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Thomas M. Deserno  
Editor

# Biomedical Image Processing

With 254 Figures

 Springer

*Editor*

Dr. Thomas M. Deserno  
RWTH Aachen  
Institut für Medizinische Informatik  
Pauwelsstr. 30  
52074 Aachen, Germany  
E-mail: [deserno@ieee.org](mailto:deserno@ieee.org)

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To Verena – the beauty and the beauty of images



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## Preface

YATBIP: Yet another textbook on biomedical image processing? – Hopefully not. . .

Based on the tutorial *SC086 – Fundamentals of Medical Image Processing* regularly offered at the International SPIE Symposium on Medical Imaging, the Springer-Verlag Series Editor of *Biological and Medical Physics, Medical Engineering* invited me in January 2009 to compile this book. Actually, the idea of providing a “suitable” textbook – comprehensive but short, up-to-date but essential, and detailed but illustrative – for novices like experts, and at reasonable costs, is not new. For years, the lack of any such textbook in image processing covering all of the special needs in biology and medicine is evident. In any teaching lecture, tutorial as well as graduate class. I’m always asked by the students to suggest literature but cannot answer satisfyingly, simply because there isn’t a “suitable” textbook yet.

So we aimed at compiling a high-quality collection of chapters, written for scientists, researchers, lectures and graduate students as well, covering the recent advantages in the broad field of biomedical imaging and image processing in an exemplary way. In February 2009, several fruitful discussions with colleagues at SPIE Medical Imaging convinced me to face the challenge, and I started recruiting author teams for contributions. Finally, 47 authors from 11 nations all over the world collaborated – all of them leading experts in their field. Intensive efforts were made to direct all authors towards a similar style of presentation and equal degree of technical details. Beside some written guidelines, the overview chapter was provided to the authors as an example before they started writing. All authors first provided a short outline and a detailed table of content, which were distributed between all contributors together with a strictly enforced time line. In October 2009, submission of chapters started, and each manuscript was edited carefully. Editor requests have been processed by the authors improving completeness and clarity of presentation, and finally in June 2010, the manuscript was submitted to the publisher.

**Fig. 1.** *Eierlegende Wollmilchsau*. Every morning, this special animal provides a cooked egg with chilled fresh milk. Its wool is used for high-quality clothes and the meat for excellent dining. It is the first *all-in-one* approach documented in history (Courtesy of: <http://neulehrer.wordpress.com/>)



As a result, this book has appeared as uniform monograph with an overview chapter contributed by the editor, followed by some twenty chapters focusing on particular parts selected from biomedical imaging and image processing. Each chapter gives an introduction and overview of recent trends in its field and provides particular case examples, usually taken from the author's own research.

Primarily addressing engineers and system developers in computer sciences, the book covers the entire processing pipeline of biomedical imaging. In particular, the following parts are included, with about three chapters in each of it:

1. Image formation
2. Image enhancement
3. Feature extraction and selection
4. Segmentation
5. Classification and measurements
6. Image data visualization
7. Image management and integration
8. Evaluation and customizing

Many people might object me at this point, because we clearly aimed at reaching the unreachable. In Germany, we have the common phrase “*eierlegende Wollmilchsau*”, a metaphor that directly translates to “egg-providing wool-milk-pig” describing the union of all benefits (Fig. 1).

You as the reader shall judge our success realizing this all-in-one approach: YATBIP or *eierlegende Wollmilchsau*? Any feedback is deeply welcome and should be directed personally to me as the editor.

Facing now the final manuscript, I want to thank Claus Ascheron for encouraging me to initiate this project, and all contributors for timely delivering their high-quality material and appropriately responding to the editorial remarks and suggestions. Jens Hoffmann was assisting me in L<sup>A</sup>T<sub>E</sub>X programming and Max Jung helped in text and image conversion and optimization.

Also, I want to mention Peter Jentsch and Dirk Bartz, who have passed away during the very last iterations of the manuscript, which leaves me behind speechless. We have included the obituaries in the next pages.



