Digitization of Medicine:

How Radiology Can Take Advantage of the Digital Revolution

King C. Li, MD, MBA, Peter Marcovici, MD, Andrew Phelps, MD, Christopher Potter, MD, Allison Tillack, PhD, Jennifer Tomich, MD, Srini Tridandapani, PhD, MD

In the era of medical cost containment, radiologists must continually maintain their actual and perceived value to patients, payers, and referring providers. Exploitation of current and future digital technologies may be the key to defining and promoting radiology's "brand" and assure our continued relevance in providing predictive, preventive, personalized, and participatory medicine. The Association of University of Radiologists Radiology Research Alliance Digitization of Medicine Task Force was formed to explore the opportunities and challenges of the digitization of medicine that are relevant to radiologists, which include the reporting paradigm, computational biology, and imaging informatics. In addition to discussing these opportunities and challenges, we consider how change occurs in medicine, and how change may be effected in medical imaging community. This review article is a summary of the research of the task force and hopefully can be used as a stimulus for further discussions and development of action plans by radiology leaders.

Key Words: Digitization; systems medicine; radiology informatics.

In the face of Medicare cost containment, all medical subspecialties must strive to eliminate waste and improve both the effectiveness and efficiency of patient care. Radiology has the added challenge of combating commoditization by finding ways to add value (1). Radiology must continually maintain its actual and perceived value to patients, payers, and referring providers. In the business world, this is considered "branding"; maintaining brand value is a constant responsibility of the organization (2). Exploitation of current and future digital technologies may be the key to defining and promoting radiology's "brand" (3).

The three core services of radiology—scheduling, imaging, and reporting—can all be commoditized. Even image interpretation could be affected by computer-aided detection software. But before searching for new avenues of value added, a business struggling with commoditization should start with determining how existing products and services can be redefined to better meet its customers' needs (4). Specific strategies include standardization, bundling, and customization—these strategies address the manner in which the same services are delivered, without actually changing the substance of those services. Standardization of reporting has certainly been an important topic in radiology (5–9) and is discussed later; standardization of scheduling and imaging should also be important goals. One example of bundling radiology services would be to enable a referring clinician to click "schedule the recommended follow-up study" on the same page as the report where the recommendation was made, therein bundling the services of reporting and scheduling. An example of customizing radiology services would be to have a computerized order entry system that allows the provider to check the box "measure tumor volume" or "automatically fax report to my office." In the non–health care setting, consumers have come to expect these standardized customer conveniences from online retailers, and the same expectations should apply to medical care. Failure to incorporate existing digital technologies into current radiology practice only enables the competition (within or outside radiology) to be the first to redefine how commoditized services can be delivered better. One aspect of radiology that cannot be commoditized is personal consultations (for patients and referring physicians) (10). How can digital technologies be used to make radiologists more effective consultants? Picture archiving and communication systems (PACS) may have made it easier for radiologists to isolate themselves, but digital technologies applied in the right way can also improve interpersonal interaction.

In many ways, efficiency in radiology has been driven by PACS, and this efficiency has become the envy of other clinical services. Radiology's success to date has largely relied on building a wall around radiologists so they could focus on interpretation, report generation, and turnaround times. We envision that PACS would continue to provide radiologists with efficiencies in the future; however, the walls would have windows allowing radiologists to communicate with

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From the Department of Radiology, Wake Forest School of Medicine, One Medical Center Boulevard, Winston-Salem, NC 27157 (K.C.L.); UCSF Benioff Children's Hospital, Department of Radiology and Biomedical Imaging, University of California, San Francisco, San Francisco, CA (P.M., A.P.); Department of Radiology, University of Washington School of Medicine, Seattle, WA (C.P.); School of Medicine, University of California, San Francisco, San Francisco, CA (A.T.); Department of Radiology, Eastern Virginia Medical School, Norfolk, VA (J.T.) and Department of Radiology and Imaging Sciences, Emory University, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia (S.T.).
Received June 30, 2013; accepted September 8, 2013. **Address correspondence to:** K.C.L. e-mail: kingli@wakehealth.edu

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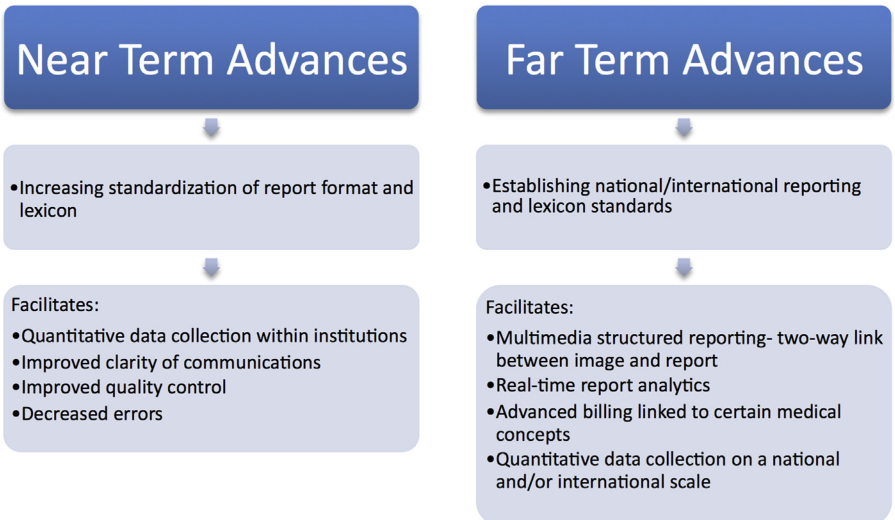

Figure 1. Near- and far-term advances of radiology reporting.

referring clinicians and patients. "Skype"-like (Microsoft Inc, Redmond, WA) technologies can easily be incorporated with PACS workstations to permit such online communications. Patient digital photographs and video-clips can be integrated with medical imaging examinations and serve as additional sources of clinical information that can enhance the interpretation of imaging studies.

Referring clinicians in the future will face more data than any one physician can cope with (clinical, genetic, laboratory, radiologic, etc). Genetic screening will hopefully identify patients at risk for future disease, and those patients will need a lifelong monitoring plan and possibly even prophylactic therapy. If disease is later detected, primary treatment and follow-up will be necessary. Who will keep track of the massive amount of data that will be generated in the life of this patient? Who will analyze past and present data when acute situations arise, warranting prompt diagnosis? The existence of different medical specialties speaks to the fact that one human physician cannot know everything. A single physician cannot be expected to decipher the massive amount of data that modern tests are yielding, and this flood of information will only increase. Within medical specialties, online knowledge databases have been developed to assist in point-of-care clinical specialist decision-making. More data are yet to come, and these fragmented online databases will be inadequate.

There is clearly a need for a centralized information management system, and why not have a single medical specialty to serve as the shepherds for the flow of data, providing patient management and diagnostic decision support? Radiology is arguably in the best position (from an informatics standpoint) to take on this potential role. If radiology does not vie for a greater clinical presence, taking the opportunity to rebrand itself in this medical informatics role (either in part or whole), another specialty will. But how can the field of radiology effect these current, let alone future, changes? Radiology cannot expect to get reimbursed for new services unless those services can be shown to improve patient outcome and/or reduce cost. So, who is going to take the plunge in making the necessary digital technology investments and do the requisite research? Redefining the role of the radiologist in current and future practice will require the concerted effort and buy-in of multiple institutions. Rather than asking, "What can a radiologist do?" we will have more creative freedom by instead simply asking, "What needs to be done?" with all the patient information that is coming our way.

The rest of this white paper is organized as follows: In Section II, the radiology report is discussed, along with ongoing efforts at developing structured reporting and a radiology lexicon, followed by a vision of the future of radiology reporting. In Section III, we discuss megatrends in computational biology and how radiologists may be best adapted to manage this impending medical information explosion. In Section IV, ongoing advances in imaging informatics that have the potential to substantially impact medical imaging are discussed, including computer-assisted detection technologies, digital communication technologies, and the merger of information systems to create links between the radiographic phenotype and the underlying patient/disease genotype. Section V is devoted to a discussion of how change is effected in medicine and provides a roadmap for how we can translate, articulate, standardize, and anticipate changes in medical imaging. Concluding remarks are provided in Section VI.

