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Information Systems and Healthcare XXXIV: Clinical Knowledge Management Systems—Literature Review and Research Issues for Information Systems

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Information Systems and Healthcare XXXIV: Clinical Knowledge Management Systems—Literature Review and Research Issues for Information Systems

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Abstract:

Knowledge Management (KM) has emerged as a possible solution to many of the challenges facing U.S. and international healthcare systems. These challenges include concerns regarding the safety and quality of patient care, critical inefficiency, disparate technologies and information standards, rapidly rising costs and clinical information overload. In this paper, we focus on clinical knowledge management systems (CKMS) research. The objectives of the paper are to evaluate the current state of knowledge management systems diffusion in the clinical setting, assess the present status and focus of CKMS research efforts, and identify research gaps and opportunities for future work across the medical informatics and information systems disciplines. The study analyzes the literature along two dimensions: (1) the knowledge management processes of creation, capture, transfer, and application, and (2) the clinical processes of diagnosis, treatment, monitoring and prognosis. The study reveals that the vast majority of CKMS research has been conducted by the medical and health informatics communities. Information systems (IS) researchers have played a limited role in past CKMS research. Overall, the results indicate that there is considerable potential for IS researchers to contribute their expertise to the improvement of clinical process through technology-based KM approaches.

Keywords: clinical knowledge management; information systems research, medical informatics, knowledge management systems

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I. INTRODUCTION

Healthcare systems around the world are facing significant challenges with respect to rising costs, medical errors, aging populations and chronic disease management, among others. In 2005, U.S. healthcare expenditures increased at twice the rate of inflation and represented roughly 16.2 percent of the GDP [Catlin, 2006]. By way of comparison, it is expected that healthcare spending in Europe will reach 10–13 percent of GDP by 2050 [NCHC, 2007]. Some estimates indicate that as many as 100,000 people die each year in the U.S. due to preventable medical errors [IOM, 2001], and experts believe that the figures are of a similar magnitude in Europe [NCHC, 2007].

Moreover, clinicians today must be informed or have access to information for more than 10,000 known diseases, thousands of medications in use and under development, some 1,100 lab tests, 300+ radiology procedures and more than 2,000 individual risk factors [Pavia, 2001]. In 2002 the National Library of Medicine's Medline database held more than 4500 journals, and contained nearly twelve million citations in thirty languages with more than 400,000 new entries added each year [Masys, 2002].

Given the knowledge-intensive nature of the clinical domain, it has become increasingly difficult for clinicians to effectively practice medicine by relying solely on memory and experience [Masys, 2002]. Apart from the broader social, political, and economic healthcare realities, a partial solution to the challenges of limited resources, patient safety, information overload, and critical inefficiency lies at the intersection of technology and knowledge management (KM).

Technology-based KM has the potential to address a number of significant challenges in the clinical setting, including: (1) Reducing the problem of information overload by facilitating access to relevant knowledge and information at the time and place of clinical intervention, (2) Improving efficiency and clinical outcome through the integration of evidence-based standardized clinical practices and guidelines, (3) Improving patient safety and reducing medical error through clinical process standardization and core competency building resulting from heightened access to clinical knowledge, and (4) Supporting individual and organizational growth through technology and KM practices by enhancing learning through collaboration, efficient knowledge creation, and improved diffusion and utilization [Bose, 2003]. In that regard, knowledge management systems (KMS) refers to a class of information systems applied to managing organizational knowledge [Alavi and Leidner, 2001]. Given the current state of healthcare and the potential role of technology, there is a tremendous opportunity for IS researchers to contribute their knowledge and expertise to effect substantive change in the clinical domain. Accordingly, the objectives of this paper include the evaluation of the current state of KMS diffusion in the clinical setting, assessment of the present status, and focus of CKMS research efforts through a review of the literature, and identification of research gaps and opportunities for future work.

The paper is organized as follows: In Section 2 we provide a background on the clinical environment, describing the key processes of diagnosis, treatment, monitoring, and prognosis. This section also introduces the relevant human roles as well as the nature and diversity of clinical knowledge. In section 3, the methodology used to select articles for analysis is presented along with the results of the literature search. Section 4 is organized around information systems' support for clinical processes and the knowledge management activities of creation, storage, transfer, and application as discussed in Alavi and Leidner [2001]. Here, we present a synthesis of the extant literature, identify research gaps, and propose directions for future research efforts. Section 5 concludes the paper with a summary of key findings, contributions, and limitations.

II. CLINICAL ENVIRONMENT

In this section, a description of the key elements of the clinical environment is provided. Specifically, this section intends to answer the following questions:

1. What are the key processes in a clinical environment?
2. What are the key roles in a clinical environment?
3. What is the nature of clinical knowledge?

We define clinical processes as medical practices directly associated with patient care at the bedside or in hospital or clinic environments, and include the processes of diagnosis, treatment, monitoring, and prognosis [Wulff, 2000]. Diagnosis refers to the evaluation of signs and symptoms for the purpose of making a determination regarding the nature or origin of disease or injury. It involves processes of evaluating cause and effect and their application in light of the evidence to arrive at substantiated conclusions. Treatment refers to the application of known disease interventions to the specifics of the patient. Monitoring is the process of evaluating diagnosis and treatment against desired outcome, and prognosis refers to the prediction of future outcomes based on specific interventions.

The first step in all of these processes includes the collection of data in the form of patient interviews, lab tests, imaging studies, medical history, and risk factors, among others. This step is followed by data analysis. Depending on whether diagnosis is certain, therapeutic decisions are made or more information is sought through additional data collection. The theoretical basis for each of these four processes is clinical decision theory (CDT), which attempts to explain their mechanics from a cognitive perspective. CDT relies on multiple scientific perspectives including epidemiology, biostatistics, medical ethics, behavioral and cognitive psychology, and specific clinical domain knowledge [Wulff, 2000].

There are two distinct roles involved in the processes of clinical care: clinicians and patients. Clinicians include physicians, mid-level providers (nurse practitioners, physician assistants) and nurses involved in the diagnosis, treatment, monitoring and prognostic activities of clinical care. Each have specific knowledge requirements. For example, while the primary care clinician is often faced with multiple, vague symptoms requiring access to a broad knowledge base, the specialist frequently requires detailed information of a specific body system for effective decision making [Essex and Healy, 1994]. Patients play an important role as well - they are the repositories of their own personal health knowledge as well as the fundamental reason for clinical quality improvement through CKMS.

The clinical processes of diagnosis, treatment, monitoring and prognosis are largely driven and shaped by knowledge, both clinical as well as contextual. Knowledge has been described and defined variously throughout the literature, the key distinction being tacit and explicit knowledge. Tacit knowledge is contextual, based on experience and not easily codifiable, while explicit knowledge is representable and able to be communicated [Nonaka, 1994; Polanyi, 1967]. In the clinical setting knowledge is present in both tacit and explicit forms, and both are required to accurately formulate diagnostic treatment and monitoring strategies. Clinicians utilize patient, biomedical, and clinical process knowledge types. Patient knowledge is both explicit knowledge of a unique patient, such as medical history, medication history, lab results, living environment, and social and occupational history; and it can be tacit and contextual in nature. Biomedical knowledge is rooted in the biological, biochemical, physiological, and anatomical sciences, among others. This knowledge is explicit in nature and well-documented, though not necessarily always accessible. Clinical process knowledge can be either explicit—in the form of clinical practice guidelines and treatment protocols, or tacit—such as it is when the clinician develops differential diagnosis skills over time and with practice.

Given the multiple dimensions and complexity of clinical knowledge and the high accuracy requirements in clinical decision making, there is a need for clinical knowledge management systems that assist clinicians with the processes of diagnosis, treatment, monitoring, and prognosis. This is accomplished through the use of technologies that support the creation, storage, retrieval, sharing, and application of clinical knowledge. The following section presents an overview of the methodology used to conduct the literature review.

III. METHODOLOGY

The study is comprised of extensive content analysis of pertinent literature in a selected list of health informatics and IS journals based on the categorical works of Morris [1998] and Wilson and Lankton [2004]. Morris and McCain [1998] utilized citation analysis from the 1997 ISI Journal Citation Reports to identify and rank a set of twenty core health informatics journals. Ranking was accomplished by determining impact factors for each journal, which function as surrogate measures for IS journal rankings. This set was later updated by Wilson et al. [2004] using 2003 ISI Journal Citation Reports data, and was expanded to include a list of the ten most highly ranked information systems journals, according to the Association for Information Systems.

