CHAPTER 1

Introduction to Medical Imaging and Image Analysis: A Multidisciplinary Paradigm

Atam P Dhawan, HK Huang and Dae-Shik Kim

Recent advances in medical imaging with significant contributions from electrical and computer engineering, medical physics, chemistry, and computer science have witnessed a revolutionary growth in diagnostic radiology. Fast improvements in engineering and computing technologies have made it possible to acquire high-resolution multidimensional images of complex organs to analyze structural and functional information of human physiology for computer-assisted diagnosis, treatment evaluation, and intervention. Through large databases of vast amount of information such as standardized atlases of images, demographics, genomics, etc. new knowledge about physiological processes and associated pathologies is continuously being derived to improve our understanding of critical diseases for better diagnosis and management. This chapter provides an introduction to this ongoing knowledge quest and the contents of the book.

1.1 INTRODUCTION

In a general sense, medical imaging refers to the process involving specialized instrumentation and techniques to create images or relevant information about the internal biological structures and functions of the body. Medical imaging is sometimes categorized, in a wider sense, as a part of radiological sciences. This is particularly

PRINCIPLES AND ADVANCED METHODS IN MEDICAL IMAGING AND IMAGE ANALYSIS

relevant because of its most common applications in diagnostic radiology. In clinical environment, medical images of a specific organ or part of the body are obtained for clinical examination for the diagnosis of a disease or pathology. However, medical imaging tests are also performed to obtain images and information to study anatomical and functional structures for research purposes with normal as well as pathological subjects. Such studies are very important to understand the characteristic behavior of physiological processes in human body to understand and detect the onset of a pathology. Such an understanding is extremely important for early diagnosis as well as developing a knowledge base to study the progression of a disease associated with the physiological processes that deviate from their normal counterparts. The significance of medical imaging paradigm is its direct impact on the healthcare through diagnosis, treatment evaluation, intervention and prognosis of a specific disease.

From a scientific point of view, medical imaging is highly multidisciplinary and interdisciplinary with a wide coverage of physical, biological, engineering and medical sciences. The overall technology requires direct involvement of expertise in physics, chemistry, biology, mathematics, engineering, computer science and medicine so that useful procedures and protocols for medical imaging tests with appropriate instrumentation can be developed. The development of a specific imaging modality system starts with the physiological understanding of the biological medium and its relationship to the targeted information to be obtained through imaging. Once such a relationship is determined, a method for obtaining the targeted information using a specific energy transformation process, often known as physics of imaging, is investigated. Once a method for imaging is established, proper instrumentation with energy source(s), detectors, and data acquisition systems are designed and integrated to physically build an imaging system for imaging patients to obtain target information in the context of a pathological investigation. For example, to obtain anatomical information about internal organs of the body, X-ray energy may be used. The X-ray energy, while transmitted through the body, goes through attenuation based on the density of the internal structures. Thus, the attenuation of the X-ray energy carries the target information about the density of internal structures which is then displayed as a two-dimensional (in case of radiography or mammography) or multidimensional (3D in case computed tomography (CT); 4D in case of cine-CT) image. This information (image) can be directly interpreted by a radiologist or further processed by a computer for image processing and analysis for better interpretation.

With the evolutionary progress in engineering and computing technologies in the last century, medical imaging technologies have witnessed a tremendous growth that has made a major impact in diagnostic radiology. These advances have revolutionarized healthcare through fast imaging techniques; data acquisition, storage and analysis systems; high resolution picture archiving and communication systems; information mining with modeling and simulation capabilities to enhance our knowledge base about the diagnosis, treatment and management of critical diseases such as cancer, cardiac failure, brain tumors and cognitive disorders.

Figure 1 provides a conceptual notion of the medical imaging process from determination of principle of imaging based on the target pathological investigation to acquiring data for image reconstruction, processing and analysis for diagnostic, treatment evaluation, and/or research applications.

There are many medical imaging modalities and techniques that have been developed in the past years. Anatomical structures can be effectively imaged today with X-ray computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, and optical imaging methods. Furthermore, information about physiological structures with respect to metabolism and/or functions, can be obtained through nuclear medicine [single photon emission computed tomography (SPECT) and positron emission tomography (PET)], ultrasound, optical fluorescence, and several derivative protocols of MRI such as fMRI, diffusion-tensor MRI, etc.

