol. 3144: M. Papatriantafyllou, P. Hunel (Eds.), *Principles of Distributed Systems*. XI, 246 pages. 2004.
- Vol. 3143: W. Liu, Y. Shi, Q. Li (Eds.), *Advances in Web-Based Learning - ICWL 2004*. XIV, 459 pages. 2004.
- Vol. 3142: J. Diaz, J. Karhumäki, A. Lepistö, D. Sannella (Eds.), *Automata, Languages and Programming*. XIX, 1253 pages. 2004.
- Vol. 3140: N. Koch, P. Fraternali, M. Wirsing (Eds.), *Web Engineering*. XXI, 623 pages. 2004.
- Vol. 3139: F. Iida, R. Pfeifer, L. Steels, Y. Kuniyoshi (Eds.), *Embodied Artificial Intelligence*. IX, 331 pages. 2004. (Subseries LNAI).
- Vol. 3138: A. Fred, T. Caelli, R.P.W. Duin, A. Campilho, D.d. Ridder (Eds.), *Structural, Syntactic, and Statistical Pattern Recognition*. XXII, 1168 pages. 2004.
- Vol. 3137: P. De Bra, W. Nejdl (Eds.), *Adaptive Hypermedia and Adaptive Web-Based Systems*. XIV, 442 pages. 2004.
- Vol. 3136: F. Meziane, E. Métais (Eds.), *Natural Language Processing and Information Systems*. XII, 436 pages. 2004.
- Vol. 3134: C. Zannier, H. Erdogmus, L. Lindstrom (Eds.), *Extreme Programming and Agile Methods - XP/Agile Universe 2004*. XIV, 233 pages. 2004.
- Vol. 3133: A.D. Pimentel, S. Vassiliadis (Eds.), *Computer Systems: Architectures, Modeling, and Simulation*. XIII, 562 pages. 2004.
- Vol. 3132: B. Demoen, V. Lifschitz (Eds.), *Logic Programming*. XII, 480 pages. 2004.
- Vol. 3131: V. Torra, Y. Narukawa (Eds.), *Modeling Decisions for Artificial Intelligence*. XI, 327 pages. 2004. (Subseries LNAI).
- Vol. 3130: A. Syropoulos, K. Berry, Y. Haralambous, B. Hughes, S. Peter, J. Plaice (Eds.), *TeX, XML, and Digital Typography*. VIII, 265 pages. 2004.
- Vol. 3129: Q. Li, G. Wang, L. Feng (Eds.), *Advances in Web-Age Information Management*. XVII, 753 pages. 2004.
- Vol. 3128: D. Asonov (Ed.), *Querying Databases Privately*. IX, 115 pages. 2004.
- Vol. 3127: K.E. Wolff, H.D. Pfeiffer, H.S. Delugach (Eds.), *Conceptual Structures at Work*. XI, 403 pages. 2004. (Subseries LNAI).
- Vol. 3126: P. Dini, P. Lorenz, J.N.d. Souza (Eds.), *Service Assurance with Partial and Intermittent Resources*. XI, 312 pages. 2004.
- Vol. 3125: D. Kozen (Ed.), *Mathematics of Program Construction*. X, 401 pages. 2004.
- Vol. 3124: J.N. de Souza, P. Dini, P. Lorenz (Eds.), *Telecommunications and Networking - ICT 2004*. XXVI, 1390 pages. 2004.
- Vol. 3123: A. Belz, R. Evans, P. Piwek (Eds.), *Natural Language Generation*. X, 219 pages. 2004. (Subseries LNAI).
- Vol. 3122: K. Jansen, S. Khanna, J.D.P. Rolim, D. Ron (Eds.), *Approximation, Randomization, and Combinatorial Optimization*. IX, 428 pages. 2004.
- Vol. 3121: S. Nikolettseas, J.D.P. Rolim (Eds.), *Algorithmic Aspects of Wireless Sensor Networks*. X, 201 pages. 2004.
- Vol. 3120: J. Shawe-Taylor, Y. Singer (Eds.), *Learning Theory*. X, 648 pages. 2004. (Subseries LNAI).
- Vol. 3119: A. Asperti, G. Bancerek, A. Trybulec (Eds.), *Mathematical Knowledge Management*. X, 393 pages. 2004.
- Vol. 3118: K. Miesenberger, J. Klaus, W. Zagler, D. Burger (Eds.), *Computer Helping People with Special Needs*. XXIII, 1191 pages. 2004.
- Vol. 3117: M. Šonka, I.A. Kakadiaris, J. Kybic (Eds.), *Computer Vision and Mathematical Methods in Medical and Biomedical Image Analysis*. XII, 438 pages. 2004.
- Vol. 3116: C. Rattray, S. Maharaj, C. Shankland (Eds.), *Algebraic Methodology and Software Technology*. XI, 569 pages. 2004.