The literature search was conducted through Web of Science, which provided access to the Science Citation Index (SCI) Expanded database and the Social Sciences Citation Index (SSCI) database. SCI and SSCI were used because they index each of the journals identified by Wilson and Lankton [2004]. To ensure that our search is inclusive, a broad keyword search for “knowledge AND (management or clinical)” over a period from 1991 to 2008 resulted in 1269 articles. The criteria for identifying relevant articles was based on the contributions of a given article to the design and evaluation of a knowledge management system in the clinical setting. Accordingly, articles are included in the review if they address any aspect of a knowledge management system which supports one or more KM processes in a clinical setting/environment. Articles with a nonclinical orientation, such as those with a primary focus on KM or KMS for medical education, medical/biological research, healthcare administration and business, healthcare policy, medical/legal, veterinary, and pharmacy issues do not meet the criteria for inclusion.

With respect to the evaluation of the initial search results for relevance, a random subset of fifty articles (from the original 1269 results) was independently reviewed by the authors using a standardized worksheet based on the aforementioned criteria. Initial comparison of the independent coding efforts indicated 88 percent inter-coder agreement with respect to relevance. Analysis of the coding results indicated that each instance of initial disagreement was related to coder error with respect to identification of the clinical setting. Clarifying the notion of a clinical setting (as outlined in the previous section), we repeated the coding for another subset of fifty randomly selected articles resulting in 100 percent inter-coder reliability. The 1269 articles were then reviewed for relevance resulting in 372 references relevant to clinical knowledge management systems. Table 1 summarizes the methodical steps in the coding process described above.

Table 1: Summarization of Article Coding Process

Coding Step	Description
Step 1	Web of Science (SCI and SSCI indexes) search: "knowledge AND (management or clinical)" from 1991 to 2008, limited to Wilson and Lankton [2004] set of IS and Health/Medical Informatics publications. The search resulted in 1269 articles.
Step 2	Assessment of inter-coder reliability—two sets of fifty random articles were evaluated independently by three authors. Set 1 achieved 88 percent inter-reliability. The coding scheme was further refined by clarifying the notion of a clinical setting for the second set resulting in 100 percent inter-rater reliability.
Step 3	All 1269 articles reviewed for relevance resulting in 372 articles
Step 4	All 372 articles were categorized according to criteria noted in Table 2 by two independent authors. Any disagreement was resolved by consensus resulting in: • Knowledge Creation: 54 articles • Knowledge Storage/Retrieval: 137 articles • Knowledge Transfer: 46 articles • Knowledge Application: 135 articles

Next, relevant articles were categorized with respect to KM process (creation, storage/retrieval, transfer, and application) and clinical process (diagnosis, treatment, monitoring, prognosis). Based on the aforementioned definitions of KM and clinical processes, each article was independently evaluated by two authors. Disagreements were then resolved by discussion and consensus. In the case of clinical processes, some articles spanned across multiple processes. In such cases, the articles were assigned to multiple clinical process categories. Table 2 summarizes the definitions used to categorize the relevant articles as per the KM Processes.

Table 2: Article Relevance Criteria by KM Process

KM Process	Criteria
Knowledge Creation	An article is included in this category if it focuses on the facilitation of the development of new tacit or explicit knowledge by a KMS. Examples of these systems include those that enable the creation of new knowledge via socialization among knowledgeable people and also systems that help find interesting patterns in data and information.
Knowledge Storage/Retrieval	An article is included in this category if it pertains to a KMS for knowledge storage and/or retrieval. Such systems enable the storage, organization, and retrieval of knowledge in various forms such as documents, databases, codified knowledge such as expert systems, documented processes and tacit knowledge possessed by individuals [Alavi and Leidner, 2001].
Knowledge Transfer	An article is included in this category if it focuses on knowledge transfer/sharing systems. Such systems support the processes through which explicit or tacit knowledge is communicated to individuals [Becerra-Fernandez et al., 2004]. Examples of such systems include discussion forums, chat groups, and collaboration systems.
Knowledge Application	An article is included in this category if it describes a knowledge application system. Such systems support the process through which some individuals utilize knowledge possessed by other individuals. Mechanisms for supporting knowledge application include routines (best practices, organizational policies, workflow systems etc.) and direction (expert systems, decision support systems, troubleshooting systems, and case-based reasoning systems) [Becerra-Fernandez et al., 2004].

Table 3 provides the definitions used to categorize articles as per the four clinical process categories of diagnosis, treatment, monitoring and prognosis.

Table 3: Clinical Process Definition	
Clinical Process	**Operational Definition**
Diagnosis	Diagnosis refers to the evaluation of signs and symptoms used to make a determination regarding the nature/origin of disease or injury.
Treatment	Treatment refers to the application of known disease interventions to the specifics of the patient.
Monitoring	Monitoring is the process of evaluating diagnosis and treatment against desired outcome.
Prognosis	Prognosis refers to the prediction of future outcomes based on specific interventions.

The search process outlined above identified 372 relevant articles from thirty-one journals, as shown in Table 4.

Table 4: Number of Articles by Journal	
Journal	**Number of Articles**
Journal of the American Medical Informatics Association	66
Artificial Intelligence in Medicine	62
Methods of Information in Medicine	42
Journal of Biomedical Informatics	28
International Journal of Medical Informatics	22
Computers in Biology and Medicine	19
Computer Methods and Programs in Biomedicine	14
IEEE Transactions on Information Technology in Biomedicine	12
International Journal of Clinical Monitoring and Computing	12
Medical Informatics	10
Computers and Biomedical Research	9
Medical Informatics and the Internet in Medicine	9
Medical Decision Making	7
CIN-Computers Informatics Nursing	7
Decision Support Systems	5
International Journal of Bio-Medical Computing	4
Journal of Clinical Monitoring and Computing	4
Bulletin of the Medical Library Association	3
Journal of Evaluation in Clinical Practice	3
Medical and Biological Engineering & Computing	3
Health Affairs	2
IEEE Engineering in Medicine and Biology Magazine	2
MISQ	1
Journal of the Medical Library Association	1
Journal of Management Information Systems	1
Health Care Strategic Management	1
British Journal of General Practice	1
Academic Medicine	1
Journal of Medical Systems	1
Communications of the ACM	1
Australian and New Zealand Journal of Medicine	1

IV. FINDINGS, DISCUSSION, AND RESEARCH ISSUES

Knowledge Creation

Knowledge creation refers to the “development of new tacit or explicit knowledge from data and information or from the synthesis of prior knowledge” [Becerra-Fernandez et al., 2004]. A total of fifty-four articles were found relevant to knowledge creation. A variety of systems and technologies support knowledge creation in the clinical environment, including neural networks, data mining techniques, Bayesian methods, and many others. These technologies make it possible for knowledge to be created from disparate data sources and used to support the clinical processes of diagnosis, treatment, monitoring and prognosis. Figure 1 depicts the distribution of articles across the four dimensions of clinical process.

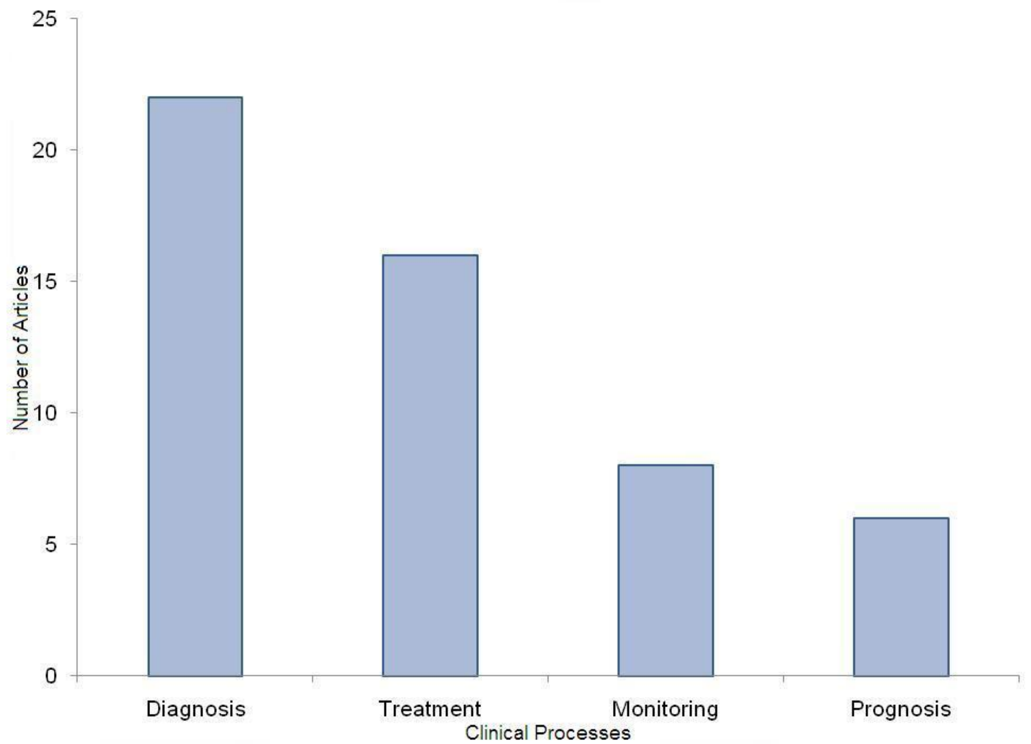

Figure 1. Distribution of Articles in Knowledge Creation Category by Clinical Process

