Informatics methods and systems in support of clinical care are well established in the health care enterprise. The new paradigm of patient-centered radiology creates new requirements and challenges that can be enabled by informatics. In particular, computer support can help referring physicians tailor their imaging requests to those procedures that would be most helpful for their patients’ clinical context. Informatics methods can assist radiologists in recognizing important findings in images as well as helping them decide the best course of action for patients given the radiologic imaging results and other clinical data. Finally, informatics methods can help engage patients in their care by providing information about their imaging procedures and results. All of these informatics technologies share in common the ability to bring together critical knowledge filtered according to the specific requirements of patients undergoing radiologic imaging, a key component of patient-centered radiology. The goals of this article are to review the opportunities for informatics in supporting patient-centered radiology, to demonstrate the potential utility of these methods, and to point radiologists to the ways that informatics will help them provide care that is tailored to each patient.

Key Words. Informatics; patient-centered radiology; knowledge representation; decision support.
Radiologists can adopt informatics methods to manage communication of results from referring physician to patients and manage the flow of information sometimes result in delayed formation in physician practices and the lack of systems to particularly important opportunity because the volume of information in physician practices and the lack of systems to manage the flow of information sometimes result in delayed communication of results from referring physician to patients (4). Radiologists can adopt informatics methods to manage the information glut and can help communicate results to patients. At the same time, radiologists will become more visible in the care process and make patients aware that radiologists serve an integral role in patient care.

A second aspect of the patient perspective in patient-centered radiology is enabling patients to participate in the medical decision-making process. Just as personalized medicine is changing how radiologists will approach interpreting images, shared decision making personalizes the patient management process. In many cases, the results of imaging are suggestive, but not conclusive, for disease. The decision support systems), and finally by ensuring that the patient is informed of the imaging results (results communication systems) and is involved in the subsequent management decisions (shared decision making).

At the heart of the challenges for patient-centered radiology are access and exploiting large amounts of information. Physicians need to access current radiologic knowledge to customize imaging and accurately interpret results. Patients need access to radiologic results in a timely fashion and in assessing the likelihood of different outcomes given these results. Informatics provides methods that can enable patient-centered radiology by helping physicians and patients manage and use knowledge: how it is acquired, used, and moved around (Fig 1). From the physician perspective, informatics can enable personalized medicine by delivering guidance for examination appropriateness specific to patients and by providing diagnostic decision support in image interpretation. From the patient perspective, it can engage them more closely in their care by communicating the results of imaging procedures and by enabling shared decision making.

The goals of this review are to discuss the opportunities for informatics in patient-centered radiology, to demonstrate the potential utility of these methods, and to point radiologists to the ways that informatics will help them provide care that is tailored to each patient. This work discusses the following informatics methods that will support key components of patient-centered radiology spanning the imaging

Figure 1. Informatics aspects supporting patient-centered radiology. Informatics supports patient-centered radiology throughout the imaging work flow, in aspects of care that involve the radiologist (dashed boxes) and the patient (dotted boxes), beginning with the imaging request (just-in-time appropriateness methods), followed by the radiologist’s interpreting the images (diagnostic decision support systems), and finally by ensuring that the patient is informed of the imaging results (results communication systems) and is involved in the subsequent management decisions (shared decision making).

work flow: test selection, test interpretation, and the communication and use of the test results (Fig 1):
- Guidance for imaging procedure appropriateness
- Diagnostic decision support for interpretation
- Results communication and shared decision making.

GUIDANCE FOR PROCEDURE APPROPRIATENESS

The first opportunity for informatics to enable patient-centered radiology is in helping referring physicians determine the most appropriate imaging tests to order for their individual patients. There are many imaging modalities, each having a variety of specialized protocols and different parameters that can be adjusted according to their goals. In patient-oriented radiology, the goal is for referring physicians to select the imaging procedures that will most likely answer the clinical questions given the histories of and current information about specific patients. The challenge of adopting a patient-centered approach in selecting the best imaging procedure for each patient is that referring physicians must be knowledgeable about which imaging procedure and protocol is appropriate in each clinical indication. Physicians vary in their knowledge of imaging appropriateness, and the best imaging procedure for each patient is not always ordered.