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## Obituaries



**Prof. Dr. Peter Jensch** died unexpectedly during the period of the proof-reading of this book chapter on April 15, 2010 after a fulfilling life. Peter Jensch was the initiator of the DICOM research activities at the OFFIS - Institute for Information Technology, Oldenburg, Germany, in the early 1990s and was pushing this topic forward for the rest of his life. The most popular result of this engagement is the well-known Open Source DICOM toolkit DCMTK that is hosted and maintained by OFFIS since 1993. Against this background, all members of the DICOM team at OFFIS

would like to thank Peter Jensch for establishing this extraordinary project and for being such a likeable, energetic boss, mentor, and colleague to us. Without him, OFFIS would not be the popular name in the world of DICOM it is today and we all would not have such encouraging opportunities and research projects we still enjoy. As Chap. 17 of this book is the last publication Peter Jensch participated in and since the content of this chapter is the very topic that strongly influenced his work, we like to use this opportunity to express our sincere gratitude to Peter Jensch.

Oldenburg, June 2010

*Michael Onken  
Marco Eichelberg  
Jörg Riesmeier*



**Prof. Dr. Dirk Bartz** died unexpectedly on March 28, 2010 while attending the thirtieth Vattenfall Berlin Half Marathon. Running half-marathon in Berlin was one of his favorite activities.

During his academic career, Dirk strongly supported the idea of building a German Interest Group on Medical Visualization and actively took part the whole time giving advice to many students; particularly supporting female researchers was an important issue. Furthermore, Dirk organized many tutorials at Visualization, Eurographics, and Computer-Assisted Radiology and Surgery (CARS).

In 2005, I was very glad that Dirk joined the effort of writing a textbook on “Visualization in Medicine”. For an 18 month period, we communicated daily on the various aspects of the book. It was enlightening and a pleasure to discuss with Dirk all the time. He was always perfectly reliable and good-humored even in situations where he had a very high workload.

In the end of 2006, Dirk became appointed as Full Professor for Computer-Assisted Surgery at the International Center for Computer-Assisted Surgery (ICCAS), Leipzig, Germany, and started to build a new research group. He focused on visualization techniques, such as illustrative rendering, perceptual studies (from Dirk I learned the term “psychophysical studies”), and applications in neurosurgery and Ear, Nose and Throat (ENT) surgery.

Dirk belonged to the core team which tried to establish a new workshop series “Visual Computing in Biology and Medicine”. It was quite natural that Dirk would host the second event, scheduled to take place in July in Leipzig. Until the very last days of his life, he discussed strategies for this workshop.

Dirk was only 42 years old, leaving behind Heidi, his wife, and his two little sons.

Magedeburg, June 2010

*Berhard Preim*

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## List of Contributors

**Mostafa Analoui**

Healthcare and Life Sciences  
The Livingston Group  
New York, NY, USA  
analoui@yahoo.com

**Romarc Audigier**

Laboratoire Vision et Ingénierie  
des Contenus, CEA-LIST  
romarc.audigier@cea.fr

**Paulo M. Azevedo-Marques**

Medical School of Ribeirão Preto  
University of São Paulo  
São Paulo, Brazil  
pmarques@fmrp.usp.br

**André G.R. Balan**

Computer Science, Mathematics  
and Cognition Center  
Federal University of ABC  
São Paulo, Brazil  
agrbalan@icmc.usp.br

**Dirk Bartz<sup>†</sup>**

Innovation Center for Computer  
Assisted Surgery (ICCAS)  
University of Leipzig  
Leipzig, Germany

**Pedro H. Bugatti**

Computer Science Department  
University of São Paulo  
São Paulo, Brazil  
pbugatti@icmc.usp.br

**Zang-Hee Cho**

Neuroscience Research Institute  
Gachon University of Medicine  
and Science, Seoul, Korea  
zcho@gachon.ac.kr

**Krzysztof Chris Ciesielski**

Department of Mathematics  
West Virginia University  
Morgantown, WV, USA  
and

Department of Radiology  
University of Pennsylvania  
Philadelphia, PA, USA  
kcies@math.wvu.edu

**Lena Costaridou**

Department of Medical Physics  
University of Patras  
Patras, Greece  
costarid@upatras.gr

**Hervé Delingette**

Asclepios Team, INRIA  
Sophia-Antipolis, France  
herve.delingette@inria.fr

**Thomas M. Deserno**

Department of Medical Informatics  
RWTH Aachen University  
Aachen, Germany  
deserno@ieee.org