Knowledge Creation Systems: Diagnosis

The clinical process of diagnosis requires evaluation of complex, interrelated and frequently contradictory information. To support this process, a number of technologies, systems, and methods have evolved. Rule induction algorithms such as ID3, and other approaches for generating clinical decision trees and rules support diagnosis for liver diseases [Babic et al., 1998], newborn syndromes [Braaten, 1996], abdominal pain [Ohmann et al., 1996], meningitis and hepatitis [Ohsaki et al., 2007], and others [Vannozzi et al., 2007; Wilcox and Hripcsak, 1998]. Diagnosis based on image data is a common method of computer mediated support, as was the case for Hothorn et al. [2003] who applied classifier trees to the diagnosis of glaucoma.

Bayesian networks play a crucial role in creating knowledge used for diagnosis. Such modeling techniques have been used in support of the diagnosis of depression [Chevrolat et al., 1998] and myocardial perfusion [Sacha et al., 2002]. In the latter case cardiac images were analyzed, while other research applied Bayesian probability measures to endoscopic images to calculate probabilities for sub-decisions [Zheng et al., 2005]. Another example of this approach includes the use of Bayesian classifiers in the diagnosis of visual field deterioration [Tucker et al., 2005],

Data mining and machine learning techniques are often used for diagnostic knowledge creation. It was noted above that Sacha [2002] used Bayesian learning as a technique for myocardial perfusion diagnosis. A data mining approach was used by [Kurgan et al., 2001] in the analysis of cardiac images for perfusion diagnosis. Both methods produced highly accurate diagnoses. For example, McSherry [1999] used data mining techniques for creating new clinical diagnostic knowledge, as did Nigrin [Nigrin and Kohane] and Tan et. al [2003], who used the technique along with genetic algorithms for hepatitis and breast cancer diagnostic support. Genetic algorithms (GA) overcome the limitations of traditional model estimation and have been used as noted above, as well as for other complex diagnostic problems such as glucose metabolism [Morbiducci et al., 2005].

Other technologies that create knowledge for clinical diagnosis include data visualization techniques [Falkman, 2001], and artificial neural networks (ANN), which excel at identifying complex relationships between data. Examples include an ANN for the diagnosis of myocardial infarction [Baxt, 1994], and an ANN for the diagnosis of lung nodules from chest images [Coppini et al., 2003]. Fuzzy Logic has been applied to problems where accurate differentiation between complex data points is required, for example, tissue characterization for liver disease diagnosis [Badawi et al., 1999]. Another approach centered on the reduction of computational resources is rough set theory. This method was used by Tsumoto [1998, 2000, 1997] to discover probabilistic rules and knowledge from clinical databases.

Knowledge Creation Systems: Treatment

Decisions with respect to patient treatment are complicated, due to the multitude of factors that must be considered [Ying et al., 2006]. In response to this, IS researchers have developed technologies, systems, and methods to assist the clinician with the treatment decision task. As with diagnosis above, knowledge creation systems oriented toward treatment utilize a variety of approaches for decision support, including ANNs, data mining, fuzzy logic and Bayesian methods, among others.

ANNs facilitate knowledge creation during the treatment process, and frequently do so by predicting patterns in data. Hemodynamic pattern identification and prediction via ANNs in the Intensive Care Unit (ICU) was accomplished by Spencer et al. [1997], and ANNs have been used to support treatment choices regarding neuromuscular blockade [Lendl et al., 1999] and third-molar treatment planning in orthodontics [Brickley and Shepherd, 1996].

Fuzzy Logic has been applied to the treatment decision process for neuromuscular blockade [Mason et al., 1999] and optimization of HIV treatment regimens [Ying et al., 2006]. Optimization of treatment planning has been addressed by Chi et al. [2008]; however, the method in this case involved the use of a unique optimization algorithm enabling construction of an expert system without a knowledge base requirement. In contrast to fuzzy and optimization methods, Zalounina et al. [2007] developed a stochastic model as a causal probabilistic network to predict future resistance to antibiotic therapy.

The creation of knowledge in support of treatment decisions has been facilitated by the novel development and use of knowledge-based systems (KBS), data mining, genetic algorithms, case-based reasoning (CBR), natural language processing (NLP), decision trees, and Bayesian methods. Examples include a KBS for medication side effects [Schmalhofer and Tschaitschian, 1998], data mining techniques for pediatric arrhythmia and kidney dialysis [Kusiak et al., 2005; Kusiak et al., 2001], and a genetic algorithm for chemotherapy drug scheduling [Liang et al., 2006]. Boyle et al. [1997] used another approach for chemotherapy treatment scheduling by developing a simulation engine using the WWW to create graphic illustrations of treatment regimens.

CBR has been used for invitro fertilization prediction [Jurisica et al., 1998], and NLP for automated treatment knowledge generation from biomedical and clinical documents [Chen et al., 2008]. Other methods include a decision tree approach enabling machine learning for pediatric abdominal pain treatment [Blazadonakis et al., 1996], and risk management in hemodialysis is addressed by formalizing the problem as a Bayesian network [Cornalba et al., 2008].

Knowledge Creation Systems: Monitoring

Creating knowledge to support the clinical process of patient monitoring is evident in the literature, albeit with less emphasis than diagnosis or treatment. Many of the same technologies and methods are used for monitoring, and include fuzzy logic, data mining, ANNs, Bayesian and time-series analyses.

Fuzzy logic-based systems have been documented in association with data mining techniques [Delgado et al., 2001], as well as in the domain of trend detection in surgical anesthesia monitoring [Jones et al., 2001]. Analysis of time-series data has a prominent role in knowledge creation. For example, Bellazzi et al. [2000, 1998] uses this approach in the diabetes domain, and Guyet et al. [2007] create knowledge from time-series data via a human-computer collaborative system.

Other methods of knowledge creation include a data mining approach for pediatric cardiac issues [Kusiak et al., 2006], and a combined data mining and ANN system using bedside monitoring data as intermediate outcome data [Silva et al., 2008]. A rules-based system proved successful at generating intelligent alarms in cardio-anesthesia monitoring [Popp et al., 1991].

Knowledge Creation Systems: Prognosis

One of the fundamental tasks of clinical medicine is the prediction of disease outcome based on intervention. Systems and technologies that support the process of prognosis include data mining, decision trees, temporal abstraction, and Bayesian methods.

Evidence for the use of data mining techniques was found in the literature. For example, data mining is used in conjunction with hierarchical decision modeling to predict long-term outcome following hip arthroplasty [Zupan et al., 2001]. Other uses of data mining techniques involve predicting early mortality in diabetic patients [Richards et al., 2001], and identification of factors contributing to preterm birth in obstetrical patients.

Apart from data mining, other techniques used for prognostic support include temporal abstraction for predicting health status from intensive care monitoring data [Verduijn et al., 2007b], a prognostic Bayesian network for clinical outcome prediction [Verduijn et al., 2007a], and a decision tree approach to extracting and using knowledge from large medical databases [Bohren et al., 1995].

Prognostic systems are tools that reveal patterns in patient data allowing prediction of disease outcome. Table 5 below illustrates the distribution of knowledge creation systems according to the underlying technology or method used.

