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## Information Systems and Healthcare XXI: A Dynamic, Client-Centric, Point-Of-Care System for the Novice Nurse

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# Information Systems and Healthcare XXI: A Dynamic, Client-Centric, Point-Of-Care System for the Novice Nurse

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**A**ssociation for **I**nformation **S**ystems

## INFORMATION SYSTEMS AND HEALTHCARE XXI: A DYNAMIC, CLIENT-CENTRIC, POINT-OF-CARE SYSTEM FOR THE NOVICE NURSE

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### ABSTRACT

Nurse clinicians need to make complex decisions on a continual basis, while delivering cost-effective treatments. The rapid proliferation of medical and nursing knowledge complicates the decision-making process, particularly for novice nurses. We describe a Clinical Decision Support System (CDSS) for the novice nurse that combines evidence-based nursing knowledge with specific patient information to create a real-time guide through the nursing diagnostic care process. The goal of the paper is to describe how an appropriately designed and evidence-based CDSS can aid the nursing practice. An off-the-shelf handheld computer is utilized to deliver clinical knowledge to the nurse, via wireless link to a central server and a data repository. In describing the software architecture of the system, particular emphasis is paid to the issue of *appropriate design* by discussing the steps taken to address system extensibility, performance, reliability, and security, which are important factors in the design of a CDSS.

**KEYWORDS:** nurse, decision, wireless, design

### I. INTRODUCTION

Acute care units are often chaotic environments that feature high activity, excessive input, uncertainty, interruptions, and competing responsibilities [Lang 1999; Sinclair 1990]. In these environments, nurses strive to provide humanistic and clinically sound nursing care to their patients in a timely manner. At the system level, this translates to patient-centered care grounded in evidence-based practice. According to some estimates, the national shortfall of nurses is expected to reach 500,000 by 2020. This means that healthcare organizations must seek a variety of solutions to reduce nurse attrition and increase their nurse efficiency [Case et al. 2002]. Clinical information systems offer such a solution for the improvement of clinical decision making

and patient outcomes [Bates et al. 2001]. However, to date, informatics has been underutilized in nursing to advance healthcare objectives. Two areas could benefit from point-of-care computer support: increasing the accuracy and efficiency of patient care delivery (cost savings) and leveraging technology to enhance patient safety (risk/error reduction). Such a device will be particularly useful to the novice nurse. As a recent theoretical understanding of the transition from novice to competent nurse illustrates [O'Neill et al. 2004a], there is a lag in this transition process regarding the development of a sense of saliency in the clinical environment as well as sufficient working knowledge to address clinical situations. The novice nurse could significantly be aided by timely guidance by an experienced nurse in the development of clinical judgment skills. However, the shortage of experienced nurses combined with the chaotic environment of acute care settings necessitates a different strategy beyond a 1:1 mentoring system.

The hand-held Nursing Computer Decision Support system (N-CODES), which is presented here, provides a means to leverage technology to fill this void and enhance the overall quality and safety of care in acute-care environments. The N-CODES project has focused on developing the processes and a prototype to determine the feasibility of converting evidence-based knowledge to a rule structure that would support a point-of-care Decision Support System (DSS). A key issue in the development of the N-CODES system was acceptability to practice, which has been an ongoing barrier with DSS among healthcare professionals. Despite their limited use, there is still a lot of ongoing investment in automated manual (cookbook) systems [Currell and Urquhart 2005]. It is valuable to design a computer support system that mimics the way expert knowledge naturally occurs in clinical environments, which will greatly facilitate acceptance by nurses. In that spirit, N-CODES does not follow a "cookbook" approach. Instead it mimics a mentor by guiding the novice nurse through the clinical decisions using data specific to an individual client and suggesting avenues to consider and data to be collected. It is important to note that this is not a prescriptive system and only the nurse in the actual clinical situation can determine the relevance and applicability of the DSS response.