# Table of Contents

## Acquisition Techniques

Ultrasound Stimulated Vibro-acoustography .....	1
<i>J.F. Greenleaf, M. Fatemi, M. Belohlavek</i>	
CT from an Unmodified Standard Fluoroscopy Machine Using a Non-reproducible Path.....	11
<i>C. Baker, C. Debrunner, M. Mahfouz, W. Hoff, J. Bowen</i>	
Three-Dimensional Object Reconstruction from Compton Scattered Gamma-Ray Data .....	24
<i>M.K. Nguyen, T.T. Truong, J.L. Delarbre, N. Kitanine</i>	

## Reconstruction

Cone-Beam Image Reconstruction by Moving Frames .....	35
<i>X. Yang, B.K.P. Horn</i>	
AQUATICS Reconstruction Software: The Design of a Diagnostic Tool Based on Computer Vision Algorithms .....	48
<i>A. Giachetti, G. Zanetti</i>	
Towards Automatic Selection of the Regularization Parameters in Emission Tomography by Fourier Synthesis.....	64
<i>P. Maréchal, D. Mariano-Goulart, L. Giraud, S. Gratton</i>	

## Mathematical Methods

Extraction of Myocardial Contractility Patterns from Short-Axes MR Images Using Independent Component Analysis.....	75
<i>A. Suinesiaputra, A.F. Frangi, M. Üzümcü, J.H.C. Reiber, B.P.F. Lelieveldt</i>	
Principal Geodesic Analysis on Symmetric Spaces: Statistics of Diffusion Tensors .....	87
<i>P.T. Fletcher, S. Joshi</i>	
Symmetric Geodesic Shape Averaging and Shape Interpolation .....	99
<i>B. Avants, J. Gee</i>	
Smoothing Impulsive Noise Using Nonlinear Diffusion Filtering .....	111
<i>O. Demirkaya</i>	

Level Set and Region Based Surface Propagation for Diffusion Tensor MRI Segmentation .....	123
<i>M. Rousson, C. Lenglet, R. Deriche</i>	
The Beltrami Flow over Triangulated Manifolds .....	135
<i>L. Lopez-Perez, R. Deriche, N. Sochen</i>	
Hierarchical Analysis of Low-Contrast Temporal Images with Linear Scale Space .....	145
<i>T. Sakai, A. Imiya</i>	
<b>Medical Image Segmentation</b>	
Segmentation of Medical Images with a Shape and Motion Model: A Bayesian Perspective .....	157
<i>J. S��n��gas, T. Netsch, C.A. Cocosco, G. Lund, A. Stork</i>	
A Multi-scale Geometric Flow for Segmenting Vasculature in MRI .....	169
<i>M. Descoteaux, L. Collins, K. Siddiqi</i>	
A 2D Fourier Approach to Deformable Model Segmentation of 3D Medical Images .....	181
<i>E. Berg, M. Mahfouz, C. Debrunner, W. Hoff</i>	
Automatic Rib Segmentation in CT Data .....	193
<i>J. Staal, B. van Ginneken, M.A. Viergever</i>	
Efficient Initialization for Constrained Active Surfaces, Applications in 3D Medical Images .....	205
<i>R. Ardon, L.D. Cohen</i>	
An Information Fusion Method for the Automatic Delineation of the Bone-Soft Tissues Interface in Ultrasound Images .....	218
<i>V. Daanen, J. Tonetti, J. Troccaz</i>	
Multi-label Image Segmentation for Medical Applications Based on Graph-Theoretic Electrical Potentials .....	230
<i>L. Grady, G. Funka-Lea</i>	
Three-Dimensional Mass Reconstruction in Mammography .....	246
<i>L. Shao, M. Brady</i>	
Segmentation of Abdominal Aortic Aneurysms with a Non-parametric Appearance Model .....	257
<i>S.D. Olabarriaga, M. Breeuwer, W.J. Niessen</i>	
Probabilistic Spatial-Temporal Segmentation of Multiple Sclerosis Lesions .....	269
<i>A. Shahar, H. Greenspan</i>	