Table 5: Distribution of Knowledge Creation Systems by Technology

Technology/Method	Number of Articles
Data Mining	12
Decision Tree	9
Bayesian	8
ANN	6
Fuzzy Logic	5
Temporal Abstraction	3
Genetic Algorithm	2
Rough Set Theory	2
Natural Language Processing	2
Visualization	1
Case-based Reasoning	1
Optimization	1
Causal Probability Network	1
Knowledge-based System	1

Knowledge Creation Systems: Research Issues

Research on knowledge creation systems has been focused primarily on support for the clinical processes of diagnosis and treatment. In the review, there are twenty-one references for diagnostic knowledge creation systems, sixteen for treatment, seven for monitoring and only six references for prognostic systems. Another area that is largely unaccounted for in the literature includes knowledge creation from tacit knowledge. Nonaka [1995] identified socialization as one of the four modes of knowledge creation and refers to the conversion of tacit knowledge into new tacit knowledge through social interaction and shared experience. The tacit knowledge held by individuals is one of the clinical organizations' most valued assets; however, the literature review did not identify any systems to support this mode of knowledge creation.

Other research areas to be considered for future work include automated knowledge creation from image analysis and text mining, as well as visualization models. As noted above, the literature review did identify some research on image analysis; however, further work remains to be done. Models that enable the visualization of data and knowledge were infrequently noted throughout the review, highlighting another area where research efforts have been insufficient. Another promising avenue for study includes the development of prognostic systems that integrate drug therapy and treatment models along with patient-specific genetic data for outcome prediction.

Knowledge Storage and Retrieval

Knowledge storage and retrieval systems enable the storage, organization, and retrieval of knowledge in various forms such as documents, databases, codified knowledge such as expert systems, documented processes, and tacit knowledge possessed by individuals [Alavi and Leidner, 2001]. A total of 137 articles were found relevant to knowledge storage and retrieval. An analysis of clinical knowledge management literature in this area shows the emergence of four major themes that include computer-based clinical knowledge representation techniques, knowledge retrieval system, knowledge acquisition and storage systems, and knowledge-base verification mechanisms. As shown in **Error! Reference source not found.**2, the knowledge representation techniques represents the largest category with seventy-two articles, followed by acquisition and storage, retrieval, and verification.

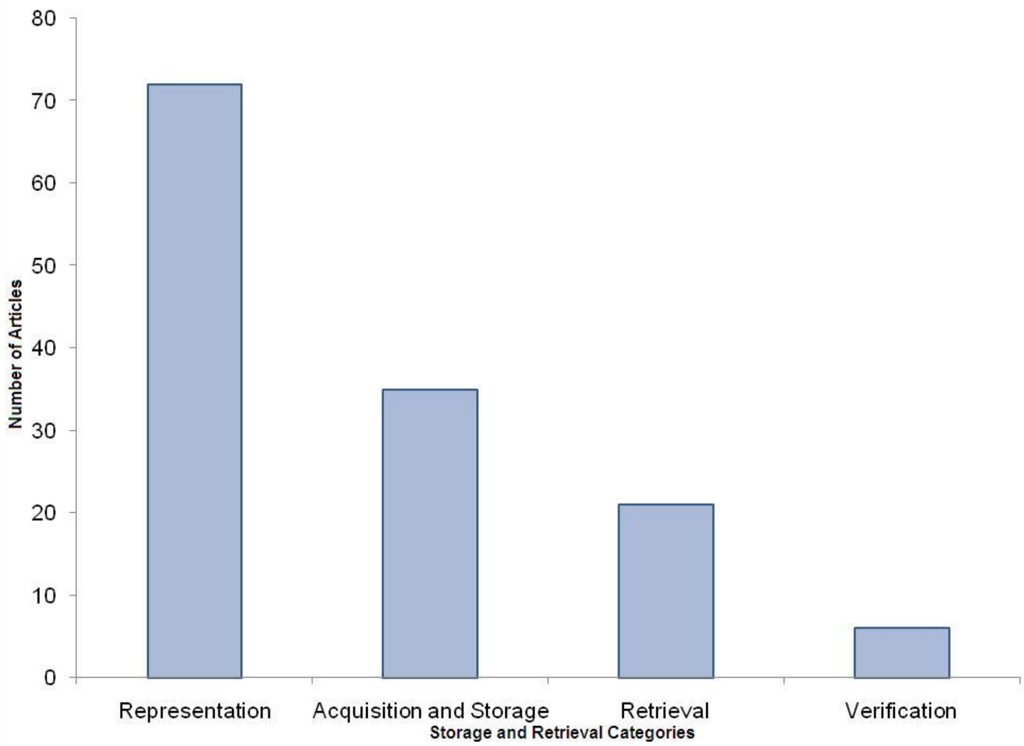

Figure 2. Distribution of Articles in Storage and Retrieval Category

Clinical Knowledge Representation

Most articles describing knowledge storage and retrieval systems for clinical knowledge management focus on computer-based clinical knowledge representation techniques. Developing effective knowledge representation mechanisms is a first step toward enabling effective storage and retrieval of clinical knowledge. The contributions in this area can be further categorized into the following classes: Medical terminology systems, clinical guideline representations, probabilistic and fuzzy knowledge representation techniques, Semantic web-based technologies and temporal knowledge representation mechanisms.

A key requirement for the unambiguous representation and storage of medical knowledge is the development of controlled medical terminologies, which, given their size and complexity, can be maintained only by using computer-based mechanisms. Several studies have looked at mechanisms for the development and maintenance of computer-based medical terminologies [Cimino, 1998a; Cimino, 1998b; Cimino et al., 1994; Harris et al., 2000; Lindberg et al., 1993; Rector et al., 1997; Schulz et al., 1997] and medical terminology servers [Cimino, 2001] for knowledge acquisition, storage, and retrieval purposes. However, effective utilization of medical terminology systems as a knowledge-base and for knowledge representation and storage requires the development of mapping mechanisms between different terminology systems and between terminology systems and natural language expressions and electronic database schemas. Toward this end, various researchers have focused on embedding clinical knowledge into healthcare information systems by developing mappings between specialized glossaries such as SNOMED and DICOM [Bidgood, 1998], mapping natural language expressions to coding schemes [Carlsson et al., 1996; Geissbuhler and Miller, 1998], integration of terminologies [Choi et al., 2005; Chute et al., 1998; Elkin and Brown, 2002; Park et al., 2007] or by embedding medical data dictionaries into healthcare information systems [Burkle et al., 1998]. Other studies on medical terminology systems include the evaluation of completeness of medical concept vocabularies for representing medical procedures [Bodenreider et al., 1998; Dykes et al., 2003] and validating their structures [Cornet and Abu-Hanna, 2005; Rogers et al., 1998].

Accumulated medical knowledge is stored and shared among practitioners in the form of clinical practice guidelines. In order to integrate clinical practice guidelines with healthcare information systems, they need to be represented in a computer interpretable format. Increased adoption of computer-based guidelines by physicians requires explicit consideration of deep medical knowledge in the design of computer-based guidelines [Barahona et al., 1995]. Several models have been proposed and evaluated for the representation of sharable computer-interpretable guidelines including GLIF [Boxwala et al., 2004; Boxwala et al., 2001; Patel et al., 1998; Patel et al., 2002], PROforma [Fox et al., 1997; Sutton and Fox, 2003], GEM [Shiffman et al., 2000; Shiffman et al., 2004], HELEN [Skonetzki et al., 2004] and GLARE [Terenziani et al., 2001].

Other clinical guideline representation studies in this area include mechanisms for visualizing the logic of clinical guidelines [Brandt et al., 1997], representing the temporal aspects of clinical guidelines [Guarnero et al., 1998], exploring XML [Hoelzer et al., 2001; Schweiger et al., 2001], relational [Hales et al., 1997; Lobach et al., 1997] and frame-based [Sorenson et al., 2008] representations of clinical guidelines. Mechanisms for converting between different guideline formats [Shahar et al., 2004], comparisons between different representation schemes [Peleg et al., 2001], decision tree methods for computerizing text guidelines [Colombet et al., 2005], and the development of ontologies to map clinical guidelines to electronic medical records [Peleg et al., 2008] have also been explored.