The paper is organized as follows: Section II describes previous work in the area of clinical decision support systems. Section III describes the system in a dynamic way by specifying its tier interoperability using the Enterprise Communication Framework. Section IV describes the static system architecture and the particular steps taken to address system extensibility, performance, security, and reliability. Section V discusses the N-CODES user trial. A conclusion and a description of future work are provided in section VI.

## **II. BACKGROUND**

Computer decision support systems can lead to enhanced evidence-based practice, error reduction, effective patient knowledge management, and increased patient safety. At the organizational level, there is a growing awareness of the knowledge overload facing the clinician. The notion of knowing everything is being replaced by the idea of knowing where to quickly access needed knowledge [Hajioff 1998]. Focus has shifted therefore to managing knowledge within healthcare environments by focusing on the structures and algorithms necessary for its acquisition, organization, and retrieval [Brailer 1999]. In addition, leaders need to find mechanisms to encourage clinicians to be conscious decision-makers. This requires the ability to structure and clarify clinical decision problems and develop a more critical attitude of examining the possibility that initial decisions might be incorrect [Nurius 1999].

### **COMPUTER DECISION SUPPORT SYSTEMS IN MEDICINE**

DSS within healthcare has been considered since the mid-1950s, with the emphasis of earlier systems being on providing a solution to the diagnostic problem, while the focus of later systems shifted to providing help in different steps of the diagnostic process [Berner 1998]. Some of the most well-known systems developed in the 1970s are (a) MYCIN, a rule-based system developed by Shortliffe for the diagnosis and treatment of certain blood infections [Shortliffe 1976], (b) AAPhelp, a system developed by DeDombal for the diagnosis of acute abdominal pain

[DeDombal et al. 1974], (c) Internist I, a system developed at the University of Pittsburgh, for the diagnosis of complex problems in general internal medicine [Myers 1990], and (d) ONCOCIN, a successor of the MYCIN system, developed at Stanford University to help physicians with the treatment of cancer patients [Shortliffe et al. 1981]. Later successful systems developed in the 1980s include Dxplain (Barnett et al. 1998), a system developed at Harvard Medical School that gives a ranked list of diagnoses, and QMR, a diagnostic DSS based on Internist I [Myers 1990]. Reviews of progress in the field of clinical DSS can be found in Bemmel and Musen [2002], Musen [1999], Teich et al. [2000], Berner [1998], and Sim et al. [2001]. Recently, there has been significant interest in the use of guideline-based decision support in medicine. A well known example in this area is the SAGE project [Beard et al. 2002], which offers guideline deployment in a decision support environment. Another area that is recently attracting interest for the application of CDSS systems is electronic prescribing [Teich et al. 2005].

In the last decade, an area that has gained importance in DSS research is the standardization of various aspects of the decision support process, such as its component processes and the language used to express the decision steps. Significant work in this area has originally been done by John Fox and collaborators, first through the Oxford System of Medicine [Krause et al. 1993], which provided a formal specification of a clinical DSS system and then the development of PROforma, a knowledge representation and formal specification language [Fox and Thomson 1998]. A well-known example of a component-based approach to decision support is the EON system [Tu and Musen 2001].

One of the leading organizations in this standardization effort is HL7 through its Decision Support Technical Committees and Service Oriented Architecture SIG. There are three recent products of HL7 that have direct effects on the standardization of the decision support process. The first one is GELLO, an object-oriented language for the expression of computable knowledge, such as "IF...THEN..." rules. GELLO was approved by HL7, in the January 2005 balloting cycle, as a standard for the expression of rules and queries regarding clinical guidelines [Sordo et al. 2003]. Another important and earlier HL7 standard of the same type is the Arden Syntax, which uses Medical Logic Modules (MLMs) to represent medical logic [Choi et al. 2006]. The second is development of a Virtual Medical Record (vMR), which defines a data model for representing patient information based on the HL7 Reference Information Model and allows decision support systems to access heterogeneous patient databases in a standardized way [Johnson et al. 2001]. Finally, the Healthcare Services Specification Project Decision Support Service, a joint project of the HL7 Clinical Decision Support Committee and Healthcare Services Specification Project (HSSP), aims at reducing the cost and complexity of CDSS by providing services for different parts of the decision support process, such as the Record Locate and Update Service, and the Decision Support Service [Kawamoto 2006].