Segmenting Cell Images: A Deterministic Relaxation Approach .....	281
<i>C.S. Won, J.Y. Nam, Y. Choe</i>	

## Registration

TIGER – A New Model for Spatio-temporal Realignment of FMRI Data .....	292
<i>P.R. Bannister, J.M. Brady, M. Jenkinson</i>	

Robust Registration of 3-D Ultrasound Images Based on Gabor Filter and Mean-Shift Method .....	304
<i>F. Cen, Y. Jiang, Z. Zhang, H.T. Tsui, T.K. Lau, H. Xie</i>	

Deformable Image Registration by Adaptive Gaussian Forces .....	317
<i>V. Pekar, E. Gladilin</i>	

## Applications

Statistical Imaging for Modeling and Identification of Bacterial Types ...	329
<i>S. Trattner, H. Greenspan, G. Tepper, S. Abboud</i>	

Assessment of Intrathoracic Airway Trees: Methods and In Vivo Validation .....	341
<i>K. Palágyi, J. Tschirren, E.A. Hoffman, M. Sonka</i>	

Computer-Aided Measurement of Solid Breast Tumor Features on Ultrasound Images .....	353
<i>M. Alemán-Flores, P. Alemán-Flores, L. Álvarez-León, J.M. Santana-Montesdeoca, R. Fuentes-Pavón, A. Trujillo-Pino</i>	

Can a Continuity Heuristic Be Used to Resolve the Inclination Ambiguity of Polarized Light Imaging? .....	365
<i>L. Larsen, L.D. Griffin</i>	

Applications of Image Registration in Human Genome Research .....	376
<i>P. Matula, M. Kozubek, P. Matula</i>	

Fast Marching 3D Reconstruction of Interphase Chromosomes .....	385
<i>P. Matula, J. Hubený, M. Kozubek</i>	

Robust Extraction of the Optic Nerve Head in Optical Coherence Tomography .....	395
<i>A. Herzog, K.L. Boyer, C. Roberts</i>	

Scale-Space Diagnostic Criterion for Microscopic Image Analysis .....	408
<i>I. Gurevich, D. Murashov</i>	

Image Registration Neural System for the Analysis of Fundus Topology ..	417
<i>V.K. Salakhutdinov, Y.G. Smetanin, D.M. Murashov, V.A. Gandurin</i>	

Robust Identification of Object Elasticity ..... 423  
*H. Liu, P. Shi*

**Author Index** ..... 437

# Ultrasound Stimulated Vibro-acoustography

James F. Greenleaf<sup>1</sup>, Mostafa Fatemi<sup>1</sup>, and Marek Belohlavek<sup>2</sup>

<sup>1</sup>Department of Physiology and Biomedical Engineering, Mayo Clinic College of Medicine  
(jfg@mayo.edu and Fatemi@mayo.edu)

<sup>2</sup>Department of Internal Medicine, Division of Cardiovascular Diseases  
Mayo Clinic, Rochester, MN, USA, 55905  
(belohlavek.marek@mayo.edu)