Beyond clinical guidelines, other clinical knowledge representation mechanisms proposed in literature include rule-based and knowledge-based mechanisms, ontologies, and probabilistic networks. Rule-based representation schemes include Arden Syntax [Hripcsak, 1994; Kuhn and Reider, 1994; Pryor, 1994; Pryor and Hripcsak, 1993], CLIPS [Pankaskie and Wagner, 1997] and Knowledge-based Temporal Abstractions (KBTA) [Shahar and Musen, 1996]. Ontologies and semantic modeling technologies have been used for a wide variety of knowledge representation tasks, including ensuring semantic consistency of shared clinical knowledge [Eccher et al., 2006], for representing shared knowledge for collaborative diagnosis [Dieng-Kuntz et al., 2006], for representing medical reasoning [Schulz et al., 1998], biomedical knowledge [Paul et al., 2006], semantic annotation of medical images [Barb et al., 2005], and for organizing clinical research results for evidence-based practice [Sim et al., 2004]. Probabilistic structures used for representing and modeling clinical knowledge include fuzzy logic and fuzzy rules [Brai et al., 1994; Kwiatkowska et al., 2007; Kwok et al., 2003; Leitich et al., 1996] and Bayesian networks [Green, 2005; Labatut et al., 2004; van Gerven et al., 2008]. Customized knowledge frameworks in specialized clinical domains, such as psychoactive drug selection [Van Hyfte et al., 2001], oncology [Bielza et al., 2008], and drug prescription databases [Riou et al., 1999] have been proposed in literature.

The temporal aspect of clinical knowledge is key to representing therapeutic knowledge required to treat patients over prolonged periods of time [Barreiro et al., 1993; Combi and Shahar, 1997; Peek, 1999]. Representation schemes for temporal aspects of clinical knowledge include those based on object oriented models [Combi and Chittaro, 1999], XML [Combi et al., 2005], rule-based [Guarnero et al., 1998], graph grammars [Muller et al., 1996], and representation schemes for temporal reasoning [Kindler et al., 1998].

Knowledge Acquisition and Storage

Knowledge capture is enabled through knowledge engineering and acquisition techniques. Several knowledge acquisition techniques have been proposed for capturing and documenting clinical knowledge. Graphical tools and methods used for knowledge acquisition include a Unified Modeling Language (UML) based knowledge acquisition method [Garde et al., 2004], graphical knowledge acquisition tools that support the specification of temporal patterns [Chakravarty and Shahar, 2001; Shahar et al., 1999], clinical guidelines [de Clercq et al., 1999; de Clercq et al., 2000; de Clercq et al., 2001], graph-based knowledge engineering techniques [Gortzis and Nikiforidis, 2008], and knowledge-base driven user interface for capturing clinician knowledge during practice [Chambrin et al., 1995].

Other contributions in this area include mechanisms for improving the human readability of medical logic modules (MLM), thereby enabling clinical experts to encode their knowledge using MLM [Choi et al., 2006], knowledge acquisition techniques for case-based reasoning in the clinical domain [Elgamal et al., 1993; Khan and Hoffmann, 2003], knowledge acquisition process for developing a knowledge-based system [Heindl et al., 2000], Internet-based knowledge acquisition methods for the development of large-scale medical expert systems [Yan et al., 2004], web-enabled XML-based knowledge authoring environment [Hulse et al., 2006; Hulse et al., 2005], and a text mining method for extracting clinical knowledge from narratives [Elgamal and Esmail, 1995; Friedman et al., 1994; Friedman and Hripcsak, 1999; Friedman et al., 2002] and for converting paper-based guidelines to computerized guidelines [Georg et al., 2005].

Articles related to clinical knowledge storage describe the design and development of medical digital libraries [D'Allesandro et al., 2005; Datri, 1994], automatic text classification and organization of clinical knowledge [Wilcox and Hripcsak, 2003], design and development of knowledge-based system [Coleman et al., 1993; Jenders et al., 1998; Jenders et al., 1994; Kalogeropoulos et al., 2003], mechanisms for structuring Artificial Intelligence (AI) knowledge-bases [Mira et al., 1998] and structure of rule-bases [Wright et al., 2007], and issues and mechanism for maintaining and combining knowledge bases [Miller, 1998; Miller et al., 1997a; Miller et al., 1998; Miller et al., 1997b]. Methodologies proposed for developing medical knowledge bases include the MACCORD methodology [Kraus et al., 1993], and a formal concept analysis based method for building clinical ontologies [Jiang et al., 2003].

Knowledge Retrieval

Effective knowledge retrieval techniques are necessary to enable the transfer and application of clinical knowledge. Proactive and context specific knowledge can be provided by integrating electronic medical records with clinical knowledge repositories. Several studies propose various retrieval mechanisms to enable such integration of electronic medical records with knowledge sources. Boulos et al. [2002] propose a semantic web-based retrieval technology that retrieves relevant clinical knowledge by automatically matching clinical codes from an electronic medical record to a knowledge base. Brennan and Aronson [2003] propose a natural language processing-based tool that automatically identifies clinical concepts from patient e-mail and links it with clinical terminologies, thereby enabling access to electronic clinical knowledge resources. Cimino et al. [1997] and Ruan et al. [2000] propose mechanisms to dictionary-based approaches to connect clinical systems with knowledge repositories. Powsner and Miller [1992], and Sneiderman [2007] propose knowledge-based mechanisms for guiding clinicians from a clinical report to relevant clinical literature. Tarczy-Hornoch et al. [1997] propose mechanisms for integrating medical records with relevant online clinical knowledge resources.

Several specialized retrieval techniques have been proposed for retrieving clinical knowledge. Examples of the specialized techniques include concept-based markup and indexing schemes that allows complex clinical queries and the retrieval of highly relevant articles [Kim et al., 1998], knowledge-based and intelligent retrieval systems for exploring time-oriented clinical data [Martins et al., 2008] and medical image-based knowledge repositories [Lowe et al., 1998; Sheng et al., 2000], agent based architectures for medical information retrieval [Walczak, 2003] and a question answering system that analyzes large number of documents to provide short coherent answers [Yu et al., 2007]. New knowledge navigation techniques such as problem focused knowledge navigation method [Meyers et al., 1998], adaptive hypermedia method [Pagesy et al., 2000], ontologies [Bratsas et al., 2007], HL7-based query models [Jenders et al., 1997], and folder based techniques [Ferri, 1995] for organizing, retrieving, and navigating clinical knowledge have been proposed. Other studies in clinical knowledge retrieval include analysis of information seeking practices of clinicians [Callen et al., 2008; Hersh et al., 2002; Hung et al., 2008; Jerome et al., 2001], and evaluation of effectiveness of retrieval techniques from various knowledge repositories such as MEDLINE [Haux et al., 1996; Haynes et al., 1994].

Knowledge-Base Verification

The verification and validation of clinical knowledge is necessary to improve the quality of clinical guidelines and knowledge-based systems and consequently the clinicians trust in the systems. Duftschmid et al. [2001, 2002] propose a knowledge-based verification method for detecting anomalies in clinical guidelines and temporal scheduling constraints. Miller et al. [1999, 2001, 2001] propose a computer-based verification tool to verify computer-based computer guidelines and to further maintain and incrementally revalidate them; ten Teije et al. [2006] propose formal methods for the verification of clinical protocols.

Knowledge Storage and Retrieval: Research Issues

As mentioned earlier, the bulk of the literature in this category addresses knowledge representation issues and is deficient in addressing knowledge retrieval issues. Most articles that deal with retrieval focus on integrating clinical information systems with knowledge repositories via simple search mechanisms, propose knowledge navigation techniques for knowledge exploration, or evaluate simple search engines. There is limited literature that discusses advanced search techniques for executing complex clinical queries on knowledge repositories. Given the inefficiency of current search techniques and the limited time availability, clinicians mostly rely on medical librarians for search and retrieval functions, thereby introducing large delays and costs in enabling knowledge transfer. Additional research on specialized domain specific search engines that can run complex clinical queries and return accurate results is necessary to increase the adoption of medical knowledge retrieval systems at the point of care.

There is limited literature on the information-seeking behavior of clinicians. While there are studies that explore knowledge sources and knowledge requirements of clinicians, there is limited research on the environment in which knowledge retrieval takes place. There is a need for understanding information-seeking behavior in the context of clinician time and motion studies to help identify most suitable retrieval mechanisms, such as mobile devices, adaptive interfaces, etc., in a given context.