## **DECISION SUPPORT SYSTEMS IN NURSING**

DSS development in nursing has been limited by a number of factors, such as the lack of models to capture nursing decision making processes and non-integrated, non-real-time patient care information systems. An exception is the system developed by Zielstorff et al. [1997] for the prevention and management of peptic ulcer, which is both real-time and patient-specific (integrated). Despite increasing end-user satisfaction, a preliminary study on 15 nurse users showed no effect on clinical decision making skills [Bakken 2006]. Two earlier systems are also worth mentioning, because of their use in clinical practice: (a) the CANDI system [Chang et al. 1988], [Roth et al. 1989]; and (b) the system developed by Koch et al. [Koch 1996; Koch and McGovern 1993]. These systems are implemented primarily as rule-based systems with the specific patient data as context and are not portable. However, as noted in Schutzman [1999], nursing units require complex, portable systems with seamless connectivity. A 1998 survey of the Health Information and Management Systems Society (HIMSS) demonstrated increased organizational interest in point-of-care systems, with 30 percent indicating spending plans for emerging technologies, particularly wireless [Schutzman 1999]. In examining the environment, the author further notes that lightweight handhelds will be most useful for extremely mobile

applications, such as nursing. In addition, Bates et al. [2001] concluded that the introduction of clinical decision support systems and better connectivity among systems could result in significant improvement in patient safety. Therefore, the N-CODES system is developed as a wireless tool with the specific needs of a modern clinician in mind.

Regarding standardization, a number of standardized nursing languages exist today that describe the diagnoses, interventions, and outcomes encountered in the nursing practice [Ozbolt 2003]. These languages include NIC (Nursing Interventions Classification) [McCloskey Dochterman, and Bulech 2004], NOC (Nursing Outcomes Classification) [Moorhead et al. 2004], NANDA (North American Nursing Diagnosis Associations) [Nanda International, 2003], and the Omaha System [Ozbolt, 2003]. All of these languages are also included in SNOMED CT, a clinical healthcare terminology with over 366,170 healthcare concepts [The American Nurses Association, 2006]. In recent years, in addition to the development of standardized languages, nurse researchers have conducted substantial research in transforming nursing intervention and diagnoses lists into formal structures such as the reference terminology model (RTM) [Choi et al. 2005; Bakken 2006].

**III. TIER INTEROPERABILITY DESCRIPTION**

The system is based on a service-oriented architecture (SOA) consisting of three tiers; presentation, computational logic (business), and database tier. The overall system architecture is shown in Figure 1, while the architecture of each tier is described in detail in Section IV. The system design is implemented on the Microsoft .NET framework with a backend Microsoft SQL Server 2000 database. The presentation (user interface) tier consists of a Personal Digital Assistant (PDA) that is seamlessly linked to the server DSS and database. The central server constitutes the middle tier which is Web-service-based and contains a nursing-rule-based inference engine for computerized decision support.