The selection of an appropriate medical imaging modality is important for obtaining the target information for a successful pathological investigation. For example, if information has to be obtained about the cardiac volumes and functions associated with

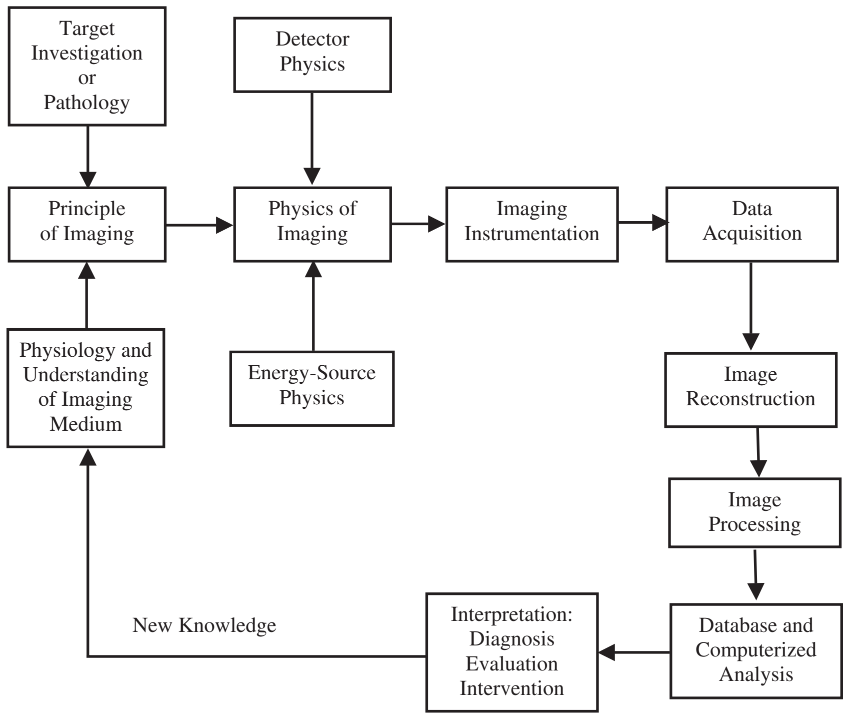

Fig. 1. A conceptual block diagram of medical imaging process for diagnostic, treatment evaluation and intervention applications.

a beating heart, one has to determine the requirements and limitations about the spatial and temporal resolution for the target set of images. It is also important to keep in mind the type of pathology being investigated for the imaging test. Depending on the investigation, such as metabolism of cardiac walls, or opening and closing measurements of mitral valve, a specific medical imaging modality (e.g. PET) or a combination of different modalities (e.g. stress-PET and ultrasound) can be selected.

1.1.1 Book Chapters

In this book, we present a collection of carefully written chapters to describe principles and recent advances of major medical imaging modalities and techniques. Case studies and data analysis protocols are also described for investigating selected critical pathologies. We hope that this book will be useful for engineering as well as clinical students and researchers. The book presents a natural progression of technology development and applications through the chapters that are written by leading and renowned researchers and educators. The book is organized in three parts: Principles of Imaging and Image Analysis (Chapters 2–10); Recent Advances in Medical Imaging and Image Analysis (Chapters 11–23); and Medical Imaging Applications, Case Studies and Future Trends (Chapters 24–32).

Chapter 2 describes some basic principles of medical imaging and image formation. In this chapter, Atam Dhawan has focused on a basic mathematical model of image formation for a linear spatially invariant imaging system.

In Chapter 3, Brent Liu and HK Huang present basic principles of X-ray imaging modalities. X-ray radiography, mammography, computed tomography (CT) and more recent PET-XCT fusion imaging systems are described.

Principles of nuclear medicine imaging are described by Lionel Zuckier in Chapter 4 where he provides foundation and clinical applications of single photon emission tomography (SPECT) and positron emission tomography (PET).

In Chapter 5, Itamar Ronen and Dae-Shik Kim describes sophisticated principles and imaging techniques of Magnetic Resonance Imaging (MRI). Imaging parameters and pulse techniques for useful MR imaging are presented.

Elisa Konofagou presents the principles of ultrasound imaging in Chapter 6. Instrumentation and various imaging methods with examples are described.

In Chapter 7, Atam Dhawan describes the foundation of multidimensional image reconstruction methods. A brief introduction of different types of transform and estimation methods is presented.

Atam Dhawan presents a spectrum of image enhancement, restoration and filtering operations in Chapter 8. Image processing methods in spatial (image) domain as well as frequency (Fourier) domain are described. In Chapter 9, Atam Dhawan describes basic image segmentation and feature extraction methods for representation of regions of interest for classification.

