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Chapter 1
Introduction

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Medical imaging informatics is the rapidly evolving field that combines biomedical informatics and imaging, developing and adapting core methods in informatics to improve the usage and application of imaging in healthcare; and to derive new knowledge from imaging studies. This chapter introduces the ideas and motivation behind medical imaging informatics. Starting with an illustration of the importance of imaging in today's patient care, we demonstrate imaging informatics' potential in enhancing clinical care and biomedical research. From this perspective, we provide an example of how different aspects of medical imaging informatics can impact the process of selecting an imaging protocol. To help readers appreciate this growing discipline, a brief history is given of different efforts that have contributed to its development over several decades, leading to its current challenges.

What is Medical Imaging Informatics?

Two revolutions have changed the nature of medicine and research: medical imaging and biomedical informatics. First, medical imaging has become an invaluable tool in modern healthcare, often providing the only *in vivo* means of studying disease and the human condition. Through the advances made across different imaging modalities, majors insights into a range of medical conditions have come about, elucidating matters of structure and function. Second, the study of biomedical informatics concerns itself with the development and adaptation of techniques from engineering, computer science, and other fields to the creation and management of medical data and knowledge. Biomedical informatics is transforming the manner by which we deal and think with (large amounts of) electronic clinical data. *Medical imaging informatics* is the discipline that stands at the intersection of biomedical informatics and imaging, bridging the two areas to further our comprehension of disease processes through the unique lens of imaging; and from this understanding, improve clinical care.

Beyond the obvious differences between images and other forms of medical data, the very nature of medical imaging set profound challenges in automated understanding and management. While humans can learn to perceive patterns in an image – much as a radiologist is trained – the nuances of deriving knowledge from an image still defy the best algorithms, even with the significant strides made in image processing and computer vision. Imaging informatics research concerns itself with the full spectrum of low-level concepts (*e.g.,* image standardization; signal and image processing) to higher-level abstractions (*e.g.,* associating semantic meaning to a region in an image; visualization and fusion of images) and ultimately, applications and the derivation of new knowledge from imaging. Notably, medical imaging informatics addresses not only the images themselves, but encompasses the associated data to understand the context of the imaging study; to document observations; and to correlate and reach new conclusions about a disease and the course of a medical problem.

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The Process of Care and the Role of Imaging

From a high-level perspective, the healthcare process can be seen in terms of three clinical questions (Fig. 1.1), each related to aspects of the scientific method. For a given patient, a physician has to: 1) ascertain what is wrong with the patient (identify the problem, develop a hypothesis); 2) determine the seriousness of a patient's condition by performing diagnostic procedures (experiment); and 3) after obtaining all needed information, interpret the results from tests to reach a final diagnosis and initiate therapy (analyze and conclude). At each point, medical imaging takes on a critical role:

1. What is wrong? Patient presentation, for the most part, is relatively subjective. For example, the significance of a headache is usually not clear from a patient's description (*e.g., my head throbs*). Imaging plays a major role in objectifying clinical presentations (*e.g.,* is the headache secondary to a brain tumor, intracranial aneurysm, or sinusitis?) and is an optimal diagnostic test in many cases to relate symptoms to etiology. In addition, when appropriately recorded, imaging serves as the basis for shared communication between healthcare providers, detailing evidence of current and past medical findings.
2. How serious is it? For many conditions, the physical extent of disease is visually apparent through imaging, allowing us to determine how far spread a problem has become (*e.g.,* is it confined to a local environment or is it systemic?). Moreover, imaging is progressively moving from qualitative to quantitative assessment. Already, we use imaging to document physical state and the severity of disease: tumor size in cancer patients; dual energy x-ray absorptiometry (DXA) scores in osteoporosis; cardiothoracic ratios; arterial blood flow assessment based on Doppler ultrasound; and coronary artery calcification scoring are all rudimentary metrics that quantify disease burden. On the horizon are more sophisticated quantitative imaging techniques that further characterize biophysical phenomena.
3. What to do? Treatment is contingent on an individual's response: if a given drug or intervention fails to have the desired effect, a new approach must be taken to resolve the problem. For many diseases, response assessment is done through imaging: baseline, past, and present studies are compared to deduce overall behavior. By way of illustration, many of today's surgical procedures are assessed on a follow-up imaging study; and the effects of chemotherapy are tracked over time (*e.g.,* is the tumor getting smaller?). Additionally, contemporary image-guided interventional techniques are opening new avenues of treatment.

