Special Issue on Pulmonary Imaging

I. Introduction to the Special Issue

ADVANCEMENTS in imaging technology have provided an increase in both the quantity and quality of the image data available to study the pulmonary system. The lungs have traditionally been imaged using planar radiography (i.e., the chest X-ray). The development of digital radiography systems and dual-energy subtraction systems have provided radiography with improved image quality and unique imaging capabilities. X-ray computed tomography (CT) imaging overcomes the limitations of projection imaging in radiography by offering a three-dimensional (3-D) depiction of the body. CT imaging technology has rapidly evolved over the past decade, first with the move toward thin-slice high-resolution CT and helical CT scanning, and then with a push toward multidetector row CT that allows multiple projections to be acquired simultaneously. These technological advances have led to improved resolution, reduced scan times, and overall, a vast improvement in the quality of the image data.

Even with these remarkable advances in X-ray imaging, other modalities still play an important role in pulmonary analysis. Positron emission tomography (PET) and single photon emission computed tomography (SPECT) remain the standard modalities for assessing lung perfusion and ventilation. Magnetic resonance (MR) imaging, using new contrast agents and/or hyperpolarized gases, shows promise to provide similar functional information and other important parameters (e.g., apparent diffusion coefficients in the lung tissue) without ionizing radiation.

Along with these improvements in imaging hardware and modalities, there is a growing interest in computerized analysis of the image data. Typical analyses include image segmentation, image registration, the detection of abnormalities for computer-aided diagnosis, and image visualization. As noted by Sluimer *et al.* [1], the number of journal articles in the area of pulmonary image processing for CT images alone has been increasing at a pace of about 50% per year for the past five years. This growth rate shows pulmonary imaging to be an exciting research area in which to work.

II. Contents of the Special Issue

A total of 33 papers were submitted in response to the call for papers for the special issue. Of these submissions, nine papers were selected for inclusion in the issue. One other paper that was not submitted specifically for the special issue was also selected for inclusion. The papers in this issue span the field from X-ray, CT, PET, and SPECT imaging of the lungs to virtual bronchoscopy. Most of the contributions focus on computer algorithms for analyzing pulmonary image data, including segmentation, registration, quantification, noise reduction, and visualization. One paper describes a novel image acquisition technique, and one paper provides an overall survey of the field. The scope of the topics addressed in the manuscripts show this to be a broad, diverse field. The ten papers also show geographical diversity, with four papers from the United States, two papers from Germany, two papers from the Netherlands, one paper from the United Kingdom, and one paper from Japan. Overall, the submissions were of high quality, and while we were not able to include all of them in the special issue, we expect that several additional manuscripts will appear in future issues of this journal.

This special issue starts with a comprehensive survey of computerized analysis of lung CT images by Sluimer *et al.* [1]. This paper gives an overview of segmentation algorithms for the major pulmonary structures (the lungs, lung lobes, airways, and vasculature), methods for pulmonary image registration, including multimodality registration, intersubject registration, and intra-subject registration, and then discusses the use of computerized image analysis techniques in clinical applications in pulmonary medicine, including applications in the detection and treatment of lung cancer, emphysema, interstitial lung disease, and pulmonary emboli.

Papers by Suzuki *et al.* [2], Kuhnigk *et al.* [3], and Reeves *et al.* [4] address the important problem of imaging lung nodules (i.e., suspected lung cancer). Suzuki *et al.* consider the problem of nodule detection in chest radiographs [2]. This contribution addresses the problem of nodules obscured by ribs or clavicles that are known to be harder to detect for both the radiologist and computer-aided diagnostic (CAD) systems. The authors use a multiresolution massive training artificial neural network to suppress shadows of bony structures. The system is trained with images from dual energy chest radiography and it largely removes ribs and clavicles while maintaining the visibility of soft tissues like lung nodules and vessels.

Reliable measurements of the size of nodules in CT are particularly important because lesion growth rate is one of the major factors that influence the choice of treatment, and change in growth rate is a good indicator of whether a particular therapy is effective or not. This problem is considered in two papers included in this issue. Kuhnigk *et al.* [3] present a new method for segmenting both small lesions and large tumors with complex connections to the lung tissue. The authors also address the problem of making accurate estimates of lesion volume in the face of partial volume effects and different image acquisition parameters. Reeves *et al.* first improve upon algorithms for lung nodule segmentation that they had previously described in earlier papers, with their new method proving to be less dependent on parameter choices and choice of seed point [4]. Next, the authors demonstrate how the reliability of the nodule growth rate estimation can be improved upon by rigidly matching the nodules from two different examinations and subsequently removing inconsistencies between the segmentations with a set of rules.