Informatics methods are being developed to provide guidance to physicians in selecting imaging procedures for their patients, by providing knowledge of imaging procedure appropriateness “just in time,” as they order imaging tests. These methods are (1) defining and encoding appropriateness guidelines for radiology and (2) order entry decision support.
Defining and Encoding Guidelines for Imaging

Efforts are being undertaken to formalize the knowledge about which imaging procedures are best for particular patients. The American College of Radiology Appropriateness Criteria have been created for the major clinical imaging indications to guide providers in making the best choices for imaging their patients (5,6). The criteria specify the different clinical contexts for imaging, the possible imaging modalities appropriate to those contexts, and the appropriateness rating for each modality in that context, as shown in Figure 2 (7).

Automated methods are being developed to promote the rapid dissemination of appropriateness criteria and to allow linking them to electronic medical records data as well as to enable computerized physician order entry (CPOE) (8). These automated methods use electronic versions of appropriateness criteria, enabling integration of the criteria with hospital systems and deployment in CPOE applications. Electronic encoding of appropriateness criteria provides a crucial informatics approach to getting them disseminated and adopted in practice, because few practitioners can stay abreast of this information and remember to apply it to their patients when these criteria are disseminated only in paper format.

Electronic encodings of appropriateness criteria contain their key content, including clinical indications, radiology subspecialties, procedures, and appropriateness ratings. At the present time, appropriateness criteria do not adopt controlled terminologies: standard names for diseases, body regions, and imaging modalities. To integrate these criteria into hospital systems, the terminology in the criteria needs to be mapped to terms used by the hospital systems, because there is more than one way of saying the same thing. For example, an appropriateness criterion might refer to “headache” (Fig 2), whereas the electronic medical record might use “HA” or “head pain.” Few medical record systems specifically record refinements such as “chronic headache” or even “worsened chronic headache with history of headache”; such distinctions are necessary to apply appropriateness criteria such as those shown in Figure 2.

An important informatics effort that is under way to address the terminological problems is RadLex, a controlled terminology for radiology. As discussed later in the section on controlled terminologies and structured reporting, RadLex
provides standard names for radiology, such as diseases and findings. RadLex also relates terms to other terms to encode radiologic knowledge for intelligent applications. Specifically, RadLex records the typology of diseases, so applications can recognize that specific diseases are subtypes of more general types of disease (Fig 3). These RadLex relations will be helpful in enabling electronic record systems to map their representations of patient information to appropriateness criteria. For example, RadLex could be used to enable a computer application to recognize that a clinical indication of “brain glioma” would be applicable to a particular patient who has “astrocytoma” (because RadLex indicates that astrocytoma is a type of brain glioma).

A component of RadLex is the Playbook, which names the imaging procedures that can be performed in the radiology department. Like the typology of diseases shown in Figure 3, the RadLex Playbook will enable systems to match their nomenclature of radiologic procedure names to the names of imaging tests in appropriateness criteria. For example, in the electronic medical record system, “head CECT” (contrast-enhanced computed tomography) could be matched to “CT, head, with and without contrast” in the electronic appropriateness criteria (Fig 2).

Order Entry Decision Support

Appropriateness criteria are useful to patient-centered radiology only if they are deployed in order entry systems so that physicians’ ordering behavior is altered. In fact, current appropriateness criteria are having little impact in practice. Incorporating such guidelines into daily practice is challenging for two reasons. First, it is difficult to make all referring physicians aware of appropriateness criteria. The criteria are published on the Web (9) and distributed as paper or Portable Document Format files, not easily accessed at the point of care. A second challenge is that there are many different guidelines, varying according to imaging modality and clinical indication, making it cumbersome for physicians to find and apply them to individual patients.