As the ubiquity and sophistication of imaging grows, methods are needed to fully realize its potential in daily practice and in the full milieu of patient care and medical research. The study of medical imaging informatics serves this function.

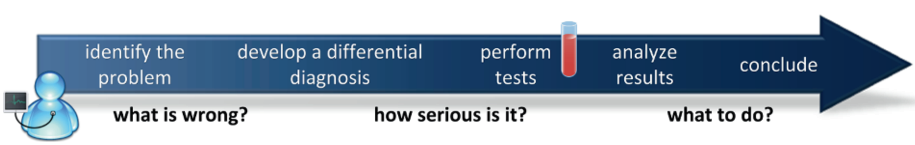

Figure 1.1: The process of care can be roughly summarized in three stages: 1) *what is wrong*, which entails identifying the problem and establishing a differential diagnosis; 2) *how serious is it*, which involves testing the differential diagnosis and determining the extent of the problem; and 3) *what to do*, which based on analysis of test results, concludes with a treatment decision.

Medical Imaging Informatics: From Theory to Application

There are two arms to medical imaging informatics: the development of core informatics theories and techniques that advance the field of informatics itself; and the translation of these techniques into an application that improves health. To demonstrate, we first consider the reasons for the improper use of imaging today, and then how imaging informatics can impact these issues.

Improving the Use of Imaging

The process of providing an accurate, expedient medical diagnosis via imaging can fail for several reasons (Fig. 1.2):

- Sub-optimal study selection. The first potential point of failure arises when an imaging study is requested. Given the fairly rapid changes across all elements of imaging technology, it is unrealistic to believe that a physician can always make up-to-date if not optimal decisions about an imaging exam [9]. Thus, the wrong study may be requested for a given patient. To reduce this problem, practice guidelines have been introduced, but are often generic and do not take into account the specific condition of the patient.
- Poor acquisition. The next potential point of failure occurs during study acquisition. Problems arise due to poor instrumentation (*e.g.,* sensitivity), equipment calibration, poor data acquisition methods, or poor technique. For example, due to the very technical nature of imaging procedures, the average clinician is unable to determine the most specific diagnostic protocol; this process is often left to a technologist or radiologist, who without fully knowing the context of the patient, may not use ideal acquisition parameters.
- Poor interpretation. Study interpretation presents an additional point for potential failure. Poor study interpretation can be due to inadequate historical medical information, poor information filtering/presentation, or poor/mismatched skills by the study reader. Studies have shown that historical clinical information can improve the perception of certain radiographic findings [3]. Poor information presentation often leads to important data being buried within the medical record. Finally, study reading itself can be improved by providing users with the facility to retrieve relevant data from online medical literature, or by choosing the best-matched readers (*i.e.,* generalist vs. specialist) for a particular exam. However, currently available search techniques do not support specific and directed retrievals and no electronic framework exists for efficiently matching a given exam with the most appropriate reader for that exam.

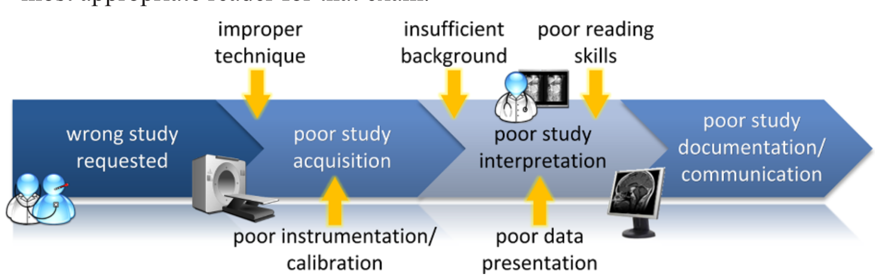

Figure 1.2: Identification of potential problems in the diagnostic process. In emergency cases, the process may also fail due to excessively long times to completion.

- Poor reporting. The last potential point of failure concerns reporting of study results, which is a key concern in the coordination of care as related to the diagnosis and intervention for a given case. This lack of coordination is due to: 1) poor documentation of study results; and 2) difficulties communicating the results of tests to referring healthcare providers. These inefficiencies can lead to problems such as initiating treatment before a definitive diagnosis is established, and duplicating diagnostic studies.