RADIOLOGY REPORT

In this section, we begin with a discussion of the radiology report and ongoing efforts to create structured reports and a radiology lexicon. These will be followed by a discussion of the future of radiology reporting (Fig 1).

The radiology report serves as the primary method of communication about patients to ordering physicians, and the wider medical community, which increasingly includes patients themselves. In the era of PACS and teleradiology, the radiology report largely represents the product by which radiologists are judged (11). Traditional, or free-text style, reporting entails the radiologist dictating the report in an essay or paragraph format, customizing the format and content to their experience and preference, including or not including specific items of their choice. This leads to a highly personalized radiology report, which, although it may convey the important findings and their meaning, is unlikely to be precisely the same when dictated by another radiologist or the same radiologist at a different time (12,13). Differences in report completeness and/or effectiveness make longitudinal comparison of reports difficult. Traditional reports are prone to internal errors, largely in part because more of the report must be dictated (14). It has been said that the primary benefit of the traditional radiology report is the ease of the dictating radiologist, which, although valid, is not a sufficient justification to continue with the status quo (11).

Structured reporting is a newer form of radiology reporting that aims to standardize both the report format and lexicon. Report standardization serves to potentially increase report completeness and effectiveness, while also capitalizing on the cognitive benefit of checklists (15). Structured reporting, due to its standardized preformatted templates, tends to have reduced internal errors, as fewer phrases, many of which are nonvarying across reports, do not need to be repeatedly spoken (14). Structured reports can be configured to incorporate quantitative aspects of imaging studies, and these can then be continuously referenced over time, potentially building an imaging-based personalized profile of the patient. As reporting systems mature, quantitative aspects of the study could be automatically or semiautomatically extracted from the study and recorded directly into the report, potentially reducing errors. Similarly, structured reporting systems could be designed to digitally extract relevant data from the health information systems at the time of the interpretation, allowing for an improved "global" consult. Additional potential benefits of structured reporting include improvements in quality control (15), improvements in communication clarity (both for an individual and on a department-wide basis) (16–22), and the potential to capture and analyze data more systematically.

For years, one specific branch of radiology, mammography, has used structured reporting, in part related to the federal Mammography Quality Standards Act of 1992. This has been shown to reduce mammography report variability and improve clarity of communication (16). However, the adoption of structured reporting is still limited outside of mammography. The Radiologic Society of North America has an ongoing radiology reporting initiative, which has been tasked with developing structured reporting standards, specifically "evaluating and developing reporting systems, processes, and tools that enable radiology information to be captured, stored, and presented in a clear, organized, and consistent format" (23). This effort has led to a freely available library of best-practice templates, which can be viewed or downloaded on an individual or department basis, as a means to begin creating structured reporting templates for their own use (23).

Radiology Lexicon

At present, there is tremendous variability in the words used by radiologists to convey findings. Although this variability allows flexibility, it also invites confusion. A "lexicon" is defined as a vocabulary of words or notions associated with their meanings, which, if adhered to, allows clarity in communication (24). Furthermore, if the meaning embedded in each word or notion can be linked within an organized hierarchy, the meaning itself can be classified and compared. Importantly, this allows for future searching of meaningful *notions* within reports, not simply exact words or phrases. Radiology reports will eventually be fully and readily searchable by computer (most likely both automatically, to generate ongoing analysis, and manually, for a point-of-care question).

There have been attempts within radiology to standardize or set forth lexicons (notably in mammography, and to some degree in other subspecialties such as chest (6) and spine imaging). For example, a "mass" is defined by the Breast Imaging-Reporting and Data System (BI-RADS) mammography lexicon as "a space-occupying lesion seen in two different projections" (25). Or, in another lexicon designed to describe liver lesions, known as The Liver Imaging Reporting and Data System (LI-RADS), the "arterial phase refers to the hepatic arterial phase unless otherwise specified" (26); by explicitly stating what arterial phase represents, the LI-RADS lexicon provides a standardized vocabulary useful for comparison. Despite these attempts, their use has been limited, perhaps in part by the lack of clearly understood intrinsic word or notion meaning. In addition, these lexicons have not yet established an accepted larger hierarchy of meanings or notions.

Outside of radiology, an illustrative and potentially useful example of a sophisticated lexicon is the ongoing effort by Google called the "The Knowledge Graph" (27). In this project, Google is attempting to assign actual meaning to words in queries, in order to improve search results, and ultimately contribute to their overall corporate mission, which is to "organize the world's information and make it universally accessible and useful." Using existing free online databases as well as its own internal cataloging of the Internet as a whole, Google is systematically creating a lexicon with meanings of words, as well as their relationship within a hierarchy. In so doing, this would allow exactly the kind of comparison and analysis that could be performed on radiology reports, if they adhered to an agreed-on lexicon. No longer, in this form of a system, is the word "bird" unrelated to the word "feather." By extension, when searching for notions or concepts, even if the exact word is not used in the query, the system retains the ability to return meaningful information.

And within radiology, an ongoing Radiologic Society of North America coordinated effort, titled RadLex, is attempting to create a comprehensive vocabulary for radiology reporting (28). This effort is specifically responsible for "creating a single language that can be used to describe salient aspects of an imaging examination (e.g., modality, technique, visual features, anatomy, and pathology)." Similar to the effort by Google, each term in this vocabulary has meaning, including synonyms. Further, the meaning of each term is nested in a hierarchy, allowing relationships to be established and explored. If reports adhere to a standardized lexicon (with embedded meaningful linkage), there is great potential to explore the radiology report database, which currently may be limited by a lack of accepted terminology.

Reporting's Future

If the near future of radiology reporting involves structured reporting and a standardized, meaningfully linked lexicon, there is even more excitement on the horizon. This territory is new, and largely uncharted, and therefore only represents an educated guess.

Initially, the concept of structured reporting will become the norm. Following this, there will be increasing national and perhaps international standards for reporting templates. Like the American College of Radiology (ACR) dose registry, these standards will allow for comparison and larger-scale research. Big data (and its analysis), a loosely defined term emerging from the information technology world meant to describe extremely large data sets, will produce tools that will directly apply to radiology report databases. These databases will become increasingly sophisticated, in large part due to pooled report data from many sources, predicated on the notion that the data must be structured in a similar way, for the purposes of comparison.

Following the widespread introduction of the RadLex Lexicon, the concept will mature and gain acceptance. This will not only enhance report clarity but eventually also may be tied to reimbursement. If the proper and agreed-on word or concept is used, the report may score higher on a scale of reimbursement and enhance the Pay for Performance metric given to that radiologist or department.

Yet later, once structured reporting and lexicons become standardized, the next generation of reporting systems will be developed. First, the notion of "Multimedia Structured Reporting" will emerge, currently being pioneered by David J. Vining, MD, professor of diagnostic radiology and medical director of the Image Processing and Visualization Laboratory at The University of Texas MD Anderson Cancer Center in Houston (29). His product (ViSion), which allows multimedia to be incorporated into the report itself, foresees a time when radiology reports evolve from the text-only era. Further, reporting systems in the future will be electronically linked to the viewing system, allowing direct exporting and two-way linking between image and report to be seamless. No longer will a measurement made on the screen require a dictation to end up in the report; it will happen without an additional step.

Another aspect of the future radiology reporting system will be real-time report-derived analytics. As the report is being made, it will automatically be compared to vast databases of reports, locally or beyond. This will not only allow for feedback to the reporting radiologist (at the time that is most helpful); it will also allow for immediate results incorporation into the medical system at large.

Communication feedback will also be embedded in the reporting system of the future. Not only will the reporting radiologist easily be able to screen share the study with other radiologists or the referring physician (or patient), but built-in live "chat" tools with demographic information capture will facilitate report documentation. These new systems will move from radiology recommendations that may or may not be heeded, to the ability to confirm a variety of end results (such as the report being read, recommended action or follow-up being taken, pathology results being finalized, etc.).