Digital Object Identifier 10.1109/TMI.2006.870840

Papers by Schilham *et al.* [5] and Xu *et al.* [6] are focused on the detection and measurement of a group of lung disorders known as chronic obstructive pulmonary disease, or COPD. Cigarette smoking is a major risk factor for COPD. Emphysema, which is one form of COPD, is characterized by an enlargement of the distal airspaces and permanent destruction of the lung tissues. These changes can be observed using thin-slice CT imaging.

Schilham *et al.* [5] consider how to best measure, or "score," the amount of emphysema present in a low-dose lung CT scan. Low-dose scanning is important because of increased interest in widespread screening of the general population for COPD. Unfortunately, as the dose is lowered, the noise level in the image data increases. Schilham *et al.* describe a nonlinear filtering method that estimates the local noise power and filters the image prior to computing an emphysema score. They compare emphysema scores measured from high-dose and low-dose scans and show good agreement.

Xu *et al.* [6] apply a texture classifier to CT images to assess emphysema and other smoking-related changes in the lung tissue. Xu *et al.* use 3-D texture features, including first- and second-order statistics and measures of fractal dimension, and a Bayesian classifier to label regions of interest into one of four diseases classes. Xu *et al.* show better discrimination using the 3-D method as compared to earlier two-dimensional texture classifiers.

Lung CT image can depict the anatomy with great detail, however, nuclear medicine techniques are usually used to assess lung function. PET and SPECT are commonly used in lung function studies, but a typical scan may take several minutes to tens of minutes to acquire. During this acquisition period, the subject is breathing, so respiratory gating and lung motion correction become critical.

Dawood *et al.* [7] have developed a method for motion correction on respiratory-gated PET/CT images. While the CT data may be acquired in less than a second, the PET data are acquired over several minutes. Dawood *et al.* propose to retrospectively respiratory-gate the PET data into eight different points along the respiratory cycle. While this respiratory gating reduces motion blur, it also reduces signal-to-noise ratio (SNR). To increase the SNR, the eight gated PET images are registered together using an optical flow technique and then matched to the lung volume for the associated CT image. The authors present results showing significant improvement in image quality with the reduced motion blur.

Ue *et al.* address a similar problem for respiratory-gated SPECT images [8]. As with PET, SPECT images are gathered across many breaths, so motion blur is significant. Ue *et al.* use respiratory-gated SPECT imaging and a nonlinear registration algorithm to align and combine respiratory-gated SPECT images. Their results show an improvement in image quality in phantom studies and in scans of human subjects.

Despite the increased use of 3-D modalities, the plain old chest radiograph remains by far the most commonly used radiological examination of the lungs. Liu *et al.* describe a new technique to reduce scatter in the acquisition of radiographs with slot-scan digital radiography [9]. By adjusting the readout electronics of a flat panel detector, they alternately reset and read out the image lines of a fan beam. The ability of this elegant technique to reduce scatter is demonstrated experimentally in an anthropomorphic chest phantom.

Chung *et al.* combine CT imaging with modern computer graphics to generate realistic virtual views of the pulmonary airways [10]. Virtual bronchoscopy has increased in popularity as computer capabilities have advanced and CT scanning technologies have improved, but unfortunately, most virtual bronchoscopic views appear artificial and do not have the realism of the view seen down a real bronchoscope. Chung *et al.* approach this problem by estimating the bidirectional reflectance distribution function (BDRF) from bronchoscopic video and matching CT data. The BDRF is then used to create a patient-specific texture map that can be used to generate a photo-realistic view during the virtual bronchoscopic rendering. The authors assess the performance of their method by having experts visually score the realism of BDRF-derived renderings and real bronchoscopic images.

III. Outlook for the Future

The papers in this issue offer an intriguing sample of the possible clinical applications that may be routinely available in the future. We expect that X-ray CT will continue to play a leading role in lung imaging. CT will become even more popular if low-dose screening for pulmonary disorders becomes widespread. Routine low-dose screening will trigger a demand for analysis tools resilient enough to handle noisier image data. The promise of MR imaging for examining pulmonary structure and function without ionizing radiation may position MR as the modality of choice for screening examinations in the future. Advances in imaging will naturally be followed by advances in image analysis. We envision that pulmonary images will be available in thin slices with cubic voxels and will be analyzed in three and four dimensions. New visualization approaches will facilitate display and interaction with the ever-growing image volumes, and will permit efficient presentation of the results of computerized image analysis. A complete, quantitative assessment of intrathoracic airways, pulmonary vasculature, and pulmonary parenchyma structure and function will provide physicians with an unprecedented amount of objective information that can and will be used for prescribing personalized medical treatment, facilitating patient follow up, and continuously monitoring disease progression.