**Jan D'hooge**

Department of Cardiovascular  
Diseases, Katholieke Universiteit  
Leuven, Leuven, Belgium  
jan.dhooge@uz.kuleuven.ac.be

**Jorge Documet**

Image Processing and Informatics  
Lab, University of Southern  
California, Los Angeles, CA, USA  
documet@usc.edu

**Marco Eichelberg**

OFFIS Institute for Information  
Technology, Oldenburg, Germany  
eichelberg@offis.de

**Hayit Greenspan**

Department of Biomedical  
Engineering, Tel-Aviv University  
Tel-Aviv, Israel  
hayit@eng.tau.ac.il

**Bart M. ter Haar Romeny**

Department of Biomedical  
Engineering, Eindhoven  
University of Technology  
Eindhoven, The Netherlands  
b.m.terhaarromeny@tue.nl

**Tobias Heimann**

French Research Institute  
of Computer Science and Automatic  
Control, INRIA  
Sophia Antipolis Cedex, France  
and  
German Cancer Research Center  
Heidelberg, Germany  
t.heimann@dkfz.de

**Steven C. Horii**

Department of Radiology  
University of Pennsylvania  
Philadelphia PA, USA  
steve.horii@uphs.upenn.edu

**Alexander Horsch**

Department of Medical Statistics  
and Epidemiology, Technische  
Universität München  
Munich, Germany

and

Computer Science Department  
University of Tromsø  
Tromsø, Norway  
alexander.horsch@tum.de

**H.K. (Bernie) Huang**

Image Processing and Informatics  
Lab, University of Southern  
California, Los Angeles, CA, USA  
hkhuang@aol.com

**Peter Jensch<sup>†</sup>**

OFFIS Institute for Information  
Technology, Oldenburg, Germany

**Jayashree Kalpathy-Cramer**

Department of Medical Informatics  
and Clinical Epidemiology  
Oregon Health & Science University  
Portland, OR, USA  
kalpathy@ohsu.edu

**Young-Bo Kim**

Neuroscience Research Institute  
Gachon University of Medicine  
and Science, Seoul, Korea  
neurokim@gachon.ac.kr

**Anh HongTu Le**

Image Processing and Informatics  
Lab, University of Southern  
California, Los Angeles, CA, USA  
anhhle@usc.edu

**Brent J. Liu**

Image Processing and Informatics  
Lab, University of Southern  
California, Los Angeles, CA, USA  
brentliu@usc.edu

**Murray H. Loew**

Biomedical Engineering Program  
Department of Electrical  
and Computer Engineering  
The George Washington University  
Washington, DC, USA  
loew@gwu.edu

**Roberto A. Lotufo**

School of Electrical and Computer  
Engineering, State University  
of Campinas (UNICAMP)  
Campinas, Brazil  
lotufo@unicamp.br

**Rubens C. Machado**

Center for Information Technology  
Renato Archer (CTI), Ministry  
of Science and Technology (MCT)  
Campinas, Brazil  
rubens.machado@cti.gov.br

**James G. Malcolm**

Department of Psychiatry, Brigham  
and Women's Hospital, Harvard  
Medical School, Boston, MA, USA  
malcolm@bwh.harvard.edu

**Henning Müller**

University of Applied Sciences  
Western Switzerland (HES-SO)  
Sierre, Switzerland

and

University and Hospitals of Geneva  
Geneva, Switzerland  
henning.mueller@hevs.ch

**Michael Onken**

OFFIS Institute for Information  
Technology, Oldenburg, Germany  
onken@offis.de

**Maria Petrou**

Informatics and Telematics Institute  
Centre for Research  
and Technology Hellas (CERTH)  
Thessaloniki, Greece  
petrou@iti.gr

**Bernhard Preim**

Department of Simulation and  
Graphics, University of Magdeburg  
Magdeburg, Germany  
preim@isg.cs.uni-magdeburg.de

**Yogesh Rathi**

Department of Psychiatry, Brigham  
and Women's Hospital  
Harvard Medical School  
Boston, MA, USA  
yogesh@bwh.harvard.edu

**Marcela X. Ribeiro**

Computer Science Department  
University of São Paulo  
São Paulo, Brazil  
mxavier@icmc.usp.br