Finally, direct communication of results with referring clinicians and, more importantly, patients will become the norm in several areas of radiology care. Already, Mammography Quality Standards Act requires that "a summary of the written report shall be sent directly to the patient in terms easily understood by a lay person." It is not inconceivable that other areas of radiology reporting will require that patients be informed directly about the results of their imaging studies. The recent positive outcome of the National Cancer Institute's National Lung Screening Trial, which found that screening with the use of low-dose computed tomography (CT) scans reduces mortality from lung cancer (30), may open up another similar venue where radiologists' direct interactions with patients may be valued. As another example, several institutions are already providing such direct patient reporting when they offer coronary calcium scoring as a screening examination; most of the patients presenting for this screening pay out-of-pocket for this examination and thus value, and even expect, the interaction with the radiologist.

Rather than being a stagnant relic of the past, the radiology report of the future will once again serve to remind others of the value of radiology.

Near-term Challenges and Opportunities in Radiology Reporting

The biggest challenge in radiology reporting is the widespread adoption of standard lexicons and structured reporting. This is also the biggest opportunity. If this can be accomplished, radiology will become the first medical specialty to be fully digitized with searchable report contents and easy integration with other digitized data. The following sections will further explain the critical importance of this major step forward.

COMPUTATIONAL BIOLOGY

Just as our communication needs and expectations change with our technologies, the medical information that we need to communicate will change, as well. The changing nature of our medical knowledge, its clinical implications, and opportunities for radiology can be seen in the rise of the newer fields of biology. "Computational biology" is broadly defined as the use of computational techniques to understand biological systems and manage large data sets. These techniques extend from the mapping of the human genome to the mathematical modeling of physiologic systems, such as the lung in the Physiome project (31–33). "Systems biology" is often defined as the study of biologic systems and how they interact at higher levels of order (34). From a top-down approach, systems biologists may use network theory to understand interactions between different systems within an organism and hypothesize new relationships from data patterns that emerge (35–38). The need for these approaches in biology is not a new idea. Even as early as the late 19th century with the idea of homeostasis, championed by Claude Bernard and Walter Cannon, it was hypothesized that networks existed within organisms whose effect was to maintain a constant internal milieu (39,40). However, it was well recognized at the time that complex systemic understanding was beyond the reach of researchers due to available knowledge, equipment, and techniques. Research at the time concentrated on identifying system components, eventually leading to the emergence of molecular biology. In the latter half of the 20th century, the improved understanding of the building blocks of organisms developed along with the exponential growth in computational power. Advances in the development of microarrays and other technologies made possible high-throughput techniques, for example, allowing the analysis of thousands of genes in a single afternoon, compared with one to two genes per month by traditional techniques just decades earlier (41,42). Consequently, investigators are able to evaluate more information in a small system like a cell in a shorter period of time. With increased computational power, complex systems could now be better modeled and tested, such as the interactions of the proteome (43,44). These technological developments finally enabled the emergence of computational and systems biology as productive, viable fields. Moreover, the dramatic increase in the volume of biologic data has now necessitated these approaches, as the patterns and relationships within the data become too complex to analyze without the help of computers (31,45,46).

As we recognize the importance of related interacting systems, efforts have turned to the mapping of the proteome, the metabolome, and other networks of components and interactions that are essential to understanding biologic processes. After the recent development of the Haplotype map, there is an increasing number of genome-wide association studies looking for associations in large populations of alleles and disease, which will enable discovery of multiple gene interactions in disease states (41,42). Genome-wide associations, compiled in a large databank, will lead to improved understanding of penetrance and improved true risk estimation (47,48), estimations that are now limited to highly penetrant, rare monogenetic diseases. At a cellular level, comparative analysis of cancer genomes has made many advances (49) and led to the discovery of dysregulation in certain common key pathways of pancreatic cancer, a finding that may lead to increased targeted research toward pathways that are common in multiple cancers (50,51). In addition, computational methods are also being used to identify and prioritize candidate genes for characterization, so that genes that are likely to be important in a particular system or disease be targeted first for analysis (52,53). Computational models are being developed to model physiologic systems that will allow us to hypothesize new treatment targets and test drug candidates "in silico" (33,54).

Advances in computational and systems biology have made a growing impact not only on biomedical research but also on the expectations of clinicians and patients. There is increasing public awareness and expectation that we discover the genetic origin of disease and develop new individualized strategies of treatment. The rapid acceleration of the mapping of the human genome and the private and public partnership in the effort brought to popular consciousness scientific advances toward personalized medicine. Although most advances and discoveries in computational and systems biology are largely still within the domain of research, they are changing the way that we expect medicine to perform and will transform our clinical experience (55).

There remain large challenges in the translation of -omics information into a clinical context. Present data sets and systems are both rich and poor, as knowledge remains in-depth only in certain areas. Although monogenetic diseases have been explored for the last half-century or longer, our understanding of multigenetic diseases is only now emerging and knowledge of how to quantify and even communicate knowledge about risk and prognosis is early at best. In fact, in some genome-wide association studies, the genetic component of risk is similar to the risk incurred by environmental factors, making the accurate calculation of risk complex and multifactorial (47). Significant advances still need to be made in translating genomics advances into a clinical environment (42,55). However, as data density increases, computational radiology will also increase in importance, through the integration of multiple databases and pattern recognition using new computational techniques (56), such as computer-assisted diagnosis (CAD), which will be discussed in the next section.

As the volume of genomics information evolves, practices of future referring physicians will need to integrate information into the clinic (47,48). However, this body of information is growing far faster than our understanding of its clinical utility. Integrating this information into an already hurried clinical environment will be complex, eventually necessitating the use of large data sets and information management techniques (56). Needing to integrate clinical, laboratory, pathology, genomic, and imaging data, clinicians will increasingly rely on information specialists to assist in the integration and interpretation of the genomics data, just as we have come to rely on genetic counselors for the discussion of risk. We have already seen that in the evaluation of

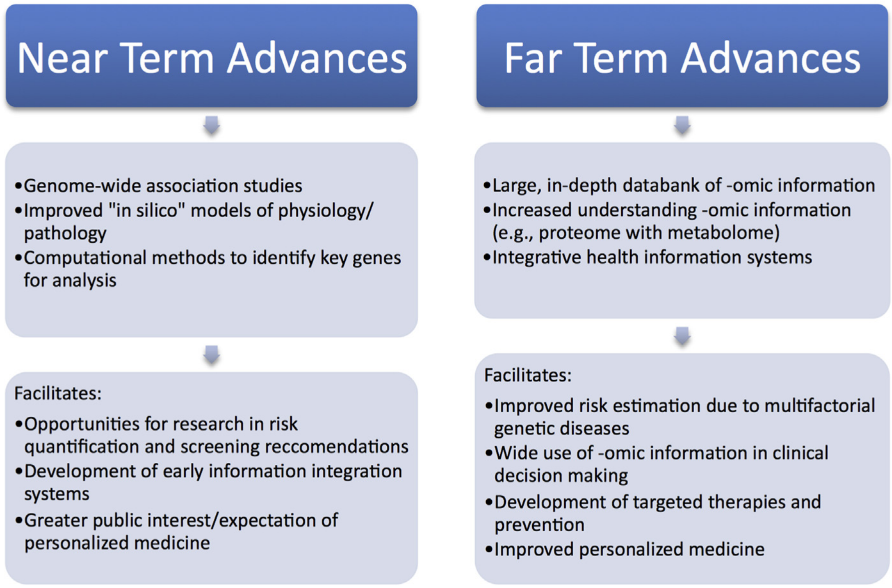

Figure 2. Near- and far-term advances of computational biology.

multigenetic diseases, genetic and environmental risk factors and their interactions become increasingly important. This differs substantially from the old model of monogenetic disease risk evaluation (57–59). Effective integration of these different types of information will be critical to determination of risk and establishment of a treatment plan, including appropriate imaging. In addition to an emerging need for information integration, improved genomic understanding will likely result in increased evidence-based imaging screening and surveillance. Radiologists will play a crucial role in defining appropriateness, containing cost and reducing unnecessary testing and radiation exposure. In addition, with the increasing reliance on nonphysician clinicians in the clinical care team, information integration and specific patient-centered imaging recommendations will be critical for patient care quality and are best provided by radiologists.