Informatics can help overcome these challenges through order entry decision support. Order entry decision support is the process by which referring physicians are guided into making better decisions about the appropriate imaging procedures for their patients by embedding appropriateness criteria into CPOE systems. Several studies have shown that order entry decision support systems can influence the orders that physicians place, both in medicine and in radiology (10–12).

A few CPOE systems have been developed that include appropriateness criteria or practice guidelines to deliver knowledge to referring physicians at the point of care (12,13). In addition to informing physicians about examination appropriateness and helping them find the best imaging procedures for their particular patients, such CPOE systems can also present the evidence supporting each of the recommendations. For example, suppose a referring physician seeing a patient with back pain and radiculopathy decides to order an x-ray of the lumbar spine. A CPOE system with decision support could access the criteria for imaging low back pain and alert the physician that in this particular patient, x-ray of the lumbar spine would not be an appropriate imaging test, and instead suggest magnetic resonance imaging of the lumbar spine without contrast. The system could cite the appropriateness criterion on which the recommendation is based and even show the evidence available from the
guideline. The physician could proceed to accept or override the advice. Such intelligent systems can be useful in guiding patient-specific care as well as providing education to physicians.

### DIAGNOSTIC DECISION SUPPORT FOR INTERPRETATION

After selecting the best radiologic procedures to be performed, patient-centered radiology requires that the most accurate interpretation be rendered given the clinical context and observed radiologic findings. Radiology interpretation includes three key steps (Fig 4): (1) perception of image findings, (2) interpretation of those findings to render a diagnosis, and (3) decisions and recommendations about patient management (next tests or treatments). Perception of image findings is clearly important in radiology, and many informatics methods collectively called computer-aided detection have been developed in several domains of radiology (14). Detecting image features is approached in a similar manner in all patients. On the other hand, interpretation and decision making depend heavily on individual patient characteristics, and these tasks should be supported in patient-centered radiology.

The need for assisted interpretation and decision making is underscored by the fact that there is a great deal of variation among practitioners in these skills. Studies have documented interobserver disagreement in the interpretation of imaging studies (15). For example, in mammography interpretation, there is substantial variation in sensitivity, specificity, and area under the receiver-operating characteristic curve among radiologists (16). Much of the variation in practice likely results from the complexity of processing the vast amounts of knowledge needed to interpret the myriad findings observed in imaging. Most of medical practice is not quantitative but based on “heuristics” to guide physicians on the basis of rules of thumb (17). Such heuristics can fail in a variety of circumstances when combinations of features related to diagnosis do not fit the expected patterns and practitioners do not recognize the impact of such circumstances.

Diagnostic decision support is an informatics method to help radiologists with image interpretation and decision making. Unlike computer-aided detection, these systems do not focus on detecting a finding of interest but rather focus on the decision process, specifically on the diagnostic reasoning process in medical applications. Decision support systems begin with the observations (the findings detected on images) and integrate them with a formal model of the knowledge used to make decisions, outputting the most likely diagnoses. Decision support systems incorporate patient-specific knowledge, such as clinical histories or results of other tests. This patient-specific information, in combination with the imaging findings, can enable these systems to help radiologists render better care that is personalized to patients and reduce variation in practice.

In most decision support applications, the computer uses a model of disease (such as a Bayesian network) that incorporates image features and clinical data as variables in the model (Fig 5). The model relates image features and other observed clinical parameters to the likelihood of each type of disease. By entering observed clinical and imaging features into the model, a post-test probability of disease can be calculated and used to guide decision making and patient management. Such decision support applications thus inform radiologists about the most likely diseases for particular patients.