From this perspective, medical imaging informatics aims to improve the use of imaging throughout the process of care. For example, what is the best imaging method to assess an individual's given condition? Are there image processing methods that can be employed to improve images post-acquisition (*e.g.,* histogram correction, denoising, etc.)? These and other questions motivate medical imaging informatics research. Indeed, imaging plays a significant role in the evaluation of patients with complex diseases. As these patients also account for the majority of expenses related to healthcare, by improving the utility of imaging, cost savings can potentially be realized.

Choosing a Protocol: The Role of Medical Imaging Informatics

To further highlight the role of medical imaging informatics, we consider the task of choosing an imaging protocol when a patient first presents in a doctor's office, addressing issues related to sub-optimal study design. When a primary care physician (PCP) decides to obtain an imaging study to diagnosis or otherwise assess a problem, the question arises as to which imaging modality and type of study should be ordered. Furthermore, the ability to make the best decisions regarding a patient is variable across individual physicians and over time. Individual physician biases often creep into decision making tasks and can impact the quality and consistency of healthcare provided [1, 6].

To ground this discussion, we use an example of a 51 year-old female patient who visits her PCP complaining of knee pain. The selection of an appropriate imaging protocol to diagnosis the underlying problem can be thought of in three steps: 1) standardizing the patient's chief complaint, providing a structured and codified format to understand the individual's symptoms; 2) integrating the patient's symptoms with past evidence (*e.g.,* past imaging, medical history, etc.) to assess and to formulate a differential diagnosis; and 3) selecting and tailoring the imaging study to confirm (or deny) the differential diagnosis, taking into account local capabilities to perform and evaluate an imaging study (there is no point in ordering a given exam if the scanner is unavailable or unable to perform certain sequences). We elaborate on each of the steps below, illustrating current informatics research and its application.

Capturing the chief complaint. As mentioned earlier, a patient's description of his or her symptoms is very subjective; for physicians – and computers more so – translating their complaints into a "normalized" response (such as from a controlled vocabulary) is tricky. For instance, with our example patient, when asked her reason for seeing her doctor, she may respond, "My knee hurts a lot, frequently in the morning." Consider the following two related problems: 1) mapping a patient-described symptom or condition to specific medical terminology/disease (*e.g.,* knee hurts = knee pain → ICD-9 719.46, *Pain in joint involving lower leg*); and 2) standardizing descriptive terms (adjectives, adverbs) to the some scale (*e.g.,* Does "a lot" mean a mild discomfort or a crippling pain? Does "frequently" mean every day or just a once a week?).

Several informatics endeavors related to the automated structuring of data are pertinent here. Electronic collections of validated questionnaires are being created, formally defining pertinent positive/negative questions and responses (*e.g.,* see the National Institutes of Health (NIH) PROMIS project [7] and related efforts by the National Cancer Institute, NCI). Such databases provide a foundation from which chief complaints and symptoms can be objectified and quantified with specificity: duration, severity, timing, and activities that either trigger or relieve the symptom can be asked. Likewise, existing diagnostic guidelines intended for non-physicians, such as the American Medical Association Family Medical Guide [5], can be turned into online, interactive modules with decision trees to guide a patient through the response process. Markedly, an inherent issue with such questionnaires is determining how best to elicit responses from patients; aspects of visualization and human-computer interaction (HCI) thus also come into play (see Chapter 4). Apart from structured formats, more complicated methods such as medical natural language processing (NLP) can be applied to structure the statement by the patient, identifying and codifying the chief complaint automatically. Chapter 6 provides an overview of NLP research and applications.

Assessing the patient. The chief complaint provides a basis for beginning to understand the problem, but a clinician will still require additional background to establish potential reasons for the knee pain. For example, does the patient have a history of a previous condition that may explain the current problem? Has this specific problem occurred before (*i.e.,* is it chronic) or did any specific past event cause this issue (*e.g.,* trauma to the knee)? The answers to these questions are all gleaned from questioning the patient further and an exploration of the medical record.