Near-term Challenges and Opportunities in Computational Biology

Although most of the recent advances from computational and systems biology remain in the laboratory, they will have a profound effect on medicine in the future (Fig 2). It is still early to contemplate widespread benefit from genomic data. However, it is not too early to further integrate clinical data with image interpretation. Academic radiology in particular can play a key role in advancing medicine through understanding the importance of genomic associations, quantifying risk and defining surveillance needs, methods, and intervals. In the near term, new avenues of radiology research will be needed to translate this information to the clinic. In addition, the present development of efficient systems and reports that integrate imaging with cogent clinical and laboratory data will pave the way for the radiologist of the future to become information consultant, as well as image interpreter.

IMAGING INFORMATICS

In light of the vast amount of information currently available to physicians today, the transition to a patient-centered, genomics-oriented approach will require continued advancements in the field of radiology informatics. While the digitization of imaging has allowed for decentralization and interruption of the previously established radiology value chain, it has also allowed for radiologists to interact with the available data in new and valuable ways using computational analysis for pattern recognition, quantification, and image manipulation. Radiologists should be prepared to embrace these new technologies and accept a greater role in their creation and management within the hospital system.

Figure 3 demonstrates a model for how these emerging informatics systems may be integrated into the daily workflow pattern of image analysis. The traditional pattern of analysis is described within the blue boxes and includes the identification of abnormal findings, followed by characterization and interpretation of those findings. The orange boxes describe how some of the current advances in radiology informatics could be integrated to support this pattern of analysis.

In this section, we will first consider how CAD technologies will affect radiology. Following this, we will discuss how emerging communication technologies will transform the practice of radiology. Finally, we will discuss how linkages can be created between imaging phenotypes and the underlying disease genotype.

CAD

CAD uses advanced pattern recognition software to identify potential regions of abnormality on radiographic studies. This relatively recent advancement in radiology informatics is already widely in use throughout the country, primarily for the detection of breast masses and calcifications on

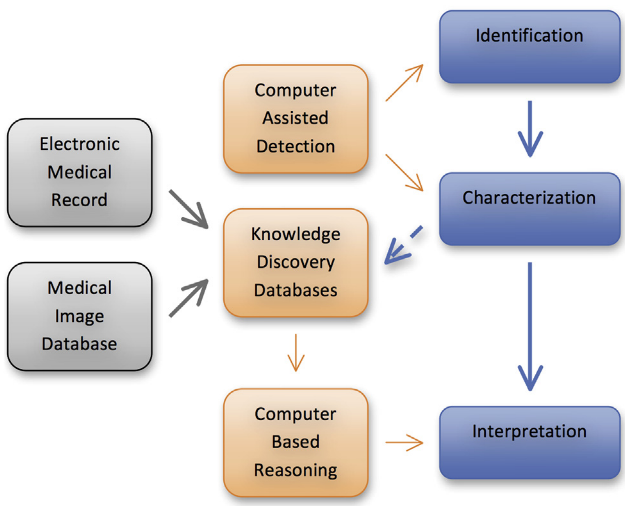

Figure 3. How radiology informatics advancements (*orange boxes*) can be implemented into the traditional method of image interpretation (*blue boxes*). The *gray boxes* demonstrate the integration of previously external sources into the Knowledge Discovery Databases.

mammography. Numerous studies have been conducted on the use of CAD with improved diagnostic sensitivity demonstrated for evaluation of lung nodules on plain radiographs (60,61) and computed tomography (CT) (62), breast nodules on mammography (63), polyps on CT colonography (64), and pulmonary emboli on CT angiography (65). While the proposed CAD algorithms studied have also been shown to result in increased false-positive results, they can be useful in providing the radiologist with a "double-check" system and, importantly, may help to decrease inter-observer variability between radiologists. Additional CAD algorithms have also been developed to systematically characterize patterns of infectious pulmonary infiltrates (66) and tree-in-bud infiltrates on CT (67).

A standardized method of characterization and reporting is essential for application of the knowledge discovery databases (KDDs) and computer decision algorithms to the CAD methods already in development. The KDDs, as described by Reiner, are a network of databases composed of supportive information that allow for patient-specific analysis of the reported radiographic findings. The databases are created from information obtained from the patient's integrated electronic medical record (EMR), radiographic findings, and standardized medical image databases (68). Essentially, they would provide integration of important patient data and knowledge resources, thereby streamlining the workflow and eliminating wasted time searching through different systems for relevant information. Through these means, relevant supportive information from the clinical database and online knowledge resource centers can be programmed to automatically populate into the radiologist's report. When used in conjunction with each other, these advancements in informatics can be used to make important advancements in standardized radiology reporting and characterization while providing patient-specific recommendations and differentials (Fig 4).

This integrated network of information systems will in turn improve the quality of radiology reporting through improved adherence to guidelines and national standards. Automatic quality comparisons between the study in question and a standardized national database can be used to prompt technologists to repeat inadequate images prior to them reaching the radiologist for interpretation (such as in the case of inadequate pulmonary arterial opacification on CT angiography studies for pulmonary embolism) or give objective quantitative data that radiologists can use to recommend additional imaging modalities (such as breast magnetic resonance imaging [MRI] for dense breasts on mammography). The potential use of this technology when applied to screening mammograms in women with dense breasts may become particularly important in the near future as national standards and recommendations regarding the use of screening MRI in this patient population are currently being debated both within the medical field as well as the political arena. Objective data identified by CAD systems, especially when used in conjunction with the clinical risk factors of the patients in question through KDDs, may help to identify those who could benefit the most from this additional tool for breast cancer screening and essentially be used as a tool for triaging women into the appropriate screening modality for them.

Ultimately, this integration of the clinical information and radiology findings will allow for the use of computer-based decision algorithms, which can be used to automatically synthesize the standardized reported data from the imaging interpretation and clinical record to generate patient specific differentials. For example, standardized imaging findings combined with imported D-dimer levels and clinical symptoms from the EMR may eventually allow for the automatic generation of post-test probabilities for pulmonary embolism in specific patients via a computer decision algorithm (69).

Communication Technologies

Along with advances in radiology informatics and CAD systems, there have also been important advancements in communication technologies throughout the health care system. EMR systems allow physicians throughout the hospital to quickly identify the patient's location and demographic information. For inpatients, many of these systems also feature a routinely updated list of all the physicians currently involved in their care, allowing for the rapid identification of the active primary physician when important information needs to be verbally communicated by the radiologist. Some of these systems even have built-in text paging systems to allow for contact to be made within the EMR system itself. The increased integration of the PACS and EMR can make all of these communication features even much more accessible to the practicing radiologist in the near future, and we can harness these advances and use them in ways that can benefit our field in particular (Fig 5).

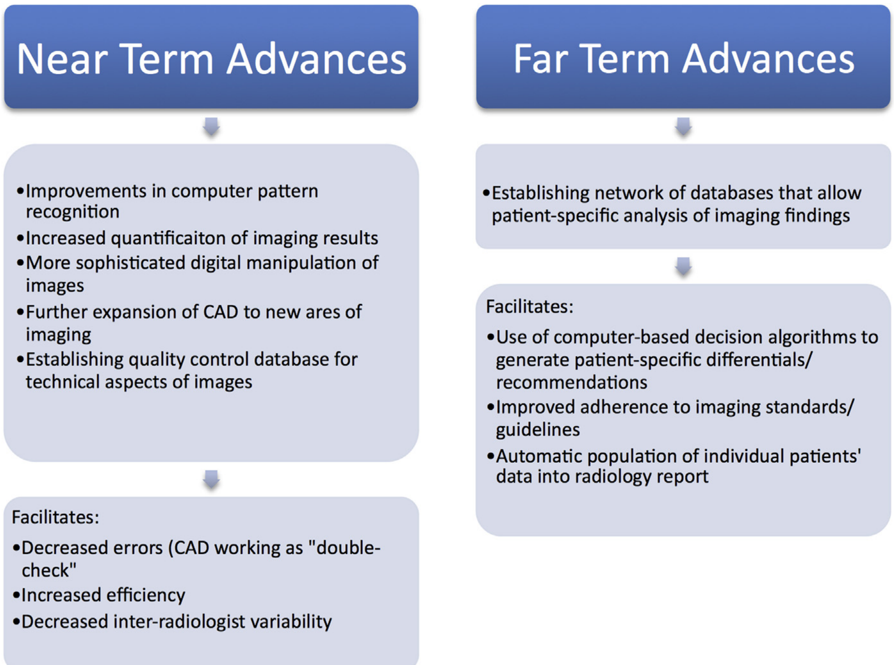

Figure 4. Near- and far-term advances of imaging informatics (computer-assisted detection).