**Jörg Riesmeier**

ICSMED AG, Oldenburg, Germany  
riesmeier@icsmed.de

**Leticia Rittner**

School of Electrical and Computer  
Engineering, State University  
of Campinas (UNICAMP)  
Campinas, Brazil  
lrittner@dca.fee.unicamp.br

**Daniel Rueckert**

Department of Computing, Imperial  
College London, London, UK  
d.rueckert@imperial.ac.uk

**André V. Saúde**

Department of Computer Science  
Federal University of Lavras  
Lavras, Minas Gerais, Brazil  
saude@dcc.ufla.br

**Julia A. Schnabel**

Institute of Biomedical Engineering  
Department of Engineering  
Science, University of Oxford  
Oxford, UK  
julia.schnabel@eng.ox.ac.uk

**Young-Don Son**

Neuroscience Research Institute  
Gachon University of Medicine  
and Science, Seoul, Korea  
ydsong@gachon.ac.kr

**Tanveer Syeda-Mahmood**

IBM Almaden Research Center  
San Jose, CA, USA  
stf@almaden.ibm.com

**Agma J.M. Traina**

Computer Science Department  
University of São Paulo  
São Paulo, Brazil  
agma@icmc.usp.br

**Caetano Traina**

Computer Science Department  
University of São Paulo  
São Paulo, Brazil  
caetano@icmc.usp.br

**Jayaram K. Udupa**

Department of Radiology  
University of Pennsylvania  
Philadelphia, PA, USA  
jay@mail.med.upenn.edu

**Carolina Y.V. Watanabe**

Computer Science Department  
University of São Paulo  
São Paulo, Brazil  
carolina@icmc.usp.br

**Carl-Fredrik Westin**

Department of Radiology  
Brigham and Women's Hospital  
Harvard Medical School  
Boston, MA, USA  
westin@bwh.harvard.edu

**Ivo Wolf**

Department of Medical Informatics  
Mannheim University of Applied  
Science, Mannheim, Germany  
i.wolf@hs-mannheim.de

**Seung-Schik Yoo**

Department of Radiology  
Brigham and Women's Hospital  
Harvard Medical School  
Boston, MA, USA  
yoo@bwh.harvard.edu

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## Acronyms

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AAM	Active Appearance Model
AAPM	American Association of Physicists in Medicine
ABCD	Asymmetry, Border, Color, and Differential structures
ACE	Associative Classifier Engine
ACR	American College of Radiology
ACSE	Association Control Service Element
ADNI	Alzheimer's Disease Neuroimaging Initiative
AE	Application Entity
AFC	Absolute Fuzzy Connectedness
AHA	American Heart Association
AIF	Arterial Input Function
AJAX	Asynchronous Javascript XML
AJCC	American Joint Committee on Cancer
ALM	Acral Lentiginous Melanoma
AMN	Atypical Melanocytic Nevi
ANN	Artificial Neural Network
AOM	Area Overlap Measure
APD	Avalanche Photodiode
API	Application Programming Interface
ASCF	Alternating Sequential Component Filter
ASD	Atrial Septal Defect
ASF	Alternating Sequential Filter
ASM	Active Shape Model
AVD	Absolute Volumetric Difference

BAA	Bone Age Assessment
BDWG	Biomarker Definitions Working Group
BI-RADS	Breast Imaging Reporting and Data System
BIR	Biomedical Imaging Resource
BSD	Berkeley Software Distribution
BSPS	Blending Softcopy Presentation States
CAD	Computer-Aided Diagnosis
CADe	Computer-Assisted Detection
CADx	Computer-Assisted Diagnostics
CARS	Computer-Assisted Radiology and Surgery
CART	Classification And Regression Tree
CAS	Chinese Academy of Sciences; Computer-Assisted Surgery
CASH	Color, Architecture, Symmetry, Homogeneity
CAT	Computer-Aided Therapy
CAVE	Cave Automatic Virtual Environment
CBIR	Content-Based Image Retrieval
CBVIR	Content-Based Visual Information Retrieval
CC	Cranio Caudal
CCD	Charge-Coupled Device
CGMM	Constrained GMM
CI	Computational Intelligence; Confidence Interval
CICE	Cumulative Inverse Consistency Error
CIE	Commission Internationale de L'Eclairage
CIMT	Carotid Intima-Media Thickness
CISTIB	Center for Computational Image and Simulation Technologies in Biomedicine
CIT	Center for Information Technology
CLEF	Cross Language Evaluation Forum
CM	Cutaneous Melanoma
CMY	Cyan, Magenta, Yellow
CNMD	Consensus Net Meeting on Dermoscopy
CNR	Contrast to Noise Ratio
CNS	Central Nervous System
CPU	Central Processing Unit
CR	Computed Radiography
CRT	Cathode Ray Tube
CS	Conformance Statement
CSF	Cerebrospinal Fluid
CSI	Chemical Shift Imaging
CSPS	Color Softcopy Presentation State
CT	Computed Tomography
CTA	CT Angiography
CTC	CT Colonography