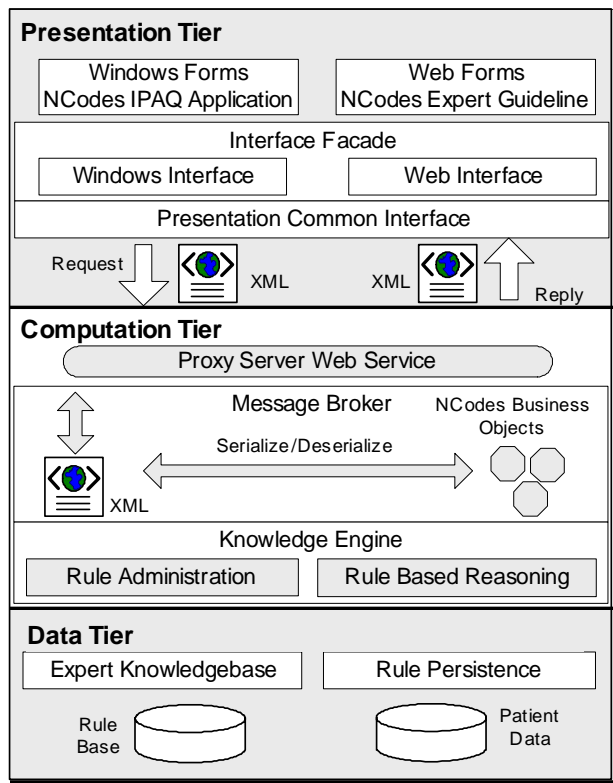


Figure 1. System Tiers and Architecture Overview

The back tier contains a database where patient facts, the rules of the inductive process, as well as rule associations and descriptions are saved. The interoperability of the N-CODES tiers will be described using the Enterprise Communication framework (ECF) methodology [AISafadi et al. 1998]. ECF was developed by the Andover Working group and is an object-oriented model aimed towards capturing the data interchange and communication between components of healthcare systems. The ECF has been adopted by the HL7 standard (Version 3.0) and consists of the following four models: use case model, domain information model, interaction model, and message model.

### **USE CASE MODEL**

This model is used to express the required functionality of the application. In all our use cases, the actor is the novice nurse. Following are the use cases.

#### **Login**

Every time a nurse logs in to start a new session, all of the clinical data of patients assigned to the particular nurse are returned to the PDA client. Additionally, all the previous assessments performed on each patient are returned to the nurse PDA and risks factors are evaluated. Let us assume, for a patient with a respiratory concern, that the nurse completes Baseline Assessment (collection of patient's vital signs) and Respiratory Assessment, and accidentally logs off without performing Refined Assessment. When she logs in again, her state is restored to Baseline Assessment plus patient facts from the previous session and Respiratory Assessment plus patient facts from the previous session. Upon restoration, the nurse will be given a choice to start from either Baseline Assessment or Refined Assessment as the new category for input.

#### **Assessment**

During each assessment, the nurse stores the patient data locally on the PDA and also communicates the data to the inference engine (server) for rule-processing to determine the next set of assessments or a recommendation based on the current data (e.g., to alert a MD).

#### **Change Assessment**

The nurse can perform various patient assessments in the order she chooses. For example, after the baseline assessment category, the next possible set of categories may be both Respiratory Assessment and Pain Assessment. If the clinician chooses to do Pain Assessment first, the Respiratory assessment is still available later as a choice in the PDA's user interface as one of the alternative decision categories for the nurse to choose from. In this sense, our system is suggestive, not prescriptive.

#### **Change Patient**

All the input data for every type of patient assessment performed are saved and the nurse can easily navigate across different patients assigned to her in the current shift.

### **DOMAIN INFORMATION MODEL**

The domain information model is discussed at two different levels: at a high level used to represent evidence-based nursing knowledge in the form of decision trees and at a low level used to represent nursing knowledge at the system level.

#### **High Level Domain Information Model**

The nursing knowledge base is described in our system in the form of practice maps that represent the clinical reasoning process for the diagnosis of a clinical condition. Practice maps are represented using decision trees, which are constructed using evidence-based knowledge

appropriate to the domain of interest. A decision tree is a data structure, in which each branch node represents a choice between a number of alternatives, and each leaf node represents a final decision. Currently, the nursing team (nursing faculty and research assistants in the N-CODES project) has created 15 decision trees for common respiratory concerns that appear in acute care environments. It has also created practice maps for the following types of clinical assessment: Baseline Assessment, Fatigue Assessment, Pain Assessment, Respiratory Assessment, and Sleep Assessment. The practice maps were based on a theoretical framework of clinical decision making [O'Neill et al. 2004b] and were organized around the questions that nurses ask themselves. These maps consist of evidence-based rules, where each piece of evidence was evaluated for quality. Specifically, we used a four-level system to rate evidence [O'Neill et al. 2004b]:

- Level 1: Systematic reviews, clinical trials, and consensus reports
- Level 2: Narrative reviews, quasi-experimental studies, published guidelines from professional organizations
- Level 3: Descriptive studies, published opinions of experts
- Level 4: Experiential knowledge

**System Level Domain Information Model**

Each nursing knowledge decision tree is represented in our system using a collection of data rules, process rules, and action paths. Data rules are in the form of "IF...THEN..." clauses, and pertain to patient data such as temperature, pressure, heart rate, etc. An example of a data rule is "If cough, then assess the timing of the cough." Each data rule has been ranked as strong, sufficient, or marginal evidence by a sophisticated ranking system that measures the strength of cumulative evidence supporting each rule [O'Neill et al. 2004b]. Finally, the rules were grouped into 15 semantic categories (See Table 1).

Table 1. Rule Categories

Assessment
Interventions
Refined assessment
Warning signs
Living with
Risk category
Risk reduction
Complications
Alerts
Patient teaching
Secondary risks or concerns
Monitoring of treatment
Protection
Emotional responses
Social response



Process rules, on the other hand, allow transition between states or types of patient assessment, where a state consists of data rules and facts from all previously performed assessments that identify a patient's current health status. An example of a process rule that leads to a different state is "If cough and high temperature, then there is high probability of pneumonia." An example of a process rule that leads to a different kind of assessment is "If cough then do cough assessment." Respiratory problems were chosen as the initial focus for the prototype from which the nursing team developed a typology to identify acute and chronic respiratory problems.

A group of data rules that are logically related in the identification of an assessment or intervention are grouped into a category. The execution of a rule in a category dictates that the clinician will execute all other rules in that category. For example, the baseline assessment category consists of data rules such as "If baseline assessment, then measure temperature," "If baseline assessment then measure heart rate," etc. In general, the data tier can be described using the following ontology:

- Data Rule: Test the patient's vital stats. For example: cough, body temperature, etc.
- Block: Grouping of associated data rules. For example, systole and diastole data rules are grouped under the block name "Blood Pressure."
- Category: A categorical group of rules. For example: Baseline Assessment, Respiratory Assessment, Respiratory Intervention, Complications, etc.
- Fact: The data rule and its value. For example: cough = Yes, temperature = 100° F.
- State: State consists of data rules and facts from all previously performed assessments that identify a patient's current health status.
- Process rule: Meta rules that fire the state transition or change the type of assessment.

Figure 2 shows part of the system level ontology as it pertains to categories, facts, and rules.

### **INTERACTION MODEL**

The nurse's interaction with the system is driven by the inference engine which is a rule-based engine (IF...THEN...) that is built from the aforementioned decision trees. This engine is responsible for computing which possible next state is the most likely best candidate state from a given set of valid next states using only the input parameters and process rules. For example, from a Baseline Assessment do we proceed to Pain Assessment, Respiratory Assessment, or some other possible state? In creating the rule engine from the decision tree, the arrows that connect branches are replaced by process rules that allow the clinicians to move from category to category. As the nurse traverses down the decision tree, a patient "case" is created by saving a temporally-stamped set of categories that the nurse visits with their associated data rules, facts, and process rules that have been fired.