An array of medical and imaging informatics research is ongoing to enrich the electronic medical record's (EMR) functionality and to bring new capabilities to the point of care. A longstanding pursuit of the EMR is to provide an automated set of relevant information and a readily searchable index to patient data: rather than manually inspect past reports and results, the system should locate germane documents, if not permit the physician to pose a simple query to find key points. Informatics work in distributed information systems concentrates on the problems of data representation and connectivity in an increasingly geographically dispersed, multidisciplinary healthcare environment. Patients are commonly seen by several physicians, who are often at different physical locations and institutions. As such, a patient's medical history may be segmented across several disparate databases: a core challenge of informatics is to find effective ways to integrate such information in a secure and timely fashion (see Chapter 3). For imaging, past exams should be made available; but instead of the whole study, only (annotated) sentinel image slices that detail a problem could be recalled. Although manual image capture and markup is presently used, automated techniques are being investigated to identify anatomical regions and uncover potential abnormalities on an image (*e.g.,* CAD); and to segment and quantify disease based on domain knowledge (see Chapter 5). For textual data, such as generated from notes and consults (*e.g.,* a radiology report), NLP techniques are being developed to facilitate content indexing (see Chapter 6). To aggregate the information into a useful tool, a data model that matches the expectations of the clinician must be used to organize the extracted patient data (see Chapter 7), and it must then be presented in a way conducive to thinking about the problem (see Chapter 4).

Specifying the study. Based on the patient's responses and review of her record, the PCP wishes to differentiate between degenerative joint disease and a meniscal tear. If a patient complains of knee pain, then traditionally as a first step an x-ray is obtained. But if the patient's symptoms are suggestive of pain when going up stairs, then a knee magnetic resonance (MR) imaging study is warranted over an x-ray (this symptom being suggestive of a meniscal tear). When asked whether going up stairs aggravates the knee pain, the patient indicated that she was unsure. Thus, her PCP must now make a decision as to what imaging test should be ordered. Furthermore, the selection of the imaging exam must be tempered by the availability of the imaging equipment, the needed expertise to interpret the imaging study, and other potential constraints (*e.g.,* cost, speed of interpretation, etc.).

First, supporting the practice of evidence-based medicine (EBM) is a guiding principle of biomedical informatics, and hence medical imaging informatics. The development and deployment of practice guidelines in diagnosis and treatment has been an enduring effort of the discipline, suggesting and reminding physicians on courses of action to improve care. For instance, if the patient's clinician was unaware of the sign of a meniscal tear, the system should automatically inform him that an MR may be indicated if she has knee pain when climbing stairs; and supporting literature can be automatically suggested for review. Second, formal methods for medical decision-making are central to informatics, as are the representation of medical knowledge needed to inform the algorithms [10]. Techniques from computer science, ranging from rudimentary rule-bases to statistical methods (*e.g.,* decision trees); through to more complex probabilistic hidden Markov models (HMMs) and Bayesian belief networks (BBNs) are finding applications in medicine (see Chapter 8). For example, the evidence of the patient's medical history, her response to the physician's inquiries, the availability of imaging, and the relative urgency of the request can be used in an influence diagram to choose between the x-ray and MR (see Chapter 9). Such formalizations are providing new tools to model disease and to reason with partial evidence. Essential to the construction of many of these models is the compilation of large amounts of (observational) data from which data mining and other computational methods are applied to generate new knowledge. In this example, these disease models can be used: to identify further questions that can be asked to further elucidate the patient's condition (improving the likelihood of choosing an optimal imaging exam); and to select the type of imaging study, and even its acquisition parameters, to best rule in/out elements of the differential diagnosis.

Ultimately, an electronic imaging infrastructure that expedites accurate diagnosis can improve the quality of healthcare; and even within this simple example of choosing an imaging protocol, the role of informatics is apparent in enhancing the process of care. When used appropriately, medical imaging is effective at objectifying the initial diagnostic hypothesis (differential diagnosis) and guiding the subsequent work-up. Given a chief complaint and initial assessment data, one can envision that specialists or software algorithms would select an imaging protocol for an appropriate medical condition even before a visit to the PCP. The PCP can then access both objective imaging and clinical data prior to the patient's visit. Medical imaging informatics research looks to improve the fundamental technical methods, with ensuing translation to clinical applications.

Cost Considerations

Some have targeted the cost of imaging as a major problem in healthcare within the United States: one 2005 estimate by the American College of Radiology (ACR) was that $100 billion is spent annually on diagnostic imaging, including computed tomography (CT), MR, and positron emission tomography (PET) scans [2]. While acknowledging that many factors are contributing to these high costs it is, however, important to separate out two issues: the healthcare cost savings generated as a result of imaging, in light of earlier diagnoses and quality of life; and the *true* cost of performing an imaging study (*i.e.,* versus what is charged).