Several knowledge acquisition techniques specifically adopted to the clinical environment have been proposed. Most of the techniques focus on the development of clinical guidelines synthesized through published medical literature. However, there is limited literature on acquisition of experience-based tacit clinician knowledge and point-of-care knowledge acquisition techniques. Given that there is a significant time lag involved in the transfer of medical knowledge validated by scientific clinical studies, tacit clinical knowledge and knowledge captured at the point-of-care can serve as a preliminary source of knowledge that can help identify promising new developments.

Clinical knowledge stored in narratives and unstructured or semi-structured text is inaccessible as it is not computer interpretable and, therefore, cannot be easily transferred. The use of text mining to convert clinical knowledge in narratives and text to a computer interpretable form can greatly increase the accessibility of such knowledge. While there are a few articles that address this issue, this topic is largely unexplored.

Knowledge Sharing

"Knowledge sharing systems support process through which explicit or tacit knowledge is communicated to individuals" [Becerra-Fernandez et al., 2004]. A total of forty-six articles were found relevant to knowledge sharing. Examples of such systems include discussion forums, chat groups, collaboration systems, web-based access to data, best practices data, and lessons-learned systems [Becerra-Fernandez et al., 2004].

The literature review identified eighteen categories of technology and methods for sharing knowledge in the clinical domain. The research area receiving the most attention in recent years is in web-based sharing tools. Examples include a knowledge exchange [Buchan and Hanka, 1997], an Internet-based knowledge source integration tool [Fuller et al., 1999], a knowledge-sharing and retrieval tool [Hersh, 1999] and web-based patient education tools [Lee et al., 2007; Smith et al., 2002]. Martens and Zapf [1993] developed a web-based referral system for knowledge sharing between physicians and patients, while Bichindaritz et al. [1998] used the WWW to create a clinical knowledge support system. Other examples include a web-based guide for librarian/clinician knowledge exchange [Rader and Gagnon, 2000], collaboration through virtual settings [Paul, 2006], and research examining knowledge source relevance and clinician search habits [Pluye et al., 2007a; Pluye et al., 2007b]. Table 6 summarizes the eighteen knowledge-sharing technologies and methods and corresponding article count for each category.

Table 6; Distribution of Knowledge Sharing Technologies and Methods

Technology/Method	Number of Articles
Web-based sharing tools	17
Knowledge exchange	4
Representation formats—GLIF etc.	4
Clinical guidelines/EBM	3
Mobile tools—PDAs, etc.	2
Ontologies	2
Database	2
KBS	2
Bayesian Network	1
Video Games	1
Intelligent System	1
System design methodology	1
Ethical decision making framework	1
Digital Library	1
Groupware	1
Semantic Modeling	1
Sharing Evaluation Tool	1
Time-based Collaboration Tool	1

A variety of other technologies support knowledge sharing in the clinical environment. Mobile technologies such as PDAs are increasingly being used to share knowledge [Brock and Smith, 2007; Buchauer et al., 1998] and support nurse decision-making [O'Neill et al., 2004; O'Neill et al., 2006]. Other research has focused on the use of ontologies [Falasconi et al., 1998; Liu et al., 2008], intelligent systems [Buchanan et al., 1995], as well as a variety of knowledge representation formalisms for knowledge sharing [Boxwala et al., 2001; Choi et al., 2005; Giorgi et al., 2001; Grutter and Fierz, 1999].

Similar to many of the technologies used for the other KM processes, knowledge sharing takes advantage of advances in the application of Bayesian networks [Lehmann and Shachter, 1994], knowledge-based systems [Balas et al., 1996; Hulse et al., 2008], semantic modeling [Barb et al., 2005], and temporal-based methods [Guyet et al., 2007]. Clinical informatics knowledge exchange has been the subject of some research. These exchanges, frequently referred to as clinical consult services, mediate the sharing of knowledge between medical librarians and clinicians and have proved effective for integrating knowledge into patient care [Jerome et al., 2001; Mulvaney et al., 2008; Viceconti et al., 1993].

Digital medical libraries can support knowledge sharing, as noted by Mendonca et al. [2001]. Groupware applications which facilitate the exchange of knowledge and discussion of radiology images [Sakellaropoulos et al., 2003], are less common than expected. One system was noted to facilitate knowledge sharing with respect to ethical decision-making in the clinical setting [Frize et al., 2005]. Knowledge sharing is also enabled through the formulation of clinical guidelines, which are, in essence, models of the patient care process. As an instantiation of evidence-based medical practice, they can serve to facilitate knowledge sharing [Sandars and Heller, 2006; Stefanelli, 2001; Vissers et al., 1996].

Knowledge Sharing: Research Issues

Compared to The KM processes of knowledge storage/retrieval and application, little research has been focused on knowledge sharing systems and technologies. Of the sharing systems research identified, considerable effort has been directed at the Internet, or WWW, as well as knowledge representation formats for sharable guidelines. Interestingly, little research to date has focused on the use of mobile technologies, such as handheld computers and PDAs. These technologies have the potential to enhance knowledge sharing, but are often dependent on clinical information systems such as electronic health records, which only recently have seen adoption and use numbers rise.

Another trend identified from the literature review is the lack of association of knowledge sharing research with the clinical processes of diagnosis, treatment, monitoring, and prognosis. Only four out of forty-eight knowledge sharing references could be identified with a particular clinical process. As a matter of relevance, future research should attempt to address the challenges of knowledge sharing within the context of these processes.

Finally, it is interesting to note that only one article dealt with the technology of groupware and group decision support. Collaborative technologies have the potential to facilitate the sharing of explicit and tacit knowledge, and future research should explore ways to make these technologies more abundant in the clinical setting.

Knowledge Application

Knowledge application systems focus on supporting the KM application process through utilization of preexisting knowledge by clinicians requiring minimal efforts in acquiring or learning that knowledge. Preexisting knowledge may be integrated into clinical processes using the mechanisms of direction and routine (Grant, 1996). A total of 135 articles were found relevant to knowledge application. Technologies such as expert systems (often referred to as knowledge-based systems or rule-based systems), decision support systems, and CBR systems are illustrative of *direction* support, where the goal is to guide decisions and actions by utilizing embedded expert knowledge rather than transfer of knowledge. Similarly, technologies such as expert systems, workflow systems, and clinical guideline-based systems are illustrative of *routines* support, where the goal is to utilize knowledge embedded in procedures, rules, scripts, and norms to guide future behavior.

In the following subsections, KMS supporting the knowledge application process are highlighted with respect to different clinical processes including diagnosis, treatment, and monitoring. Within each clinical process, discussion is structured-based so as to illustrate key application areas for KMS in clinical applications, while highlighting emerging themes and gaps in the literature. Readers are referred to Figure 3 for the distribution of articles in this category.

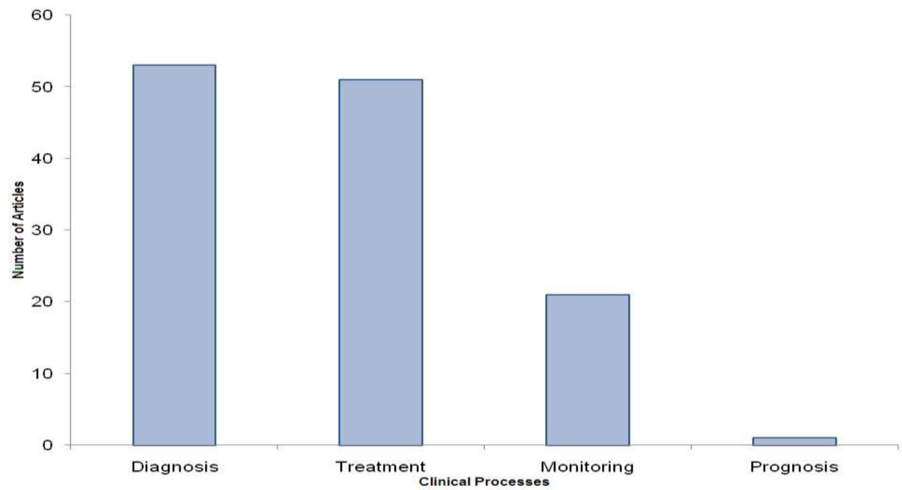

Figure 3. Distribution of Articles in Knowledge Application Category

Knowledge Application: Diagnosis

Diagnosis is a complex clinical process involving the synthesis of vast amounts of biomedical knowledge with clinical knowledge. The goal of knowledge application systems is to assist clinicians in making diagnostic decisions [Hasman et al., 2003]. Several studies have reported on developing knowledge application systems where clinicians' knowledge is embedded in the system to support different use cases occurring in clinical diagnosis processes.