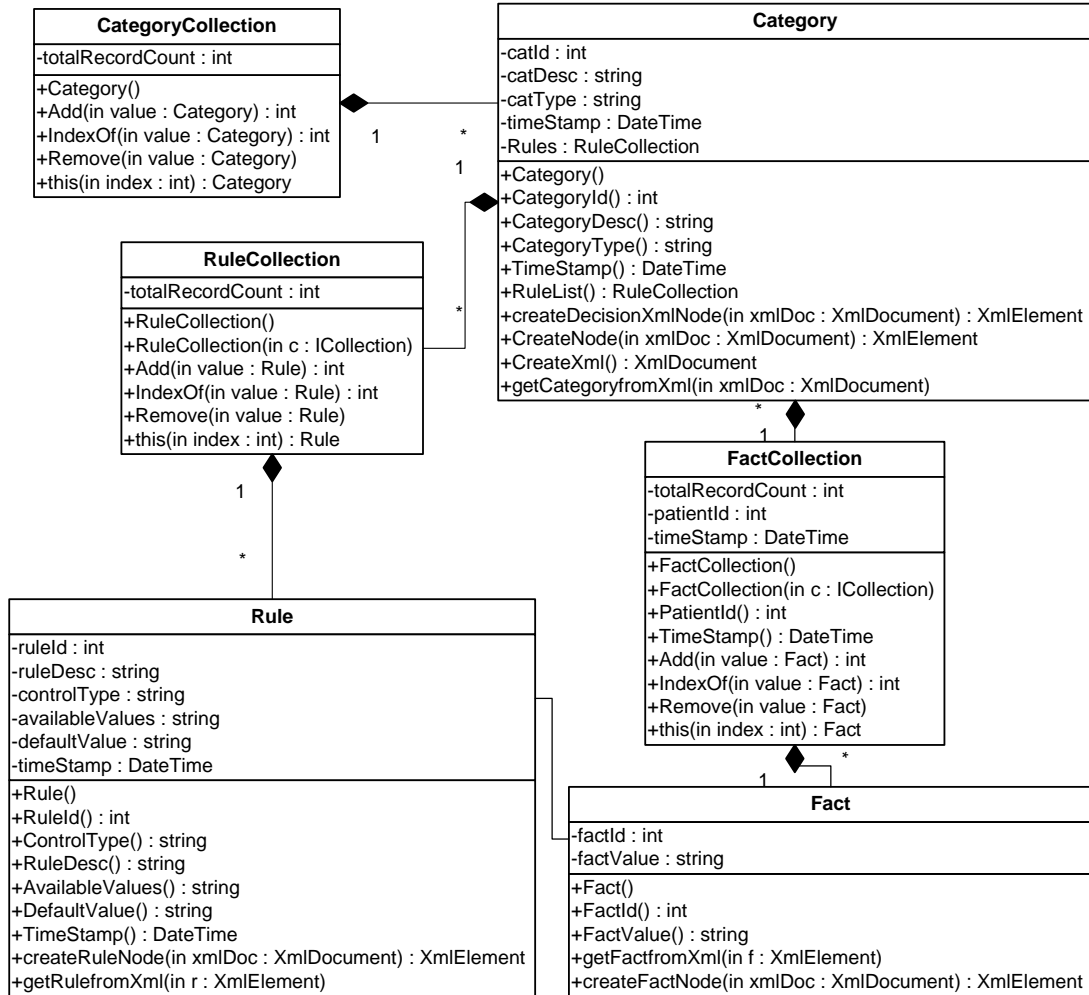


Figure 2. Part of N-CODES System Level Ontology

Figure 3 depicts an example of this interaction with the system in the form of a state transition diagram. Different paths through the state diagram correspond to different patient cases. Let us assume that states  $S_0$ ,  $S_1$ ,  $S_2$ , and  $S_3$  (in Figure 3) constitute case 1 and follow its pathway. At  $S_0$ , the nurse downloads the previous facts of the patient from the server and enters his/her risk factors in the system. The  $S_1$  state consists of the Baseline Assessment (BLA) plus the facts for all the data rules in BLA. Let us assume that, following the completion of BLA, the following process rule is applied:

*IF {Pain = Yes} THEN {Do Pain Assessment} WHEN {BLA}*

Then the nurse gathers facts for all the data rules of Pain Assessment (PA). This set of data rules and associated facts along with whatever have been collected so far (in this case PA+ facts and BLA +facts) constitutes state  $S_2$ . Using these data, the following process rule is then applied:

*IF {Pain Location = Facial} THEN {Do Acute Sinusitis Refined Assessment} WHEN {BLA + PA}*

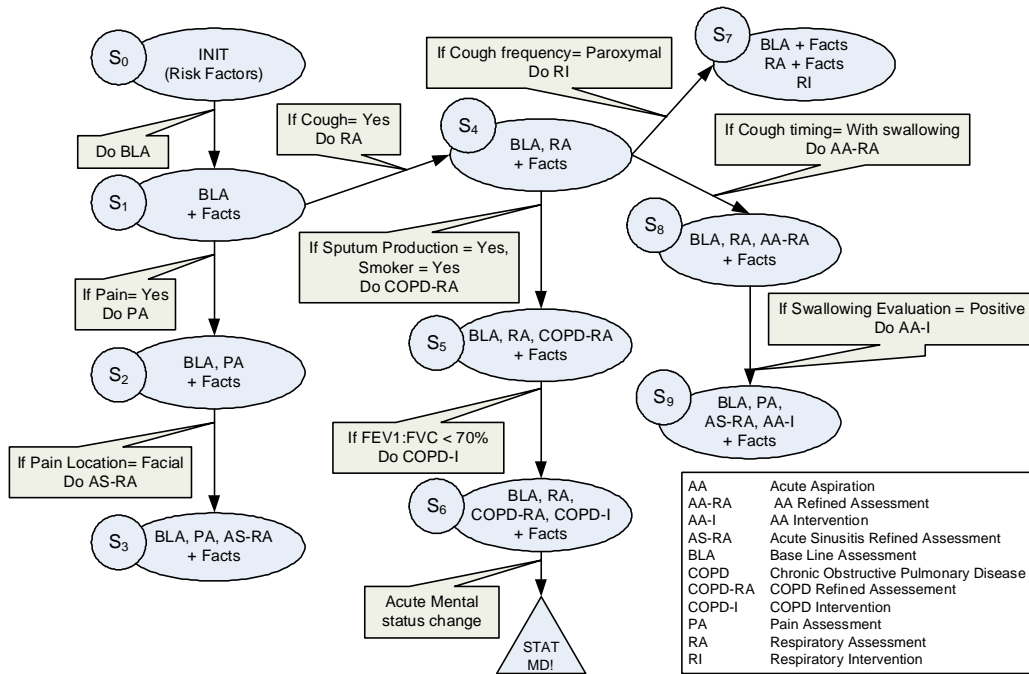


Figure 3. State Transition Diagram

Thus, the final stage of case 1, S<sub>3</sub>, consists of BLA + facts, PA + facts, Acute Sinusitis Refined Assessment + facts.

```

<Patient>
  <PatientID>12345</PatientID>
  <Category>
    <CategoryID>2</CategoryID>
    <FactsTimeStamp>9/7/2006 11:52:12 AM</FactsTimeStamp>
    <FactList>
      <Fact>
        <FactId>9</FactId>
        <FactValue>Value_0</FactValue>
      </Fact>
      <Fact>
        <FactId>10</FactId>
        <FactValue>Value_1</FactValue>
      </Fact>
      .....
      <Fact>
        <FactId>23</FactId>
    </FactList>
  </Category>
</Patient>
    
```

```

<FactValue>Value_14</FactValue>
</Fact>
</FactList>
</Category>
</Patient>
    
```