The input to decision support applications is usually a controlled terminology-encoded structured radiology report (Fig 6), that conveys the imaging observations and the key clinical information to the decision support application. The decision support application uses its model of disease to deduce the best course of action and reports that information to the practitioner. For example, a decision support system for mammography was recently created to inform radiologists as to the likely diagnosis and to provide guidance regarding biopsy recommendations of suspicious lesions (18–20). A radiologist enters the findings using a structured reporting form, and information in that form is processed by the system to produce its output (in this case, a differential diagnosis, ranked by probability of disease; Fig 5). The system suggests whether the practitioner should biopsy a lesion depending on whether the probability of malignant disease exceeds a predetermined threshold. If the practitioner does biopsy a lesion, another decision support system can help determine whether a benign biopsy result might be due to sampling error (21).
RESULTS COMMUNICATION AND SHARED DECISION MAKING

Once a radiologist provides an interpretation and recommendation, those results must be communicated to the referring physician and the patient in a timely manner. Communicating the results of imaging procedures is a crucial aspect of patient-centered radiology as well as medical quality. The impact of the communication of radiology results on quality is particularly important; recent studies have raised concern about errors related to critical test result communication in ambulatory care (22,23). One study found that communication errors are responsible for 10% of errors in radiology (24). The active engagement of radiologists in communicating results to patients is being advocated to enhance quality and to ensure patient-centered care by making patients equal partners with referring physicians in accessing imaging information (3,25). The American College of Radiology has developed guidelines for communicating critical imaging findings (26). Radiologists are advised to expedite reports that indicate significant or unexpected findings “in a manner that reasonably ensures timely receipt of the findings.” Current practice guidelines on communicating results differentiate “routine” and “non-routine” examinations (26,27) to deal with the pragmatic aspects of triaging these communications according to urgency in high-volume practice settings. Beyond communicating critical results, it may also be desirable for radiologists to follow up on their recommendations to ensure that their recommendations were actually carried out; for example, if a follow-up examination is suggested, it is important to check if an examination was subsequently obtained.

Most institutions have policies in place about communicating critical test results by phone, but such methods are prone to human failure; malpractice cases have arisen from failing to get the message to referring physicians. At the same time, radiologists face substantial challenges in the timely and appropriate communication of diagnostic test results. Current radiology reporting systems are not designed to provide timely and patient-centered communication of results. The increasing caseload of radiology is challenging the ability of radiologists to communicate the results of every case, and there is variability in radiologist training in how to communicate those results (28).

As radiology has entered the digital age of radiology and electronic communication, informatics methods are ripe to be applied to ensure that radiologic findings are promptly and clearly communicated to patients and their physicians. There are two informatics methods that can be used to improve communication between radiologists and referring physicians and patients: (1) structured reporting and controlled terminology for recording the radiology results and (2)
electronic notification and reminder systems to ensure receipt of the communications and appropriate follow-up on the imaging results.

**Structured Reporting and Controlled Terminology**

The radiology report is the vehicle through which imaging procedures are recorded and transmitted to patients and referring physicians. Most radiology reports are unstructured text, varying in quality. In patient-centered radiology, the report must serve the needs of the consumers of the information: patients and physicians. These consumers find clarity, brevity, and clinical correlation most valuable (29). Unfortunately, radiology reports often fall short in meeting these characteristics; the language and structure in reports may vary, be ambiguous, and lead to miscommunication. For example, in an analysis of the 15 most commonly used words and phrases for conveying diagnostic certainty in radiology reports, there was poor concordance on diagnostic certainty associated with these phrases, potentially leading to compromised care (30).

Several specific attributes of radiology reports have been identified that improve their value in conveying results to those who receive them: standard language, a structured format, and consistent content (31). These attributes are being addressed by two key informatics approaches: standard language is being developed through controlled terminology, and standardized format and content of reports is being addressed through structured reporting.

Structured reporting is the creation of standardized, organized information from templates navigated via menus into a natural-sounding language report (32). The goal of structured reporting is to provide a method of reporting the essential core content using consistent terminology and organization, replacing the dictation and transcription processes for documenting medical image interpretation. A common implementation of structured reporting systems is the fill-in form template (Fig 6), which usually combines consistent organization with controlled terminology for naming the findings.