CTE	Cumulative Transitive Error
CTK	Common Toolkit
CTR	Cardio-Thoracic Ratio
CVP	Closest Vessel Projection
DAG	Directed Acyclic Graph
DBM	Deformation-Based Morphometry
DBT	Digital Breast Tomosynthesis
DCE	Dynamic Contrast-Enhanced
DCE-MRI	Dynamic Contrast-Enhanced Magnetic Resonance Imaging
DCMR	DICOM Content Mapping Resource
DCMTK	OFFIS DICOM ToolKit
DDSM	Digital Database for Screening Mammography
DES	Density Emitter Model
DeVIDE	Delft Visualisation and Image Processing Of Development Environment
DFT	Discrete Fourier Transform
DICOM	Digital Imaging and Communications in Medicine
DICOM SR	DICOM Structured Reporting
DIMSE	DICOM Message Service Element
DKFZ	Deutsches Krebsforschungszentrum
dMRI	Diffusion Magnetic Resonance Imaging
DNA	Deoxyribonucleic Acid
DOF	Degree Of Freedom
DP	Detection Performed
DPV	Dermatoscopic Point Value
DR	Digital Radiography
DSA	Digital Subtraction Angiography
DSI	Diffusion Spectrum Imaging
DTI	Diffusion Tensor Imaging
DTM	Decision Tree Method
DVD	Digital Versatile Disc
DWT	Discrete Wavelet Transform
ECG	Electrocardiography
EEG	Electroencephalography
ELM	Epi-Luminescence Microscopy
EM	Expectation Maximization
EN	European Norm
ENT	Ear, Nose, and Throat
EPI	Echo Planar Imaging
EXACT	Extraction of Airways from CT
F-FP-CIT	<sup>18</sup> FluoroPropyl-CarbomethoxyIodophenyl-norTropane

XXXII Acronyms

FA	Fractional Anisotropy
FB	Filtered Backprojection
FC	Fuzzy Connectedness
FDA	Food and Drug Administration
FDG	$^{18}\text{F}$ -Fludeoxyglucose
FDI	Fédération Dentaire Internationale
FEM	Finite Element Model
FFD	Free-Form Deformation
FFDM	Full-Field Digital Mammography
FID	Free Induction Decay
Fiji	Fiji Is Just ImageJ
FISH	Fluorescent In-Situ Hybridization
FLT	$^{18}\text{F}$ -L-Thymidine
fMRI	Functional MRI
FND	False Negative Dice
FOV	Field-Of-View
FPD	False Positive Dice
FROC	Free-Response Receiver Operating Characteristic
FSC	File Set Creator
FSR	File Set Reader
FSU	File Set Updater
FWHM	Full Width Half Maximum
GA	Genetic Algorithms
GC	Graph Cut
GDCM	Grassroots DICOM Library
GG	Generalized Graph
GIF	Graphics Interchange Format
GIFT	GNU Image Finding Tool
GIMIAS	Graphical Interface for Medical Image Analysis and Simulation
GLCM	Gray-Level Co-occurrence Matrices
GMM	Gaussian Mixture Model
GMP	Good Manufacturing Practice
GNU	GNU's Not Unix
GPA	Generalized Procrustes Analysis
GPU	Graphics Processing Unit
GPS	Grayscale Softcopy Presentation State
GTC	Generalized Tanimoto Coefficient
GUI	Graphical User Interface
HARAG	Hierarchical Attributed Region Adjacency Graph
HARDI	High Angular Resolution Diffusion Imaging
HD	Hausdorff Distance
HIPAA	Health Insurance Portability and Accountability Act