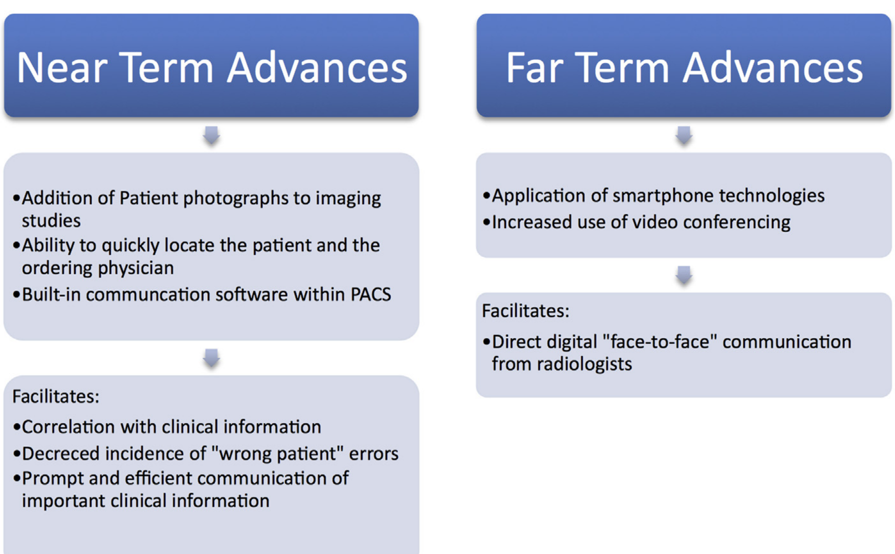

Figure 5. Near- and far-term advances of imaging informatics (communications technologies).

Advances in camera technologies, which are increasingly being incorporated into cellular phones and computers, may permit the acquisition of patient photographs at the time of medical imaging. Ramamurthy et al (70) provided the technological basis for a tool that would allow portable radiography machines to seamlessly and simultaneously acquire patient photographs along with portable chest radiographs. In a simulated study, Tridandapani et al (71) showed that wrong-patient errors, when one patient's study is erroneously introduced into another patient's folder, can be missed by interpreting radiologists; only 3 of 24 errors introduced into a reading list consisting of 200 chest radiograph pairs were noted by the readers. However, when similar radiographs were shown along with patient photographs obtained at the point of care, radiologists' error-detection rate increased significantly and they noticed 16 of 25 such errors. Interestingly, adding photographs did not increase the interpretation time of the radiologists. More importantly, radiologists who participated in the study thought that their reports were more relevant since they were able to correlate radiographs with the physical appearance of the patients. Thus, the addition of visible light images, through photographs and cine-clips, may significantly add to the interpretation value of radiologic examinations.

In the future, we envision that when interpreting radiologists have a clinical question, they will be able to look at

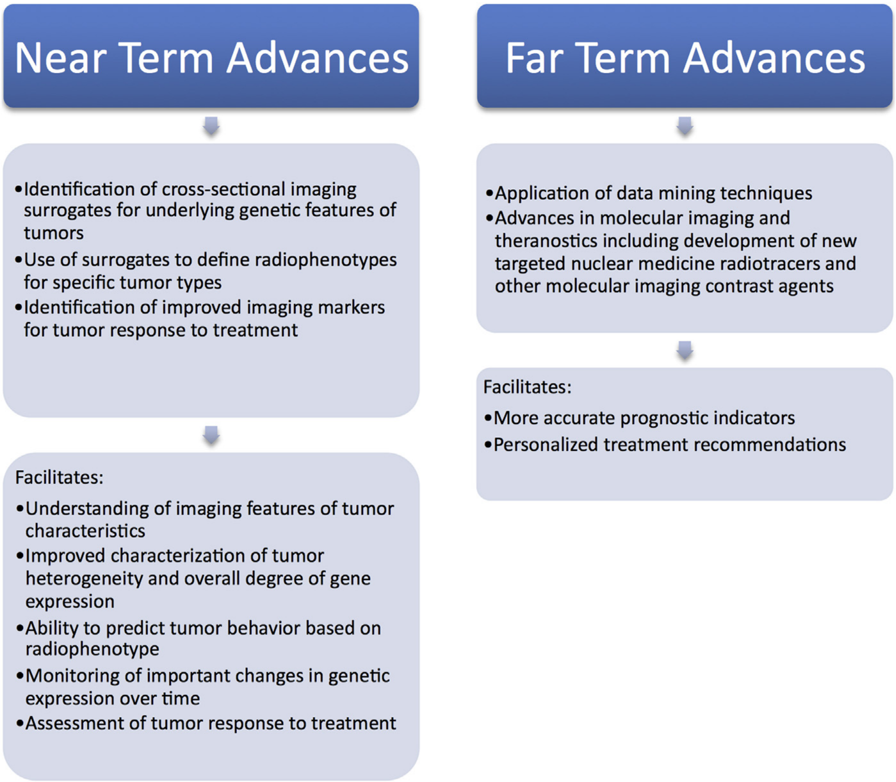

Figure 6. Near- and far-term advances of imaging informatics (linking imaging phenotype to patient/disease genotype).

such point-of-care photographs to assist them with their interpretation. For example, if a tube is seen on a portable radiograph and it is unclear if the tube is inside or outside the patient, then a point-of-care facial photograph showing that there were no tubes entering the patient's nose or mouth may allay the fear of the radiologist that there may be a potential feeding tube in the lungs. This can significantly improve radiologists' and referring clinicians' efficiencies, since the need to make a call to the clinical service to determine if there is a feeding tube in place can be circumvented.

As radiologists increase their clinical role, the need to communicate directly with patients and referring clinicians will likely increase as well. Already, most radiology information systems (RIS) and PACS integrate well with EMRs through the Health Level Seven International (HL7) interoperability standards. This implies that information such as patient location, if the patient is an inpatient, and demographic and contact information are all readily available through RIS or PACS. Thus, there are very few technological barriers to radiologists' ability to contact patients with a single click of a button through PACS workstations and conducting video communication either in the patient's room or on their smartphones if the patient is an outpatient.

Linking Imaging Phenotype to Patient/Disease Genotype

In addition to reducing potential errors, improving workflow, and allowing for improvements in radiology's ability to provide patient-specific diagnoses, the merger of information systems will create links between the radiographic phenotype and the underlying patient/disease genotype. This connection is vital to allow the use of data mining techniques to facilitate further advancements in the fields of molecular imaging and theranostics (a portmanteau of therapeutics and diagnostics). These fields, in turn, can improve the ability of imaging studies to predict mortality, therapeutic response, and the underlying patient/disease genotype on the basis of the radiologic phenotype (Fig 6).

The current methodology for evaluation of oncologic processes relies heavily on the procurement and analysis of pathologic specimens for tumor characterization. This approach is limited by the underlying heterogeneity of tumor composition and the inability to assess the dynamic interaction between the tumor and the surrounding environment in vivo. Tissue sampling is also an invasive process and is therefore often only performed for the initial diagnosis and a few other time points in limited number of tumor sites, even though tumor genotypes are known to vary from site to site and change over time, especially as they are challenged with radiation and chemotherapy treatment regimens. Radiology has the benefit of being able to noninvasively evaluate the entire tumor and tumors at multiple sites within its native environment over long periods of time. The improved ability to characterize the underlying genetic expression of these tumors through radiographic imaging can, therefore, have great clinical significance for the patient and his or her treating physician.