In Chapter 10, Atam Dhawan and Shuangshuang Dai present principles of pattern recognition and classification. Genetic algorithm based feature selection and nonparametric classification methods are also described for image/tissue classification for diagnostic applications.

Advances in MR imaging with respect to new methods and pulse sequences associated with functional imaging of brain are described by Dae-Shik Kim in Chapter 11. Diffusion and diffusion-tensor based magnetic resonance imaging methods are described by Dae-Shik Kim and Itamar Ronen in Chapter 12. These two chapters bring the most recent developments in functional brain imaging to investigate neuronal information including homodynamic response and axonal pathways.

Chapter 13 provides a spectrum of optical and fluorescence imaging for 3-D tomographic applications. Through specific contrast imaging methods, Sachin Patwardhan, Walter Akers and Sharon Bloch explore molecular imaging applications.

In Chapter 14, Qi Duan, Elsa Angelini, Shunichi Homma and Andrew Laine presents recent investigations in dynamic ultrasound image analysis for tracking endocardium in 4D cardiac imaging.

Chien-Min Kao, Emil Y. Sidky, Patrick LaRiviere, and Xiaochuan Pan describe recent advances in model based multidimensional image reconstruction methods for medical imaging applications in Chapter 15. These methods use multivariate statistical estimation methods in image reconstruction.

Shape-based optical image reconstruction of specific entities from multispectral images of skin lesions is presented by Song Wang and Atam Dhawan in Chapter 16.

Clinical multimodality image registration and fusion methods with nuclear medicine and optical imaging are described by Pat Zanzonico in Chapter 17. Pat emphasizes on clinical needs of localization of metabolic information with real time processing and efficiency requirements.

Recently wavelet transform has been extensively investigated for obtaining localized spatio-frequency information. The use of wavelet transform in medical image processing and analysis is described by Atam Dhawan in Chapter 18.

Medical image processing and analysis often require a multiclass characterization for image contents. Atam Dhawan presents a probabilistic multiclass tissue characterization method for MR brain images in Chapter 19.

In Chapter 20, Mathieu De Craene and Alejandro F Frangi present a review of advances in image registration methods for constructing standardized computational atlases.

In Chapter 21, HK Huang, Zheng Zhou and Brent Liu describe information processing and computational methods to deal with large image archiving and communication corresponding to large medical image databases.

Brent Lu, in Chapter 22, describes knowledge mining and decision making strategies for medical imaging applications in radiation therapy planning and treatment.

With large image archiving and communication systems linked with large image databases, information integrity becomes a critical issue. In Chapter 23, Zheng Zhou, HK Huang and Brent J Liu present lossless digital signature embedding methods in multidimensional medical images for authentification and integrity.

Medical imaging applications in intensity modulated radiation therapy (IMRT), a radiation treatment protocol, are discussed by Yulin Song in Chapter 24.

In Chapter 25, Maria Law presents the detailed role of medical imaging based computer assisted protocols for radiation treatment planning and delivery.

Recently developed fMR and diffusion-MR imaging methods provide overwhelming volumes of image data. A productive and useful analysis of targeted information extracted from such MR images of brain is a challenging problem. In Chapter 26, Angela Laird, Jack Lancaster and Peter Fox describe recently developed maximum likelihood estimation based "meta" analysis algorithms for the investigation of a specific pathology. In Chapter 27, Christos Davatzikos presents dynamic brain mapping methods for analysis of patient specific information for better pathological characterization and diagnosis. Tianming Liu and Stephen Wong, in Chapter 28, explore a recently developed model-based image analysis algorithms for analyzing diffusion-tensor MR brain images for the characterization of neurological disorders.

Model-based intelligent analysis and decision-support tools are important in medical imaging for computer-assisted diagnosis and evaluation. Xiang Sean Zhou, in Chapter 29, presents specific challenges of intelligent medical image analysis, specifically for the interpretation of cardiac ultrasound images. However, the issues raised in this chapter could be extended to other modalities and applications. In Chapter 30, Yulin Song and Guang Li present an overview of future trends and challenges in radiation therapy methods that closely linked with high resolution multidimensional medical imaging.

Heinz U Lemke and Leonard Berliner, in Chapter 31, describes specific methods and information technology (IT) issues in dealing with image management systems involving very large databases and widely networked image communication systems.

To conclude, Chapter 32 presents a glimpse of future trends and challenges in high-resolution medical imaging, intelligent image analysis, and smart data management systems.