Controlled terminology is also crucial to improve the clarity of radiology communication. Controlled terminology has been mentioned earlier in the context of clearly defining and encoding appropriateness criteria. The need for this technology was highlighted by a recent study that reviewed radiology reports and found that there were up to 14 different terms used to describe the single finding of “interstitial edema/infiltrate” (33). Controlled terminologies have been created in other domains besides radiology, most notably the Systematized Nomenclature of Medicine—Clinical Terms in pathology (34); however, until recently, radiology lacked its own standard terminology.

The RadLex project, sponsored by the Radiological Society of North America, undertook the task of creating a standard lexicon for radiology (35). RadLex enlisted the collaboration of other key radiology organizations, including the American College of Radiology, as well as subspecialty societies, to develop a comprehensive radiology lexicon (35,36). RadLex has been designed to satisfy the needs of software developers, system vendors, and radiology users by adopting the best features of existing terminology systems. As radiology systems adopt the RadLex controlled terminology, the clarity and consistency of radiology reporting will improve.

**Electronic Notification and Reminder Systems**

Quality improvement efforts often focus on timely report generation. However, this is insufficient to ensure that the results of imaging procedures have been communicated and acted on. Electronic notification and reminder systems track patient events and clinical data and alert physicians if pre-specified criteria are met or if particular actions should be undertaken. In the imaging domain, these systems can enable...
radiologists to categorize their interpretations (eg, routine, important, urgent, stat) and to automatically invoke the appropriate notification procedures (eg, phone, page, e-mail) for communicating results to referring physicians and patients. These systems can even track the receipt of the message and send reminders or invoke escalation processes to ensure that the information is acted on.

Electronic alerts and reminder systems have been created in radiology. Homegrown radiology information systems have also been developed to facilitate the communication of critical radiology results and to document those results and communications (37). Some institutions have created custom Web-based systems to communicate and track radiology results; such systems have been shown to improve communication among radiologists, clinicians, and technologists (38,39).

Electronic communication systems can also deliver results directly to patients. Some hospitals already provide online access to patient medical records, and commercial efforts such as those by Google and Microsoft (40) are making electronic access of medical data to patients a routine capability. The Web-based distribution of radiology results has likewise been advocated for imaging (38,39), though only few prototype systems have been built to date. The Integrating the Healthcare Enterprise effort has developed technical profiles to provide a framework for image sharing, which will provide crucial infrastructure for communicating images to patients. In fact, several projects have already applied the Integrating the Healthcare Enterprise technical profiles to facilitate the secure and confidential exchange of electronic images over the Internet (41).

**Shared Decision Making**

Patients want to actively participate in their care. Enabling patients to participate in decisions related to the outcome of imaging is an important goal of patient-centered radiology. An important informatics method that supports shared decision making is decision support. Decision support systems in radiology generate a probability estimate of disease likelihood: a number that needs interpretation in the context of other patient-specific factors and patient preferences to guide management (Fig 5). Obtaining a probability for malignancy from a decision support application gives the radiologist, patient, and referring physician the opportunity to engage in shared decision making. There is increasing interest in shared decision making in the radiology community in relation to screening tests (42). Each patient has his or her own risk tolerance, utilities for the different possible management alternatives, and outcomes to weigh in making medical decisions as a result of imaging. Giving patients a probability of disease before and after imaging can help inform them of their own individual risk. For example, the availability of a post-test probability of malignancy would allow decisions to be based on personal preference in the context of discussions with radiologists, referring physicians, and others. Formal utility assessment and decision analysis can be carried out using well-established principles of medical decision making in difficult cases.

Another informatics method that supports shared decision making is “just-in-time” information retrieval, an informatics technique to deliver knowledge needed by radiologists and patients at the time decisions are made on the basis of imaging results. There are a number of radiology-specific resources on the Web, such as ARRS GoldMiner (http://goldminer.arrs.org) and Yottalook (http://yottalook.com) (Fig 7). There are also efforts to put radiology knowledge into electronic format, enabling radiologists to find information on the Web or while viewing images in the Picture Archiving and Communication System (http://chorus.rad.mcw.edu, https://my.statdx.com). These resources, like electronic texts, provide generic knowledge about radiology imaging results: facts that are generally true about all patients having particular diseases. However, they do not provide diagnoses for specific patients. For such “personalized medicine” tasks, decision support systems play a crucial role, as discussed earlier.