**Abstract.** Vibro-acoustography is a method of imaging and measurement that uses ultrasound to produce radiation force to vibrate objects. The radiation force is concentrated laterally by focusing the ultrasound beam. The radiation force is limited in depth by intersecting two beams at different frequencies so that there is interference between the beams at the difference frequency only at their intersection. This results in a radiation stress of limited spatial extent on or within the object of interest. The resulting harmonic displacement of the object is detected by acoustic emission, ultrasound Doppler, or laser interferometry. The displacement is a complicated function of the object material parameters. However, significant images and measurements can be made with this arrangement. Vibro-acoustography can produce high resolution speckle free images of biologically relevant objects such as breast micro-calcification and vessel calcifications, heart valves, and normal arteries. Vibro-acoustography can also make spot measurements such as microbubble contrast agent concentration in vessels. Several examples of these results will be described.

## 1 Introduction

It is well known that changes in the elasticity of soft tissues are often related to pathology. Traditionally, physicians use palpation as a simple method for estimating the mechanical properties of tissue. Physicians use a static force applied with their hands and obtain a crude estimation of tissue elasticity the sense of touch. Thus, the force is applied on the body surface and the result is a collective response of all the tissues below. Clinicians can sense abnormalities if the response to palpation is sufficiently different from that of normal tissue. However, if the abnormality lies deep in the body, or if is too small to be resolved by touch, then palpation fails. The dynamic response of soft tissue to a force is also valuable in medical diagnosis. For instance, rebound of tissue upon sudden release of pressure exerted by the physician's finger on the skin provides useful diagnostic information about the tissue.

Quantitative measurement of the mechanical properties of tissues and their display in raster format is the aim of a class of techniques generally called elasticity imaging, or elastography. The general approach is to measure tissue motion caused by an external (or, in some methods, internal) force and use the degree of displacement to reconstruct the elastic parameters of the tissue. The excitation stress can be either

static or dynamic (vibration). Dynamic excitation is of particular interest because it provides more comprehensive information about tissue properties over a spectrum of frequencies. In many elasticity imaging methods, ultrasound is used to detect the motion or displacement resulting from the applied stress. Magnetic resonance elastography is a recently developed method [1] that employs a mechanical actuator to vibrate the body surface and then measures the resulting strain waves with a phase sensitive magnetic resonance imaging (MRI) machine.

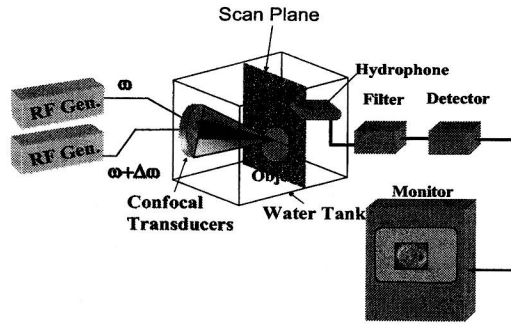
The majority of elasticity imaging methods is based on an external source of force in which the object is pressed by a known amount of force or displacement, and the resulting internal deformations are measured by means of pulse-echo ultrasound. The elasticity of the region of interest is then calculated based on the resulting deformation in relation to the magnitude of the applied force (or displacement). Normally, the region of interest rests deep in the body and away from the source of the force. The problem with this method, termed elastography, is that the force actually exerted on the region of interest depends on the elastic properties of the tissues located between the source and the region of interest. Hence, the deformation and the estimated elasticity of the region of interest are subject to the variability of the intervening tissues.

An alternative strategy is to apply a localized stress directly in the region of interest. One way to accomplish this is to use the radiation pressure of ultrasound. Acoustic radiation force is the time average force exerted by an acoustic field on an object. This force is produced by a change in the energy density of an incident acoustic field [2]; for example, due to absorption or reflection. The use of ultrasound radiation force for evaluating tissue properties has several benefits, for example:

- (a) Acoustic (ultrasound) energy is a non-invasive means of exerting force.
- (b) Existing ultrasound technology and devices can be readily modified for this purpose, thus eliminating the need for developing a new technology.
- (c) Radiation force can be generated remotely inside tissue without disturbing superficial layers.
- (d) The radiation stress field can be highly localized, thus allowing for interrogation of a small excitation point.
- (e) Radiation force can be produced in a wide range of frequencies or temporal shapes.