HIS	Hospital Information System; Hue, Intensity, Saturation
HL7	Health Level Seven
HRRT	High-Resolution Research Tomograph
HSV	Hue-Saturation-Value
HU	Hounsfield Unit
IBSR	Internet Brain Segmentations Repository
ICA	Independent Component Analysis
ICC	International Color Consortium
ICCAS	International Center for Computer-Assisted Surgery
ICP	Iterative Closest Point
ID	Identifier
IDEA	Image Diagnosis Enhancement Through Associations
IDL	Interactive Data Language
IFT	Image Foresting Transform
IGS	Image-Guided Surgery
IGSTK	Image-Guided Surgery Toolkit
IGT	Image-Guided Therapy
IHE	Integrating the Healthcare Enterprise
IHS	Intensity, Hue, Saturation
IOD	Information Object Definition
IP	Internet Protocol
IR	Information Retrieval
IRB	Institutional Review Board
IRFC	Iterative Relative Fuzzy Connectedness
IRMA	Image Retrieval in Medical Applications
ISO	International Organization for Standardization
ITK	Insight Segmentation and Registration Toolkit
JPEG	Joint Photographic Experts Group
JSW	Joint Space Width
k-NN	k-Nearest Neighbor
KIN	Key Image Note
KLT	Karhunen-Loève Transform
LA	Left Atrium
LAC	Los Angeles County Hospital
LCD	Liquid Crystal Display
LDA	Linear Discriminant Analysis
LGPL	Lesser General Public License
LIDC	Lung Image Database Consortium
LMM	Lentigo Maligna Melanoma
LoG	Laplacian Of Gaussian
LONI	Laboratory Of Neuro Imaging
LRA	Logistic Regression Analysis
LS	Level Set
LSA	Lenticulostriate Arterie

XXXIV Acronyms

LSO	Lutetium Oxyorthosilicate
LUT	Look-Up Table
LV	Left Ventricle
MAF	Multimod Application Framework
MAP	Maximization A Posteriori; Mean Average Precision
MATLAB	MATrix LABoratory
MC	Micro-Calcification
MDL	Minimum Description Length
MedGIFT	Medical GIFT
MEDICOM	Medical Image Communication
MeSH	Medical Subject Headings
MHD	Manhattan Distance
MI	Mutual Information
MICCAI	Medical Image Computing and Computer Assisted Intervention
MIP	Maximum Intensity Projection
MIPAV	Medical Image Processing, Analysis, and Visualization
MIT	Massachusetts Institute of Technology
MITK	Medical Imaging Interaction Toolkit
ML	Maximum Likelihood; MeVis Image Processing Library
MLO	Medio-Lateral Oblique
MOD	Magneto Optical Disk
MP	Morphological Processing
MPM	Maximization of the Posterior Marginals
MPPS	Modality Performed Procedure Step
MPU	Multi-Level Partition of Unity
MRA	Magnetic Resonance Angiography
MRF	Markov Random Field
MRI	Magnetic Resonance Imaging
MRM	Magnetic Resonance Mammography
MRML	Medical Reality Markup Language; Multimedia Retrieval Markup Language
MRS	Magnetic Resonance Spectroscopy
MRSI	Magnetic Resonance Spectroscopy Imaging
MS	Multiple Sclerosis
MSW	Multi-Scale Watershed
MTF	Modulation Transfer Function
MV	Mitral Valve
NA-MIC	National Alliance for Medical Image Computing
NASA	National Aeronautics and Space Administration
NCBC	National Centers for Biomedical Computing
NCC	Normalized Cross Correlation