**DISCUSSION**

The core aspects of patient-centered radiology that informatics can support include physician-specific activities (selecting the appropriate imaging procedures for particular patients and rendering the best imaging interpretation that is personalized to each patient) and patient-specific interests (communicating the results of imaging procedures and shared decision making). These share in common the need to manage large amounts of complex information, a task that is difficult for people without computer assistance. In fact, in current unaided practice, communication sometimes breaks down, decisions can be made without access to all the necessary information, and there is variation in physician practice.

The goal of informatics is to bring the relevant medical knowledge to physicians and to patients (1) to inform and to help radiologists provide the best care on the basis of all patient-specific information and (2) to engage patients in their health care delivery. These goals are well aligned with the objectives of patient-centered radiology. A few core informatics methodologies are common to several patient-centered radiology applications. The first methodology is controlled terminology. Creating and adopting a constrained list of terms in radiology is crucial for clear communication of imaging results to referring physicians and patients and to
permit computer applications to process radiology information unambiguously.

The second informatics methodology is decision support. A vast amount of radiology knowledge currently disseminated in published articles can be codified into computer models that can provide direct diagnostic guidance to radiologist for each patient on the basis of patient-specific characteristics. Such applications are the essence of translational medicine, by applying the knowledge in the literature to transform practice.

A third key informatics methodology is the electronic representation and transmission of information. Radiology is now an all-digital discipline, yet much of the workflow continues to adopt paper-based and film-based practice. Such work flow is inefficient, particularly with respect to communicating the results of imaging studies to referring physicians and patients. Patients are increasingly accessing their medical records online, though images are generally not part of these systems. In the future, imaging will become part of online health information systems, streamlining the dissemination of imaging results to patients and referring physicians, and more closely engaging patients in their care.

Although the informatics methods discussed in this work are promising in enabling patient-centered radiology, there could be challenges in adopting these methods. In fact, few of the informatics methods described here are widely adopted among health care institutions. The first challenge is that commercial products vary in their features and ability to deliver the functionality required. Most existing hospital systems focus on storing and retrieving patient-specific information, but few incorporate additional knowledge such as appropriateness criteria or decision support models. It is often possible to add this functionality by working with the vendors, though this can be a long and costly process.

A second challenge is that most informatics approaches require hospitals to integrate patient data that exist in many different proprietary information systems. Although standards such as Health Level 7 and Digital Imaging and Communications in Medicine have improved interoperability in terms of messaging and the storage of data, these standards do not address directly linking data from the same patient across disparate systems, a task required to provide the necessary data for many of the informatics approaches discussed in this review. Integrating the Healthcare Enterprise is creating profiles to address the problem of matching patients in different information systems. As standard terminologies such as RadLex emerge, data integration and interoperability challenges may become more tractable and the future.

A final challenge to adopting informatics methods for patient-centered radiology is cost. Informatics systems, programming staff for in-house solutions, and consultation and support require investment, both financial and personnel. In the increasingly competitive radiology environment, such costs could clearly prove to be a valuable investment by enabling institutions to more readily provide patient-centered radiology services.

In the long-term, as standards and interoperability methods mature, health care information systems will likely evolve to provide the necessary informatics infrastructure for patient-centered radiology. Just as Internet technologies are...
now pervasive in most homes and integral to how people find and use information, in the future, informatics approaches and intelligent systems will also become pervasive in hospitals, being used routinely by physicians and patients as radiology becomes increasingly patient-centered.

CONCLUSION

Patient-centered radiology is an important emerging paradigm that brings challenges to radiologists and patients as well as opportunities for informatics. The core methods of informatics in patient-centered radiology help physicians and patients access the exploding amount of data, particularly imaging data, in a timely and efficient manner. Computer applications will soon be appearing to improve the clarity of imaging data, in a timely and efficient manner. Computer

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