An "appropriate" process of care that disregards issues related to utilization review and approvals required for imaging studies can be very effective for care of the patient as well as cost-effective. In one study performed by us for a self-insured employer group, we removed all of the requirements for (pre-)approval of imaging studies and allowed primary care physicians to order imaging based on their diagnostic hypothesis and the need of the patient. The imaging costs were instead capitated for the employer group. The number of cross-sectional images, particularly CT and MR, more than doubled and the number of projectional images decreased. However, the net effect was not only significant cost savings to the employer group but also much higher quality and satisfaction by patients [12]. A follow-up study further showed improved health (lowered incidence of chronic disease, decreased number of hospitalizations and emergency room visits, etc.), continued high levels of patient satisfaction, and lowered expenditures within the cost-capitated imaging environment relative to a control group [4]. All of this is to suggest that it is not necessarily the overuse of imaging that is inherently costly, and that there are in fact cost-savings introduced through the unrestricted use of imaging. Of course, a capitated cost agreement with unfettered usage of imaging is not the norm. Unfortunately, the cost of imaging studies is rarely the true cost of performing the study. As an example, presently charges for a brain MR imaging study with and without contrast are in excess of $7,000 at some institutions – largely because of professional fees and attempts to recoup costs (*e.g.,* from non-paying and uninsured individuals). Yet in one internal study we conducted in the 1990s to understand the real cost of CTs and MRs, it was concluded that the price of an MR study is no more than $200 and the price of a CT less than $120. These costs included technologists time, materials used (*e.g.,* contrast) and the depreciation of the scanning machines over five years. Even adjusting for inflation and a moderate professional fee, one can argue that the charges seen today for imaging largely outpace the true cost of the exam. Hence, a current practical challenge for medical imaging informatics is to develop new paradigms of delivery that will encourage the use of imaging throughout the healthcare environment while still being cost-effective.

A Historic Perspective and Moving Forward

Medical imaging informatics is not new: aspects of this discipline have origins spanning back over two or more decades [14]. As such, it is useful to consider this field's interdisciplinary evolution to understand its current challenges and future. Below, we consider four different eras of technical research and development.

PACS: Capturing Images Electronically

Concurrent to the progress being made with respect to CT and MR imaging, initial efforts to create an electronic repository for (digital) imaging in the 1980s led to the creation of picture archive and communication systems (PACS). [8, 11] provide some perspective on the early development of PACS, which focused on linking acquisition devices (*i.e.,* scanners), storage, intra-site dissemination of studies, and display technologies (soft and hard copy). With the introduction of PACS, some of the physical limitations of film were overcome: images were now available anywhere within an institution via a display workstation, and multiple individuals could simultaneously view the same study. Preliminary work also highlighted the need to integrate PACS with other aspects of the healthcare environment and for common data standards to be adopted. Development of the latter was spearheaded by a joint commission of the ACR in conjunction with the National Electrical Manufacturer's Association (NEMA), later leading to establishment of the now well-known DICOM (Digital Imaging and Communication in Medicine) standard. While some academic research in PACS is still being performed today, arguably much of this work has transitioned to industry and information technology (IT) support.

Teleradiology: Standardizing Data and Communications

In 1994, DICOM version 3.0 was released, setting the stage for digital imaging and PACS to be embraced across a broader section of the healthcare arena. At the same time, MR and CT scanners were becoming widespread tools for clinical diagnosis. Recognizing early on the potential for data networks to transmit imaging studies between sites, and partly in response to a shortage of (subspecialist) radiologists to provide interpretation, the next major step came with teleradiology applications. [18] describes the genesis of teleradiology and its later growth in the mid-1990s. Key technical developments during this era include the exploration of distributed healthcare information systems through standardized data formats and communication protocols, methods to efficiently compress/transmit imaging data, and analysis of the ensuing workflow (*e.g.,* within a hospital and between local/remote sites). Legal policies and regulations were also enacted to support teleradiology. From a clinical viewpoint, the power of teleradiology brought about consolidation of expertise irrespective of (physical) geographic constraints. These forays provided proof positive for the feasibility of telemedicine, and helped create the backbone infrastructure for today's imaging-based multi-site clinical trials. Although DICOM provided the beginnings of standardization, there was a continued need to extend and enhance the standard given the rapid changes in medical imaging. Moreover, researchers began to appreciate the need to normalize the meaning and content of data fields as information was being transmitted between sites [15]. Newer endeavors in this area continue to emerge given changes in underlying networking technology and ideas in distributed architectures. For instance, more recent work has applied grid computing concepts to image processing and repositories.