NCI	National Cancer Institute
NEMA	National Electrical Manufacturers Association
NHLBI	National Heart Lung and Blood Institute
NIH	National Institutes of Health
NIREP	Non-Rigid Image Registration Evaluation Project
NLM	National Library of Medicine
NM	Nodular Melanoma
NMF	Non-Negative Matrix Factorization
NMI	Normalised Mutual Information
NMR	Nuclear Magnetic Resonance
NN	Nearest Neighbor
NNT	Number Needed to Treat
NR RD	Nearly Raw Raster Data
NURBS	Non-Uniform Rational B-Spline
OA	Osteo arthritis
OAI	Osteo arthritis Initiative
OCT	Optical Coherence Tomography
ODF	Orientation Distribution Function
OFFIS	Institute for Information Technology
OOI	Object Of Interest; Organ Of Interest
OSA	Obstructive Sleep Apnea
OSGi	Open Services Gateway Initiative
OSI	Open System Interconnection
OTS	Off-The-Shelf
PA	Postero-Anterior
PACS	Picture Archiving and Communication System
PCA	Principal Component Analysis
PCS	Profile Connection Space
PCSP	Pseudo-Color Softcopy Presentation States
PD	Pharmacodynamic
PDE	Partial Differential Equation
PDM	Point Distribution Model
PET	Positron Emission Tomography
PK	Pharmacokinetic
PMT	Photo-Multiplier Tube
POC	Proof Of Concept
POM	Proof Of Mechanism
ppm	Parts Per Million
pQCT	Peripheral Quantitative Computed Tomography
PSF	Point Spread Function
PSL	Pigmented Skin Lesion

XXXVI Acronyms

PSP	Photostimulable Phosphor
PWF	Post-Processing Work Flow
Q/R	Query/Retrieve
QBE	Query By Example, Query By Image Example
QBI	Q-Ball Imaging
QBIC	Query By Image Content
QDE	Quantum Detection Efficiency
RA	Right Atrium
rCMRGlc	Regional Cerebral Metabolic Rate of Glucose
RF	Radio Frequency
RFC	Relative Fuzzy Connectedness
RGB	Red, Green, and Blue
RIRE	Retrospective Image Registration Evaluation
RIS	Radiology Information System
RNA	Ribonucleic Acid
ROC	Receiver Operating Characteristic
ROI	Region Of Interest
RPC	Rich Client Platform
RREP	Retrospective Registration Evaluation Project
RSNA	Radiological Society of North America
RV	Random Variable, Right Ventricle
SCP	Service Class Provider
SCU	Service Class User
SD	Standard Deviation
SE	Standard Error
SER	Signal Enhancement Ratio
SFM	Screen-Film Mammography
SGLD	Spatial Gray Level Dependence
SIF	Single Image Finding
SIFT	Shift-Invariant Feature Transform
SIM	Scaling Index Method
SINR	Simple Image and Numeric Report
SiPM	Silicon Photomultiplier
SMART	System for the Mechanical Analysis and Retrieval of Text
SNR	Signal-to-Noise Ratio
SOFA	Simulation Open Framework Architecture
SOP	Service Object Pair; Standard Operating Procedure
SOR	Successive Over-Relaxation
SPECT	Single Photon Emission Computed Tomography
SR	Structured Reporting; Super Resolution
SRN	Square Root of the Norm of Coefficients
SSD	Sum of Squared Differences

SSM	Statistical Shape Model, Superficial Spreading Melanoma
STAPLE	Simultaneous Truth and Performance Level Estimation
SVD	Singular Value Decomposition
SVM	Support Vector Machine
TBM	Tensor-Based Morphometry
TCL	Tool Command Language
TCP	Transmission Control Protocol
TEE	Transesophageal Echocardiography
TIFF	Tagged Image File Format
TMG	Tensorial Morphological Gradient
TREC	Text Retrieval Conference
UofU	University of Utah
UCLA	University of California at Los Angeles
UID	Unique Identifier
UK	United Kingdom
UPF	Universitat Pompeu Fabra
US	Ultrasonography, Ultrasound, United States
USB	Universal Serial Bus
USC	University of Southern California
VBM	Voxel-Based Morphometry
VD	Volumetric Difference
VL	Virtual Machine
VME	Virtual Medical Entities
VOI	Volume Of Interest; Value Of Interest
VOLCANO	VOLume Change Analysis of NOdules
VPE	Visual Programming Environment
VR	Value Representation; Virtual Reality
VSD	Ventricular Septum Defect
VSG	Visualization Sciences Group
VTK	Visualization Toolkit
W3C	World Wide Web Consortium
WS	Watershed
WSDL	Web Service Description Language
XA	X-ray Angiography
XIP	eXtensible Imaging Platform
XRF	X-ray Radio-Fluoroscopy
ZIB	Zuse Institute Berlin