While the creation and development of new specific radiotracers for use in nuclear medicine imaging can be used to directly target underlying genes and tumor types, a more practical way to usher in the widespread use of systems diagnostics in the near future is to identify surrogate imaging features on the most commonly used imaging modalities that can be used to infer the underlying molecular genotype and the degree of gene expression as well as make important observations regarding the interaction of the tumor cells with their surrounding environment. In their work on glioblastoma multiforme (GBM) and hepatocellular carcinoma, Kuo et al demonstrated the ability to use specific imaging phenotypes to predict gene expression in patients with known cancer using the standardized characterization of findings on cross-sectional imaging modalities (72,73). Their methodology focuses on first identifying and quantifying distinctive imaging traits on cross-sectional imaging studies of known cancers. Next, they use a module networks algorithm to search for associations between the expression level of known genes identified by microarray analysis and the distinctive imaging traits (aka radiophenotypes) previously identified. Once potential associations have been identified, these connections can be validated through additional trials using the application of hypothesized prediction rules to an independent data set of tumors. For instance, they noted that the presence of "internal arteries" and the absence of "hypodense halos" together carried a 12-fold increased risk of underlying microscopic venous invasion in patients with hepatocellular carcinoma (73).

The identification of associations between the underlying genotype and the radiographic phenotype can in turn be used to predict tumor behavior and prognosis, such as in the case of GBM, which demonstrated a strong association between the infiltrative phenotype and a poor prognosis (72). Interestingly, Kuo et al's research on GBM demonstrated that tumor size (one of the more commonly used imaging traits currently used to assess malignancy and treatment response) did not demonstrate a significant correlation with the proliferation cluster when analyzed alone (72). They hypothesized that mass effect may be a better surrogate for the tumor proliferation rate because it incorporates the response of the surrounding tissue into the equation (72).

In the future, the use of these surrogate imaging markers may allow radiologists to recommend potential therapeutic treatment regimens based on the radiologic phenotype of the diseased and surrounding tissues and to better evaluate the tumor's response to ongoing therapies. For example, Kuo et al's research on GBM found a positive correlation between the contrast enhancement of the tumor on MRI and the genetic expression of the "hypoxia module," which was composed of genes associated with angiogenesis and tumor hypoxia (72). Associations such as this can be used to identify patients who may respond (or not respond) to certain chemotherapy regimens. A patient demonstrating radiophenotype consistent with a high level of expression of the proangiogenic vascular endothelial growth factor (VEGF) gene in the tumor may, for instance, respond better to anti-VEGF chemotherapy regimens compared to a different patient with the same histologic tumor type but a lower level of expression of the VEGF gene according to the radiophenotype.

Research like this represents an exciting new frontier for the clinical applicability of radiophenotyping and demonstrates how the fusion of imaging and genomic data sets can be used to improve the quality of personalized radiographic interpretations for our patients and their care teams. In addition, it raises another potential tool for CAD beyond its current use, as Kuo et al point out that "the application of more quantitative image analysis tools should also allow for richer image feature extraction and should facilitate the standardization and adoption of these types of imaging biomarkers by decreasing the potential for inter-observer bias" (72). To accomplish this, however, complete integration of the many available digital resources must be achieved along with standardized characterization of the radiologic information leading to "systems diagnostics."

Near-term Challenges and Opportunities in Imaging Informatics

In the near term, the greatest opportunity in imaging informatics is in enhancing the communication between radiologists and all the groups with which we interact, especially referral physicians, patients, other health care providers, and the government. Leveraging technologies to reestablish ourselves in the mind of patients as physicians who are directly participating and critical to their care should be pursued with utmost urgency. Mobile communication tools such as smartphones, iPads, and other mobile devices should be used to help achieve this goal. The greatest challenge in the near term is to shift our reliance on radiologic pathologic correlation as the basis of our image interpretations and move toward systems diagnostics. This will require a fundamental change in our research, training, and continuing education. The next section will explore how this can occur.

HOW CHANGES OCCUR IN THE PRACTICE OF MEDICINE

Radiologists have been successful in the past in establishing and maintaining control over medical imaging. However, concerns about the cost of imaging and worries over commoditization of radiological practice have led to increased efforts by radiologists to demonstrate that they "add value" to health care. In the face of trends toward "genomics" and "system" approaches in the life sciences and medicine, radiologists need to evolve from image interpreters into integrative diagnosticians who are the primary providers and coordinators of medical information.

As sociologist Joan Fujimura observes, "Changing conventionalized and embedded work organizations involves a lot of convincing and persuading, buying and adopting, teaching and learning" (74). Given the complexity and expense of bringing about change in medical practice, what might encourage radiologists to shift their behaviors? It is impossible to predict with certainty what actions or arguments will persuade radiologists to adopt a systems-based approach to imaging and diagnosis. However, investigating the various strategies that have been used in the past to successfully promote behavioral change among radiologists can suggest tools and techniques to aid in encouraging radiologists to adopt systems-based practices. For the purposes of this article, these strategies have been divided into four general categories: translation, articulation, standardization, and anticipation. We will now discuss these categories in detail.

Translation

As philosopher of science and sociologist Bruno Latour points out, "The first and easiest way to find people who will immediately believe the statement, invest in the project, or buy the prototype, is to tailor the object in such a way that it caters [to] these people's explicit interests" (75). The ability to translate the interests of potential "allies" or stakeholders into the language of one's own research—that is, to convince others that their interests and concerns are the same as yours—has been a highly successful technique used by scientists to garner support for particular innovations. For example, Latour shows how the acceptance and success of the anthrax vaccine ultimately relied on Pasteur's ability to translate the concerns of French cattle farmers into the language of microbiology (76).

PACS provides a more contemporary and radiology-specific example illustrating how the ability to translate others' interests is key in promoting innovation adoption. In the late 1990s, PACS developers, supporters, and manufactures were baffled as to why PACS had been so quickly adopted by a small group of "innovators," only to be ignored by "early and late majority users" (77). Interestingly, it was after advocates of PACS shifted from primarily representing PACS as a tool for radiologists and began stressing the ways that PACS could address the specific concerns of referring providers that adoption began to increase substantially.

Similarly, translation is a strategy that can be used to promote digitization and systems diagnostics among radiologists and in medicine more broadly. The first step is to identify groups of potential "allies" or stakeholders to be enrolled. This list should include not just radiologists and radiology professional groups but also other referring providers, including primary care physicians, as well as insurance companies, hospitals, and other payer groups, regulators, and administrators, and manufacturers of genomic, imaging, and informatic technologies. In addition, the importance of patient advocacy groups should not be overlooked.

Once these stakeholder groups have been identified, the interests and commitments of each should be determined and addressed. Venues should then be established to encourage communication and collaboration among stakeholder groups. These venues can include interdisciplinary working groups or task forces, research interest groups, conferences, email newsgroups, and web sites. These venues provide an opportunity to "learn the language" of other stakeholder groups and identify their priorities and concerns while also demonstrating to those groups the utility and benefits of new approaches. For example, multidisciplinary conferences beginning in the early 1980s that were sponsored by the International Society for Optical Engineering (SPIE) were instrumental in fostering collaborative relationships among researchers, clinicians, and technology manufactures that enabled the development of digital radiology and PACS (78). Similarly, organizing and promoting systems diagnostics conferences and working groups can help radiology show ownership over genomics technologies and the information it produces while also guiding the research agenda and defining the parameters of its use (Fig 7).

Further, it is important to stress that translation involves not only defining and addressing the interests of others but also convincing them of what their interests *ought* to be. Emphasizing digitization and systems diagnostics as technologically and scientifically advanced and "cutting-edge" can help to persuade students, new investigators, and established researchers to adopt this approach. Likewise, emphasizing the promise of genomic technologies and digitization in medicine can help secure the support of entrepreneurial businesses and technology development firms.

Articulation

In medicine, innovations must make a place for themselves in contexts that already contain established techniques and procedures. This often requires negotiating between behaviors that are established or accepted and those that are considered "new." In fact, research in the social sciences has shown that for the life sciences, emphasizing the transformative potential of an innovation is crucial for its widespread adoption. However, in the clinical sciences, it has been most effective to stress that novel techniques can be integrated into existing clinical practices rather than representing an entirely new approach to a problem (79,80). Therefore, the concept of articulation involves demonstrating the advantages and utility of an innovation while not undermining more traditional standards of practice (81). One of the central ways that articulation is accomplished is through correlation studies that link the methodologies and results of past research or clinical practice with what is being produced by the new approaches.