Integrating Patient Data

Alongside teleradiology, medical informatics efforts started to gain further prominence, launching a (renewed) push towards EMRs. It became quickly evident that while many facets of the patient record could be combined into a single application, incorporating imaging remained a difficultly because of its specialized viewing requirements (both because of the skill needed to interpret the image, and because of its multimedia format). Conversely, PACS vendors encountered similar problems: radiologists using imaging workstations needed better access to the EMR in order to provide proper assessment. Hence in this next major phase of development, processes that were originally conceived of as radiology-centric were opened up to the breadth of healthcare activities, sparking a cross-over with informatics. For example, the Integrating the Healthcare Enterprise (IHE) initiative was spawned in 1998 through HIMSS and RSNA (Healthcare Information and Management Systems Society, Radiological Society of North America), looking to demonstrate data flow between HL7 and DICOM systems. Additionally, drawing from informatics, researchers began to tackle the problems of integration with respect to content standardization: the onset of structured reporting; the creation and use of controlled vocabularies/ontologies to describe image findings; and the development of medical natural language processing were all pursued within radiology as aids towards being able to search and index textual reports (and hence the related imaging). Though great strides have been made in these areas, research efforts are still very active: within routine clinical care, the process of documenting observations largely remains *ad hoc* and rarely meets the standards associated with a scientific investigation, let alone making such data "computer understandable."

Understanding Images: Today's Challenge

The modern use of the adage, "*A picture is worth ten thousand words*," is attributed to a piece by Fred Barnard in 1921; and its meaning is a keystone of medical imaging informatics. The current era of medical imaging informatics has turned to the question of how to manage the content within images. Presently, research is driven by three basic questions: 1) what is in an image; 2) what can the image tell us from a quantitative view; and 3) what can an image, now correlated with other clinical data, tell us about a specific individual's disease and response to treatment? Analyses are looking to the underlying physics of the image and biological phenomena to derive new knowledge; and combined with work in other areas (genomics/proteomics, clinical informatics), are leading to novel diagnostic and prognostic biomarkers. While efforts in medical image processing and content-based image retrieval were made in the 1990s (*e.g.,* image segmentation; computer-aided detection/diagnosis, CAD), it has only been more recently that applications have reached clinical standards of acceptability. Several forces are driving this shift towards computer understanding of images: the increasing amount and diversity of imaging, with petabytes of additional image data accrued yearly; the formulation of new mathematical and statistical techniques in image processing and machine learning, made amenable to the medical domain; and the prevalence of computing power. As a result, new imaging-based models of normal anatomy and disease processes are now being formed.

Knowledge creation. Clinical imaging evidence, which is one of the most important means of *in vivo* monitoring for many patient conditions, has been used in only a limited fashion (*e.g.,* gross tumor measurements) and the clinical translation of derived quantitative imaging features remains a difficulty. And, in some cases, imaging remains the only mechanism for routine measurement of treatment response. For example, a recent study suggests that while common genetic pathways may be uncovered for high-grade primary brain tumors (glioblastoma multiforme, GBM), the highly heterogeneous nature of these cancers may not fully lend themselves to be sufficiently prognostic [17]; rather, other biomarkers, including imaging, may provide better guidance. In particular, as the regional heterogeneity and the rate of mutation of GBMs is high [13], imaging correlation could be important, providing a continuous proxy to assess gene expression, with subsequent treatment modification as needed. In the short-term, the utilization of imaging data can be improved: by standardizing image data, pre- and post-acquisition (*e.g.,* noise reduction, intensity signal normalization/calibration, consistent registration of serial studies to ensure that all observed changes arise from physiological differences rather than acquisition); by (automatically) identifying and segmenting pathology and anatomy of interest; by computing quantitative imaging features characterizing these regions; and by integrating these imaging-derived features into a comprehensive disease model.