Expert systems, founded on rule-based reasoning mechanisms are noted to be the most widely used technology for this purpose. A common application of expert systems is in utilizing knowledge about patients' symptoms and related data, in conjunction with a clinical knowledge base, to formulate an accurate diagnosis [Pesonen et al., 1994; Vingtoft et al., 1994; Wolfram, 1995; Zhao et al., 1994]. Another typical use case of expert systems is supporting accurate interpretation of test results. Several studies report on developing expert systems for integrating results from clinical tests or signal analysis tools with qualitative knowledge of physicians [Boufriche-Boufaida, 1998; Garibaldi et al., 1999; Garibaldi et al., 1997; Mishra and Dandapat, 1993]. Yet another common use case for expert systems is image segmentation for better diagnosis, for example, X-ray image analysis in orthodontic cases [Davis and Forsyth, 1994], and radiograph image analysis in pediatric cases [Oliveira et al., 2008].

In areas where medical knowledge is often imprecise and uncertain, fuzzy logic and Bayesian networks are candidate technologies serving as reasoning mechanisms in expert systems. Fuzzy expert systems based on fuzzy sets and relations have been developed by some researchers [Fathitorbaghan and Meyer, 1994; Georgopoulos et al., 2003]. Similarly, researchers have proposed Bayesian belief network-based expert systems, for example, in interpreting test results from echocardiography [Diez et al., 1997], and in diagnosing lower back pain [Lin et al., 2006].

Clinical decision support systems (CDSS) supporting diagnosis processes are a related suite of technologies, which are often referred to as *medical diagnostic decision support (MDDS) systems* [Peleg and Tu, 2006; Wigertz, 1995]. They vary greatly in the nature of decision support offered, biomedical context, knowledge sources, information transfer, and impact [Berlin et al., 2006]. Knowledge-driven CDSS, a class of decision support technologies similar to expert systems incorporating a rule-base component, have been developed by several researchers [Coulson et al., 2001; Economou et al., 2001; Kahn, 1993; Nguyen et al., 2000; Wyatt, 1997]. Model-driven CDSS, another class of decision-support technologies, incorporates models for generating decisions based on relevant clinical knowledge parameters and patient data. For example, model-driven MDSS systems have been developed for applications, such as diagnosing brain disorders [Siregar and Toulouse, 1995], diagnosing pneumonia in the intensive-care unit [Lucas et al., 2000], and extracting cardiac imaging structures [Pfeifer et al., 2006]. In recent years, with the advancement of distributed technologies, web-based knowledge application systems have emerged for supporting clinical diagnostic processes [Eich and Ohmann, 2000; Ekdahl et al., 2000; Seka et al., 1997].

Evaluation is key in understanding if the implemented knowledge application system is indeed functioning as an effective aid in the diagnosis process, and if so, how effective and useful it is. In that regard, researchers have reported on extensive field studies, which involve comparing the diagnoses provided by the KMS to those suggested by clinicians [Berner and Maisiak, 1999; Berner et al., 1999; Bonis et al., 2008; Boonfalleur et al., 1995; Bruning et al., 1997; Edwards et al., 1995; Hu et al., 2006; Innis, 1997; Korpinen et al., 1994; Kotzke and Pretschner, 1992; Leitich et al., 2001; Lejbkowicz et al., 2002; Martin, 2001; Moens, 1992; Moens et al., 1992; Molino et al., 2000; Ridderikhoff and vanHerk, 1997]. Overall, these results indicate that KMS certainly enhances the clinical practitioners' diagnostic capability, resulting in an improved overall diagnostic accuracy. Alternative knowledge reasoning algorithms have been compared to determine which technology suits better for the diagnosis problem under consideration. Researchers have reported on such experimental studies, emphasizing the context-specific nature of problems and value in conducting such studies [Krusinska et al., 1993; Molino et al., 1996; Todd and Stamper, 1994].

A complex relationship has been noted to exist between clinicians' confidence in system-provided diagnoses and correctness of the diagnoses, which can play a crucial role in acceptance of such KMS [Westbrook et al., 2005]. Interfacing diagnosis support KMS with hospital information systems can avoid manual data entry, thus improving physician acceptance as well as productivity [Borst et al., 1999; Brigl et al., 1998; Buscher et al., 2002; Ivandic et al., 2000; Wong et al., 1994].

Knowledge Application: Treatment

Following diagnosis, prescribing specific therapy advice based on clinical guidelines is the main goal of clinical treatment processes and need to be supported through knowledge application systems. Expert systems or knowledge-driven CDSS, similar to diagnosis processes, are seen to be the most prevalent type of technologies used for therapy planning and configuration [Burkle et al., 1997; Heermann and Thompson, 1997; Im and Chee, 2003; Marin et al., 1993; Muller et al., 1997]. They are used for test selection, for example, to administer nuclear medicines [Houston and Tindale, 1996]. While rule-based reasoning is primarily used, other techniques, such as constraint satisfaction [Smith et al., 1998] and fuzzy logic [Greenhow et al., 1992], have been used in a few cases for prescribing and planning drug therapy. An integrated approach combining different reasoning mechanisms, such as rule-based, heuristic, and algorithmic techniques, has been proposed for therapy planning in certain complex domains, such as renal dialysis [Raghavan et al., 2005]. In spite of much research on therapeutic planning, development of knowledge application systems for predicting treatment outcomes, or, in other words, prognosis, is minimal [Frize et al., 1998].

Patient management during treatment processes includes not only providing recommendations on preferred interventions, i.e., therapy planning, but enabling critical analysis of interventions instituted, generating reminder alerts on questionable data, and investigating any potential drug interactions. Some knowledge application systems with such a patient management focus during treatment processes have been reported [Leaning et al., 1992; Sonnenberg et al., 1994]. Web-based [Riva et al., 1998] and mobile [Buchauer et al., 1998] knowledge application systems are being developed to harness the advances in distributed and mobile computing and promote effective collaboration among clinicians. Tele-consultation systems, which build on distributed computing infrastructures, also require therapy planning and monitoring support, such as in diabetic patient management [Montani et al., 1999].

Clinical practice guidelines are used to model the current state of knowledge in a given biomedical domain and describe how to apply that knowledge for the desired clinical outcome. Several knowledge application systems focus on implementing computerized therapeutic guidelines to make them accessible to clinicians during the treatment process and provide a shared best practice knowledge base for disease management [Bouaud et al., 1998; Gordon et al., 1994]. Moreover, integration of computerized clinical protocol support systems with electronic patient records systems is important to ensure seamless flow of information and improved disease management [Ball et al., 2003; Musen et al., 1996; van Oosterhout et al., 2005]. In spite of numerous computerized implementations of clinical practice guidelines [Wang et al., 2004], there is still little evidence of physicians compliance to formal standards [Caironi et al., 1997; Seroussi et al., 2001; Sward et al., 2008]. Some systems have been developed to analyze the utilization and adherence to clinical guidelines for clinical performance improvements [Balas et al., 1996].

Patient care workflow management systems (sometimes referred to as careflow systems), based on clinical guidelines, have been developed to span across the clinical processes of diagnosis, treatment, and monitoring, in order to provide an integrated system for managing different clinical activities, knowledge, and resources [Dang et al., 2008; Dazzi et al., 1997; Quaglini et al., 2000; Quaglini et al., 2001]. Given the knowledge-intensive and specialized nature of most clinical processes, special attention should be given to exception management occurring in normal flow of activities [Panzarasa et al., 2002].

Evaluation studies have focused on comparing system-generated therapy plans with physician-generated therapy plans, such as parenteral nutrition plans [Horn et al., 2002], ventilator therapy [Miksch et al., 1996; Shahsavar et al., 1995], and many others [Lau, 1994; Vollebregt et al., 1999]. Reduced errors and omissions in resultant plans generated with KMS indicates promise in providing improved patient care. However, in some cases CDSS implementations have shown to introduce errors [Coiera et al., 2006]. Other studies have examined the impact of computerized guidelines and decision support on decision quality, reporting positive results on average [Hanzlicek et al., 2005; Hozo and Djulbegovic, 1999; Sintchenko et al., 2004; Zielstorff et al., 1997]. Other patient-oriented evaluation metrics have been used to measure the impact of using KMS applications in the therapeutic process, for example, readability and cultural sensitivity of decision tools [Thomson and Hoffman-Goetz, 2007], improved patient choice [Holmes-Rovner and Rovner, 2000], reduced decisional conflict in patients [Col et al., 2007; Protheroe et al., 2007]. It has been suggested that use of key performance indicators can be advantageous in understanding the impact of KMS on clinical processes [Berler et al., 2005].