For example, PACS developers realized that for widespread adoption of PACS to take place, radiologists would have to be convinced not only that digital images would allow the same diagnostic accuracy as analog images but also that digital displays represented an improvement over interpretation of film-based images at a view box (82). A wealth of research was conducted that compared radiologists' ability to correctly identify pathology using film-based versus digital images (83–85), as well as studies that examined and contrasted radiologists' efficiency and workflow with analog film as

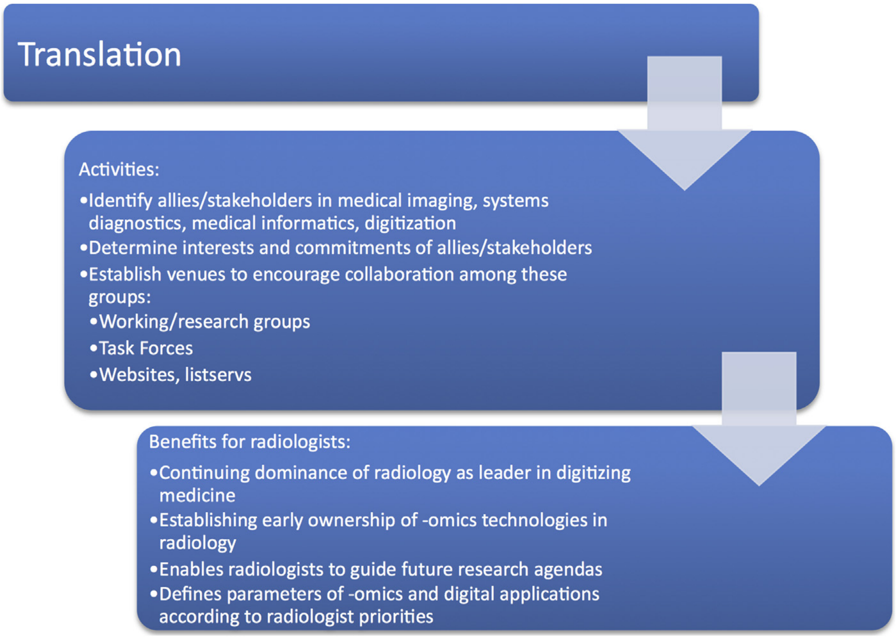

Figure 7. Effecting behavioral change in radiology: translation activities and benefits.

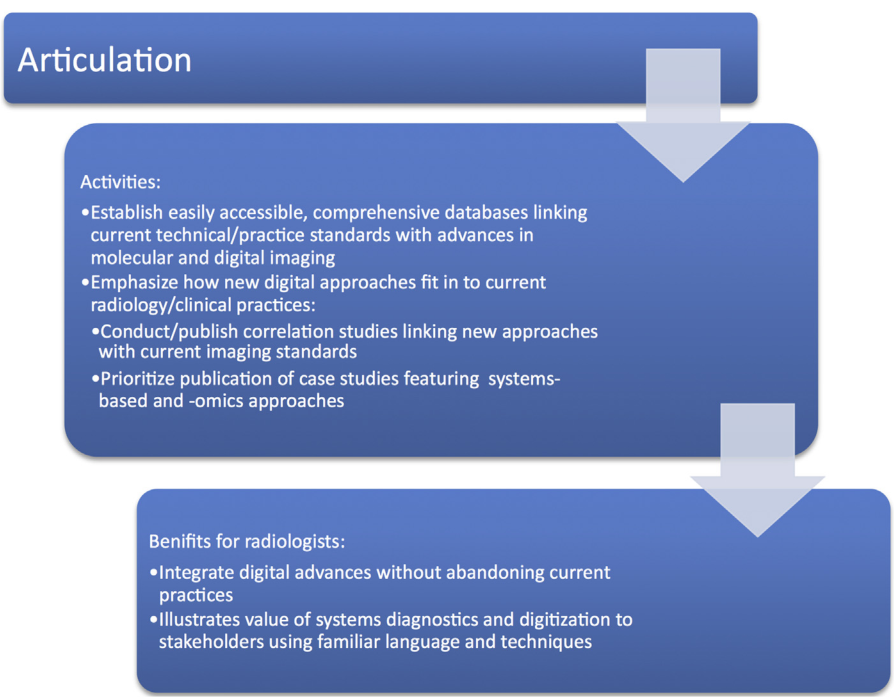

Figure 8. Effecting behavioral change in radiology: articulation activities and benefits.

opposed to PACS (86–88). By emphasizing film-based images and work practices as the "gold standard" by which PACS and digital imaging were judged, PACS researchers were able to show how digital imaging was an improvement to current radiological practice without discrediting the techniques and standards with which radiologists were most comfortable. The work of establishing equivalences between different "ways of seeing" (analog versus digital images) was an important step in ensuring the eventual success of PACS.

Such articulation work will be valuable to radiologists advocating digitization and a systems-based approach to diagnosis. In addition, the generation of case studies can help illustrate the value of digital technologies and systems diagnostics to a variety of stakeholders. For example, case studies may act as blueprints for researchers on how to conduct similar studies and for health care providers on how to use such approaches in their daily practice. Additionally, the creation of an easily accessible, comprehensive database that correlates existing radiological knowledge and imaging phenotypes with the information emerging from molecular imaging and genomics research, as discussed earlier, will further the process of articulation (Fig 8).

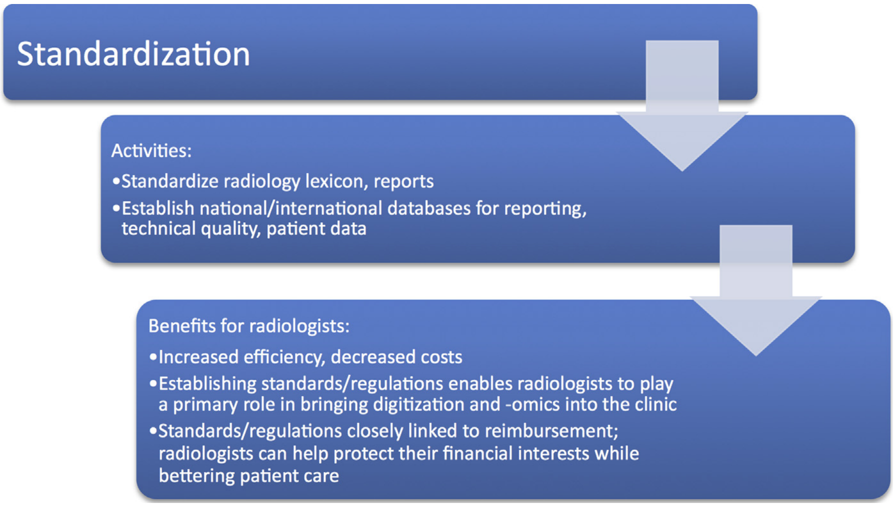

Figure 9. Effecting behavioral change in radiology: standardization activities and benefits.

Standardization

The process of standardization involves making tasks and materials explicit and routine, yielding tools and practices that are more portable and less time consuming and expensive to produce. With standardization, data and activities become comparable over time and space (89). Standards can determine *what* is done in a particular situation, *who* does it, and *how* it is done. Thus, being able to dictate and control standards represents a considerable source of power in medicine.

Standardization generally reduces the intellectual, financial, and practical investment needed to adopt a new innovation and therefore is an important (although often difficult and labor intensive) strategy for promoting behavioral change. For instance, the creation of the Digital Imaging and Communications in Medicine (DICOM) standards through a partnership between the ACR and the National Electrical Manufacturers Association enabled imaging devices from different manufacturers to communicate, store, and manage data as part of a single system (90). Yet, the establishment of DICOM was highly political, as the manufacturers of imaging devices wanted to maintain proprietary control over the imaging data itself as well as controlling which displays, software, and storage devices their products would work with. Eventually, radiologists partnered with the Food and Drug Administration (FDA) to persuade these vendors to collaborate with the ACR/National Electrical Manufacturers Association working groups and "voluntarily" adopt DICOM standards (91). Without such standards, the development of PACS and teleradiology could not have moved forward and become successful. Similarly, establishing standards will enable adoption of the tools and techniques of digitization, systems diagnostics, and molecular imaging to become less expensive, less complex, and more widespread. By playing a significant role in the establishment and regulation of such standards, radiologists will help secure their role in bringing these approaches into the clinic (Fig 9).