These features make radiation force methods highly attractive compared to other, mostly mechanical excitation methods used in elasticity imaging. Tissue probing with the radiation force of ultrasound can be accomplished with a variety of methods depending on the excitation and detection methods used. Similar to elasticity imaging methods with mechanical excitation, radiation force methods can use either a static or dynamic stress.

Using a dynamic radiation force to remotely probe tissue has certain unique characteristics and capabilities that can provide a new family of methods in the field of tissue characterization and imaging. It is insightful to set this new field apart from conventional ultrasound tissue characterization imaging. A major difference is that the dynamic radiation stress allows one to analyze the object based on its low frequency structural vibration properties as opposed to its ultrasonic parameters.



**Fig. 1.** Schematic of experiment setup

The dynamic radiation force methods may be categorized as:

- (a) Transient methods, where an impulsive radiation force is used and the transient response of the tissue is detected by Doppler ultrasound [3].
- (b) Shear-wave methods, where an impulsive or oscillating radiation is applied to the tissue and the resulting shear wave is detected by ultrasound or other methods [4,5,6].
- (c) Vibro-acoustography, a method recently developed by the authors, where a localized oscillating radiation force is applied to the tissue and the acoustic response of the tissue is detected by a hydrophone or microphone [7].



**Fig. 2.** Vibro-acoustic image of US quarter obtained with the setup of Fig. 1.

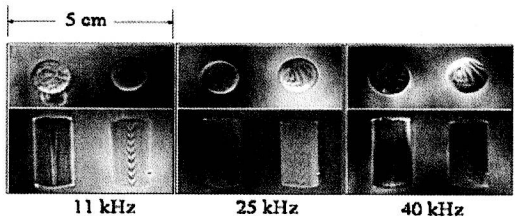


## 2 Theory

Acoustic radiation force is a time average force exerted by a propagating acoustic wave on an object. This force is an example of a universal phenomenon in any wave motion that introduces some type of unidirectional force on absorbing or reflecting targets in the wave path. For a review of this topic the reader may refer to [2].

Consider a plane ultrasound beam interacting with a planar object of zero thickness and arbitrary shape and boundary impedance that scatters and absorbs. The radiation force vector,  $\mathbf{F}$ , arising from this interaction has a component in the beam direction and another transverse to it. The magnitude of this force is proportional to the average energy density of the incident wave  $E$  at the object, where  $\langle \rangle$  represents the time average, and  $S$  the area of the projected portion of the object [8]:

$$\mathbf{F} = d\mathbf{r}S \langle E \rangle . \tag{1}$$



**Fig. 3.** Vibro-acoustic image of a hard (left) and a soft (right) urethane cylinder embedded within agar gel. Top row are images from the ends of the cylinders and bottom row are imaged from the side of the cylinders. The low difference frequencies, 11 kHz and 25 kHz, show the difference in stiffness of the two cylinders.

Here  $d\mathbf{r}$  is called the vector drag coefficient with a component in the incident beam direction and another transverse to it. The coefficient  $d\mathbf{r}$  is defined per unit incident energy density and unit projected area. For a planar object, the magnitude of  $d\mathbf{r}$  is numerically equal to the force on the unit area of the object per unit energy density. Physically, the drag coefficient represents the scattering and absorbing properties of the object. The drag coefficient can also be interpreted as the ratio of the radiation force magnitude on a given object to the corresponding value if the object were replaced by a totally absorbing object of similar size. For simplicity, we assume a planar object oriented perpendicular to the beam axis. In this case, the transverse component vanishes, thus, the drag coefficient (force) will have only a component normal to the target surface which we denote by scalar  $dr(F)$ . To produce a time-varying radiation force, the intensity of the incident beam can be modulated in various ways.