In spite of extensive development and evaluation efforts [Ruland and Bakken, 2002], acceptance and adoption of KMS systems by clinical practitioners is seen as a major challenge [Bates et al., 2003; Teich et al., 2005]. Taking a "socio-technical" approach to development and implementation of KMS, incorporating continual organizational inputs and endorsements have resulted in success stories [Goldstein et al., 2004; Sjoborg et al., 2007; Timpka and Johansson, 1994]. Cognitive task analysis has been used for enhancing integration of technology into the clinical work environment [Baxter et al., 2005].

Knowledge Application: Monitoring

Knowledge application systems for monitoring treatment plans have been proposed by researchers, particularly for high dependency environments such as intensive care units, neonatal units, operating and recovery rooms [Bowes et al., 1991; Taboada et al., 1997]. Ventilator therapy support in intensive care monitoring is a typical application use case [Seroussi et al., 1995; Summers et al., 1993]. Most of these KMS follow a rule-based approach and can be considered as applications of expert systems. However, there are some developments in using other knowledge reasoning mechanisms such as case-based reasoning for monitoring purposes [Bichindaritz et al., 1998].

Clinical alerts and reminder systems are a key component of many monitoring systems and have seen application of fuzzy logic reasoning techniques [Becker et al., 1997] and rule-based techniques [Ludemann, 1994; Lussier et al., 2007]. Patient data encoded with EMR can be used to automatically detect adverse clinical events, thus enhancing disease surveillance [Hazlehurst et al., 2005]. Task scheduling and communication management systems have been successfully used in telemedicine settings, particularly in critical care units [Vazquez et al., 2007]. While clinical alert and reminder management systems provide useful information, they bring with them possibility of information overload. Some studies have indicated mixed opinions with safety issues on one hand, and performance issues on the other hand [van der Slis et al., 2008].

Evaluation studies for KMS in monitoring processes mainly deal with measuring the ability of the system to ensure successful implementation of care plans and adaptation to the patient's post-treatment needs. Evaluation has shown promising results in cases including ventilation therapy support systems [Bottino et al., 1997; Dojat et al., 1992; Dojat et al., 1997; Kwok et al., 2004], clinical alert systems [Koski et al., 1994; Sukuvaara et al., 1993], monitoring potential drug interactions [Gronroos et al., 1997], and others [Fan et al., 2004; Urschitz et al., 1998]. Simulation test methodology has been useful for testing rare and complex cases [Larsson et al., 1997].

Knowledge Application: Research Issues

Rule-based approach is the most prominent knowledge reasoning technique used at the core of most clinical knowledge application systems. Model-based reasoning, case-based reasoning, constraint satisfaction, and fuzzy logic have been used in some application systems, although sparingly. Notably, applications of other reasoning techniques such as diagrammatic reasoning, and variants of CBR including analogy-based reasoning and exemplar-based reasoning are lacking. Approaches that go beyond the traditional rule-based reasoning techniques need to be further explored to solve complex diagnosis, treatment, and monitoring problems. Most knowledge application systems are based on knowledge elicited from experts. While there is literature that discusses knowledge creation systems based on data mining techniques, there is significant scope for applying similar techniques for knowledge application as well [Horn, 2001].

There is an abundance of literature that discusses knowledge application systems that are designed for use by clinicians. However, there is a need for developing patient-centered knowledge application systems that can help patients in decision making related to their treatments [Haux, 2002, 2006; Haux et al., 2002; Scott and Lenert, 1998]. Another area of research with potential for further research is patient care workflow management systems. Patient care workflow management systems have been developed in integration with clinical practice guidelines. However, one of the main limitations noted for such systems is limited flexibility and adaptation capabilities to respond to changing patient care needs. Advances in dynamic workflow systems need to be leveraged to overcome these limitations and provide the much needed flexibility in handling normal as well as exceptional occurrence of events.

There is minimal literature on knowledge application systems for clinical prognosis. Estimating treatment outcomes can lead to better response readiness, in turn leading to better patient care. This is a key issue that seeks attention. Even in the case of clinical processes of treatment, diagnosis and monitoring, knowledge application systems have focused on clinical settings such as primary care, hospitals, and intensive care units, there is a noticeable dearth of systems geared for medical emergency response. Information systems research developments focused on crisis and emergency management systems may be applied to filling this research gap.

V. CONCLUSION

This paper reviewed high quality medical/health informatics and information systems literature in an attempt to evaluate the current state of knowledge management systems diffusion and research in the clinical setting. The review identified 372 articles pertaining to clinical knowledge management systems, technologies, and methods capable of supporting the four key clinical processes of diagnosis, treatment, monitoring and prognosis. Such support is accomplished through the use of IT-enabled approaches to the management of knowledge creation, storage and retrieval, sharing, and application. With respect to potential research gaps, the paper highlights several important matters regarding CKMS as follows:

Knowledge creation: Research on knowledge creation systems has focused primarily on the processes of diagnosis and treatment, leaving substantial room for further work on creating knowledge for better clinical monitoring and prognosis. Another area study is the creation of new tacit knowledge. In healthcare, the challenge is that tacit knowledge is often held closely to the individual for a variety of complex social and organizational reasons. The IS perspective can be of tremendous value here.

Knowledge retrieval: The review also highlights the need for greater focus on knowledge retrieval mechanisms in the clinical setting. There is a need for research on advanced search techniques for executing complex clinical queries on knowledge repositories. Further work is needed with respect to the information needs and search behavior of clinicians. Certainly IS research on mobile computing and distributed systems can inform this challenge.

Knowledge sharing: With regard to knowledge sharing, research is needed that situates knowledge sharing technologies and mechanisms in the context of the clinical processes . Other opportunities for IS researchers exist in the development of collaboration technologies that enable the sharing of both tacit and explicit knowledge in the clinical setting.

Knowledge application: Finally, for knowledge application, technologies and methods that extend the traditional rule-based reasoning techniques need to be further studied. Specific areas of research include patient centered decision support systems and knowledge application systems for clinical prognosis. Knowledge application research for advanced clinical workflow and emergency/crisis management are also needed.

Overall, the research presented here provides an awareness of past and present CKMS research and makes it possible to identify gaps in our knowledge of such systems. This is important because it enables researchers to move toward new research frontiers in CKMS. Moreover, the study has shown that there is limited CKM research published in IS journals. We suggest that despite the availability of specialized avenues for clinical and healthcare oriented KMS research, IS researchers and journals have an important role to play in future CKMS research. Information systems can make a significant contribution to knowledge in this field. The experience and knowledge accumulated in the traditionally technology and business-focused IS discipline has the potential to inform and direct the growing medical informatics field. IS researchers can contribute to the diversity of traditional IS literature by actively seeking to publish high-quality medical/health IS research in traditional outlets. Journals and other publications typically reserved for traditional IS research can also play a significant role through the development of appropriate outlets for such study.

It is important to point out that given that the goal of the paper is to highlight the important research developments and opportunities for IS researchers, a comprehensive review of all pertinent issues is attempted only within the scope outlined in the methodology section. Specifically, our review of the literature is limited to a set of journals identified by Wilson and Lankton [2004] as described in the methodology section.

Knowledge management systems support the KM processes of knowledge creation, storage/retrieval, transfer and application thereby supporting the clinical processes of diagnosis, treatment, monitoring and prognosis. This is accomplished through a variety of technologies, systems and methods as outlined in the sections above. Given the advancements in medical and biological knowledge along with the burden of managing such a vast and complex array of clinical knowledge, their value as clinical tools are essential to the practice of medicine and clinical care.

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Editor's Note: The following reference list contains hyperlinks to World Wide Web pages. Readers who have the ability to access the Web directly from their word processor or are reading the paper on the Web, can gain direct access to these linked references. Readers are warned, however, that:

1. These links existed as of the date of publication but are not guaranteed to be working thereafter.
2. The contents of Web pages may change over time. Where version information is provided in the References, different versions may not contain the information or the conclusions referenced.
3. The author(s) of the Web pages, not AIS, is (are) responsible for the accuracy of their content.
4. The author(s) of this article, not AIS, is (are) responsible for the accuracy of the URL and version information.

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