Anticipation

"Scientific facts are like trains, they do not work off their rails. You can extend the rails and connect them but you cannot drive a locomotive through a field" (78). This observation by Latour highlights the importance of establishing an infrastructure for innovations *before* they are widely adopted. While a certain amount of research and data are necessary to establish the utility of a new concept or technology, the ability to anticipate the data and develop systems to address possible regulatory, ethical, practical, and financial challenges "down the road" is crucial for promoting and supporting the adoption of an innovation.

For example, a group of radiologists and researchers concerned over the burgeoning size and number of imaging studies spearheaded a series of workshops and conferences known as SCAR TRIP [Society for Computer Applications in Radiology (now SIIM, Society for Imaging Informatics in Medicine) Transforming the Radiological Interpretation Process]. The purpose of these meetings was to encourage collaboration among radiologists, other physicians, scientific researchers, manufacturers of imaging equipment and software, and government agencies to discuss and plan for the "information overload" associated with continually advancing imaging technologies (92). The overall focus of the SCAR TRIP Initiative was to identify and anticipate key areas for future radiological research and development as well as potential roadblocks and barriers to that research. Rather than wait until the amount of imaging information overwhelmed current technologies, this program sought to take a proactive approach to the problem of data overload.

Anticipating possible road blocks to the adoption of systems diagnostics and digitization and building an infrastructure to address those problems before they happen will help speed the shift in the role of the radiologist from imager to diagnostic specialist. Additionally, engaging diverse groups of stakeholders in defining and anticipating key issues will help encourage processes of translation and articulation (Fig 10).

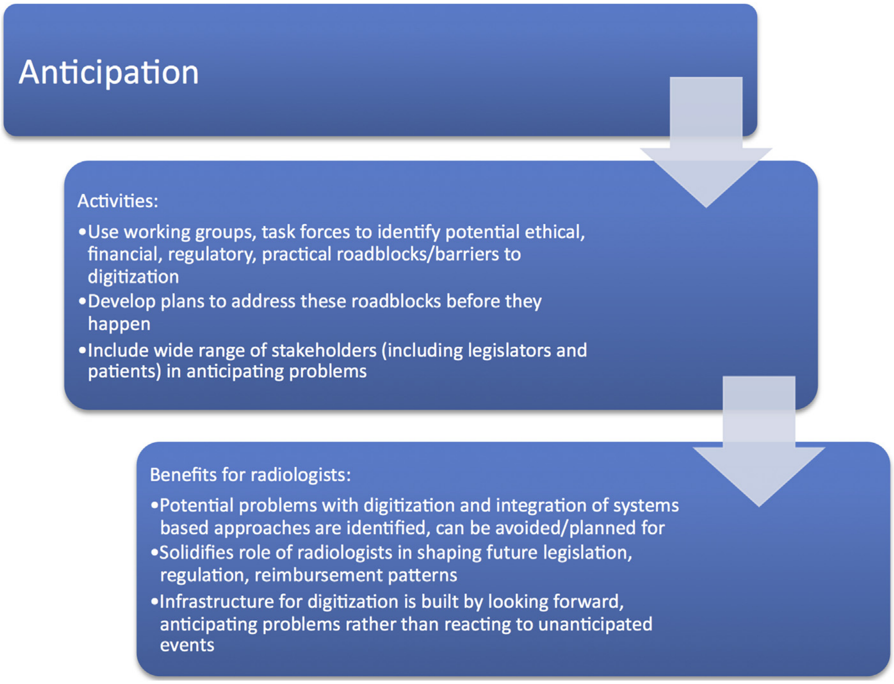

Figure 10. Effecting behavioral change in radiology: anticipation activities and benefits.

Competition for the Role of Medical Informatician

Like radiologists, pathologists are looking to expand their role in medicine and are laying claims to becoming the primary curators and analysts of all patient information, including personalized genomic data. The parallels between pathology and radiology are striking; both specialties are struggling to shrug off perceptions of their work as based primarily on personal intuition and embrace more quantitative, formalized and standardized approaches to patient care (93).

In fact, pathologists have taken several important steps toward adopting a systems-based approach to diagnostics. For example, since 2008 the *American Journal of Pathology* (AJP) has adopted specific strategies to support and encourage the publication of genomic-based research. These strategies include soliciting and accepting more genomics articles with particular emphasis on those that combine these new research techniques with the more established pathological standards of cellular and morphologic analysis (94). In addition, the AJP editors have appointed additional associate editors who are involved in translational and/or genomics research and have expanded the "Short Communications" section to promote exposure of cutting-edge research. Further, pathologists have conducted and published several pilot studies using a "systems pathology" approach, including prostate cancer (95,96) and breast cancer (97).

Moreover, in October 2010, a group of researchers from the Department of Pathology and the Center for Biomedical Informatics at Harvard Medical School organized a "Stakeholder Summit" on the topic of "genome-era" pathology in Cold Spring Harbor, New York. Conference attendees included Dr Eric Green, the director of the National Human Genome Research Institute (and a pathologist), and representatives from insurance companies, several pathology professional organizations, personalized medicine advocacy groups, manufacturers of genomic testing and informatics technologies, the military, and academic medical centers. The goal of the conference was to "develop a national strategy to ensure that the performance, interpretation, and regulation of genome-based clinical testing come directly under the purview of pathologists and their national organizations" (98).

The strategy articulated at this conference involves pathologists positioning themselves to curate and integrate patients' information, designing training and accreditation programs to encourage genome-era medical expertise, and gaining control of the regulation and oversight of genome-based laboratory tests. In addition, the conference participants defined a series of "blue dot" projects to help move their agenda forward, including studies to demonstrate the utility and value of a genomics-based approach to laboratory testing, establishing a comprehensive database of human genome sequence variants, and implementing various multi-institutional projects to assess and standardize whole-genome sequencing technologies.

Clearly, pathology has already begun to maneuver their discipline to lay claim to the role of primary medical informatician. By supporting genomics researchers and encouraging their collaboration with pathologists, publishing case studies featuring a systems pathology approach, convening multidisciplinary conferences and working groups on "genome-era" pathology that include a wide variety of stakeholders, and creating new practice standards, regulatory standards, and training programs, pathology is actively engaged in translation, articulation, standardization, and anticipation of systems diagnostics.

Near-term Challenges and Opportunities in Effecting Change

The shift to a systems-based approach to medicine relies on the ability to collect, organize, store, and analyze huge collections of data. As leaders in the digitization of medicine and the development of medical informatics, radiologists already have the skills and technology in place to deal with the “deluge” of information that will be generated by systems diagnostics. Further, radiologists have already formed robust ties with computer scientists, informatics specialists, physicists, and technology manufacturers that will be crucial in designing and implementing new diagnostic and information technologies. The major challenge for us is to come together as a specialty and start taking the necessary steps as outlined in this section to effect change.

CONCLUSION

Digitization of medicine represents unprecedented opportunities and challenges for radiologists. We have presented three major trends in digitization of medical imaging: (1) the reporting paradigm, (2) computational biology, and (3) imaging informatics. We also discussed how change occurs in medicine, and how change may be effected in the medical imaging community. We argue that to remain leaders in the digital reshaping of medical practice, radiologists must recognize and embrace both the near-term trends and far-term opportunities that digitization holds while actively pushing the boundaries of current practices and technologies. Of course, given the limited scope of our discussion, we have only focused on a partial list of the possible benefits that digital advances may offer. Much more research is needed to map out a complete overview of advantages as well as barriers to digitizing the clinic and bringing a systems-based approach to medical diagnostics. However, despite these limitations, we believe that we should not view the shift to systems diagnostics as a potential turf battle with pathologists. Rather, it is an opportunity for radiologists to form new alliances and relationships with other disciplines and specialties, and to lead the way in ushering in a new era of patient-centered, collaborative, and team-based care.

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