One can assume that every picture – including medical images – contain a huge amount of information and knowledge that must be extracted and organized. Knowledge can be conveniently categorized twofold [16]: *implicit*, which represents a given individual's acumen and experience; and *explicit*, which characterizes generally accepted facts. Clearly, implicit knowledge is advanced through current informatics endeavors, as employed by the individual scientist and clinician. But informatics can further serve to create explicit knowledge by combining together the implicit knowledge from across a large number of sources. In the context of healthcare, individual physician practices and the decisions made in routine patient care can be brought together to generate new scientific insights. That is to say that medical imaging informatics can provide the transformative process through which medical practice involving imaging can lead to new explicit knowledge. Informatics research can lead to means to standardize image content, enabling comparisons across populations and facilitate new ways of thinking.

References

1. Aberegg SK, Terry PB (2004) Medical decision-making and healthcare disparities: The physician's role. J Lab Clin Med, 144(1):11-17.
2. American College of Radiology (ACR) (2005) ACR chair tells House Committee unnecessary and inferior medical imaging lowers quality of care, costs taxpayers. American College of Radiology. http://www.acr.org. Accessed April 23, 2009.
3. Berbaum KS, Franken EA, Jr., Dorfman DD, Lueben KR (1994) Influence of clinical history on perception of abnormalities in pediatric radiographs. Acad Radiol, 1(3):217-223.
4. Bui AA, Taira RK, Goldman D, Dionisio JD, Aberle DR, El-Saden S, Sayre J, Rice T, Kangarloo H (2004) Effect of an imaging-based streamlined electronic healthcare process on quality and costs. Acad Radiol, 11(1):13-20.
5. Clayman CB, Curry RH (1992) The American Medical Association Guide to Your Family's Symptoms. 1st updated pbk. edition. Random House, New York.
6. Croskerry P (2002) Achieving quality in clinical decision making: Cognitive strategies and detection of bias. Acad Emerg Med, 9(11):1184-1204.
7. DeWalt DA, Rothrock N, Yount S, Stone AA (2007) Evaluation of item candidates: The PROMIS qualitative item review. Med Care, 45(5 Suppl 1):S12-21.
8. Dwyer III SJ (2000) A personalized view of the history of PACS in the USA. Medical Imaging 2000: PACS Design and Evaluation: Engineering and Clinical Issues, vol 3980. SPIE, San Diego, CA, USA, pp 2-9.
9. Edep ME, Shah NB, Tateo IM, Massie BM (1997) Differences between primary care physicians and cardiologists in management of congestive heart failure: Relation to practice guidelines. J Am Coll Cardiol, 30(2):518-526.
10. Greenes RA (2007) A brief history of clinical decision support: Technical, social, cultural, economic, and governmental perspectives. In: Greenes RA (ed) Clinical Decision Support: The Road Ahead. Elsevier Academic Press, Boston, MA.
11. Huang HK (2004) PACS and Imaging Informatics: Basic Principles and Applications. 2nd edition. Wiley-Liss, Hoboken, NJ.
12. Kangarloo H, Valdez JA, Yao L, Chen S, Curran J, Goldman D, Sinha U, Dionisio JD, Taira R, Sayre J, Seeger L, Johnson R, Barbaric Z, Steckel R (2000) Improving the quality of care through routine teleradiology consultation. Acad Radiol, 7(3):149-155.
13. Kansal AR, Torquato S, Harsh GI, Chiocca EA, Deisboeck TS (2000) Simulated brain tumor growth dynamics using a three-dimensional cellular automaton. J Theor Biol, 203(4):367-382.

14. Kulikowski C, Ammenwerth E, Bohne A, Ganser K, Haux R, Knaup P, Maier C, Michel A, Singer R, Wolff AC (2002) Medical imaging informatics and medical informatics: Opportunities and constraints. Findings from the IMIA Yearbook of Medical Informatics 2002. Methods Inf Med, 41(2):183-189.
15. Kulikowski CA (1997) Medical imaging informatics: Challenges of definition and integration. J Am Med Inform Assoc, 4(3):252-253.
16. Pantazi SV, Arocha JF, Moehr JR (2004) Case-based medical informatics. BMC Med Inform Decis Mak, 4:19.
17. The Cancer Genome Atlas Research Network (2008) Comprehensive genomic characterization defines human glioblastoma genes and core pathways. Nature, 455(7216):1061-1068.
18. Thrall JH (2007) Teleradiology: Part I. History and clinical applications. Radiology, 243(3):613-617.