While pulmonary imaging and image analysis is a critically important topic in its own right, the future will see investigators systematically explore interrelationships between the lungs and other organs. For example, if the lungs are imaged, the resulting image data may also provide information about the heart, diaphragm, and liver. Combined heart-lung segmentation and analysis approaches, which take advantage of the anatomic relationships between the heart and lungs and can accommodate the four-dimensional character of cardiac motion, may be developed in the near future. Computer-aided detection and computer-aided diagnostic methods that go far beyond currently existing pulmonary nodule detection systems will soon appear. Again, the interaction of the pulmonary and cardiac information will likely play an important role. All in all, combining information about the lungs and the heart will only be the first step leading to a complex model-based multiorgan analysis of the entire human body. If this special issue contributes to achieving any small part of this grand vision, it justifies its existence.

JOSEPH M. REINHARDT, *Guest Editor*
The University of Iowa
Department of Biomedical Engineering
Iowa City, IA 52242 USA

BRAM VAN GINNEKEN, *Guest Editor*
University Medical Center Utrecht
Image Sciences Institute
Utrecht, 3508 GA The Netherlands

MILAN SONKA, *Guest Editor*
The University of Iowa
Departments of Electrical & Computer Engineering
and Ophthalmology Visual Sciences
Iowa City, IA 52242 USA

ACKNOWLEDGMENT

The guest editors wish to thank the *Transactions on Medical Imaging* Editor-In-Chief and editorial staff for their assistance in preparing this issue. They would also like to acknowledge the many reviewers that provided expert critiques of the manuscripts under consideration for the special issue, and thank them for their prompt responses to their requests for an expedited review schedule. Finally, they would like to thank all of the authors that submitted manuscripts for the issue; they are excited by the state-of-the-art research work they have shown, and look forward to working together with them to advance this field even further.

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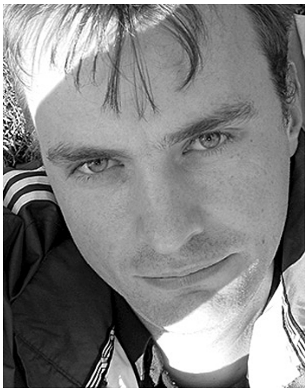
Joseph M. Reinhardt (S'84–M'85–SM'02) received the B.S. degree from Carnegie Mellon University, Pittsburgh, PA, in 1985, the M.S. degree in 1988 from Northeastern University, Boston, MA, in 1988, and the Ph.D. degree from Pennsylvania State University, University Park, in 1994, all in electrical engineering.

From 1985 to 1990, he worked as a radar systems engineer at Raytheon Company, Wayland, MA. He was a member of the Department of Radiology at the University of Iowa, Iowa City, as a Postdoctoral Fellow (1994–1996) and as an Assistant Research Scientist (1996–1997). In 1997, he joined the Department of Biomedical Engineering at the University of Iowa, where he is currently an Associate Professor. His research focuses on medical image processing and analysis.

Dr. Reinhardt is a fellow of the AIMBE and an Associate Editor of the IEEE TRANSACTIONS ON MEDICAL IMAGING.



Bram van Ginneken (A'01–M'04) studied physics at the Eindhoven University of Technology, Eindhoven, The Netherlands, and at Utrecht University, Utrecht, the Netherlands. In 2001, he received the Ph.D. degree from Utrecht University for work carried out at the Image Sciences Institute, University Medical Center Utrecht, on computer-aided diagnosis in chest radiography.

He is currently working as an Associate Professor at the Image Sciences Institute. His research interests include pattern recognition, image segmentation and computer-aided diagnosis.

Dr. van Ginneken is Associate Editor of IEEE TRANSACTIONS ON MEDICAL IMAGING.

Milan Sonka (M'94–SM'00–F'02) received the Ph.D. degree in 1983 from the Czech Technical University, Prague, Czechoslovakia.

He is Professor of Electrical and Computer Engineering at the University of Iowa, Iowa City, His research interests include medical imaging and knowledge-based image analysis. A major focus of his research in the last several years has been on the development of clinically applicable automated techniques for cardiovascular analysis, pulmonary CT image analysis, cell tracking and cellular shape analysis, and augmented reality image-based surgical planning. He is the first author of the book Image Processing, Analysis and Machine Vision published in 1993 by Chapman and Hall in London, second edition 1998 by PWS, Pacific Grove, California. He has co-authored or co-edited 10 other books including the Handbook of Medical Imaging, Volume II-Medical Image Processing and Analysis published in 2000. He has authored seven book chapters, more than 60 journal papers, 160 conference papers, and 60 abstracts.

Dr. Sonka is a fellow of the AIMBE. He is Associate Aditor of the IEEE TRANSACTIONS ON MEDICAL IMAGING and member of the editorial board of the *International Journal of Cardiovascular Imaging*.