Figure 4 (a). XML Document Containing Patient Facts

**MESSAGE MODEL**

Our data are encoded in XML, embedded in a SOAP message, and communicated to the server via the Web service. SOAP messages are themselves XML documents and consist of three elements: Envelope, Header (optional), and Body. For example, when the nurse completes Baseline Assessment and clicks the “Get Decision” button, the system generates an XML document containing all the data rules and their corresponding facts. Figure 4(a) shows a part of a XML file containing patient facts.

```

<Patient>
  <PatientID>4</PatientID>
  <CategoryList>
    <Category>
      <CategoryID>17</CategoryID>
      <CategoryName>AS Refined Assessment</CategoryName>
      <CategoryShortName>AS RA</CategoryShortName>
      <TimeStamp>4/12/2006 2:28:41 PM</TimeStamp>
    </Category>
    <Category>
      <CategoryID>19</CategoryID>
      <CategoryName>Respiratory Assessment</CategoryName>
      <CategoryShortName>RA</CategoryShortName>
      <TimeStamp>3/24/2006 10:05:15 AM</TimeStamp>
    </Category>
  </CategoryList>
</Patient>
    
```

Figure 4 (b). XML Document Containing Decision Categories

The client invokes the getDecision Web service method and passes this XML document as the parameter. This XML document (which may be serialized into a String representation) becomes the Body of a SOAP message, which is communicated to the server. On the server side, the rule engine parses the Body of the SOAP message to obtain the rules and their facts and updates the state in the corresponding patient history. The rule engine then runs the inference algorithm to generate the next possible set of categories. Figure 4(b) shows a part of the XML document

containing the decision categories. Similarly, Figure 4(c) shows a part of a XML document containing rules for a category.

```

<Category Parameter="1">
  <CategoryID>1</CategoryID>
  <CategoryDescription>Baseline Assessment</CategoryDescription>
  <CategoryDisplay>BLA</CategoryDisplay>
  <CategoryType>Data Entry</CategoryType>
  <CategoryTimeStamp>3/22/2006 2:42:35 PM</CategoryTimeStamp>
  <RuleList>
    <Rule>
      <RuleId>1</RuleId>
      <ControlType>scrollbar</ControlType>
      <RuleDescription>temperature</RuleDescription>
      <AvailableValues>95,120,5</AvailableValues>
    </Rule>
    <Rule>
      <RuleId>14</RuleId>
      <ControlType>combobox</ControlType>
      <RuleDescription>cough</RuleDescription>
      <AvailableValues>Yes,No</AvailableValues>
    </Rule>
  </RuleList>
</Category>

```

Figure 4(c). XML Document Containing Rules

#### IV. SOFTWARE ARCHITECTURE

In this section, the architecture of each of the system's three tiers is described. Particular attention is paid to the steps taken to address the issues of system extensibility, reliability, performance, and security. The latter three were dictated by the stringent requirements on clinical systems, while system extensibility was considered to support our system extensions in the future in various ways, such as incorporation of case-based reasoning in its inference logic or the addition of practice maps for the cardiac and gastrointestinal systems.

##### PRESENTATION TIER

The front tier utilizes a smart client, namely a PDA-type, handheld computer (iPAQ), which is linked wirelessly to a central server. Wi-Fi Connection 802.11b is used for wireless access. The functionality of the PDA is twofold: patient data collection and decision support. Regarding data collection, the PDA allows a nurse to download a set of assigned patient information from the server at the start of a nursing shift. In addition, throughout the course of the nurse's shift, the

PDA allows collection and storage of patient vital signs and other pertinent care and patient information. The PDA's decision support component acts as a stand-alone nursing coach, assisting the nurse in making the appropriate assessments and interventions based on the patients' historical and present state of health. It is important to note here that the actual decision support logic resides in the computational logic tier (on the server); the presentation tier simply serves as the communication mechanism between the user and the computational logic tier. There are three processes that reside on the hand-held computer: the transmission and reception process; the interface process; and the presentation engine. The transmission and reception process is responsible for the continuous upload and download of data. The interface process has the function of providing relevant input and output information consistent with the state of patient assessment or care review the nurse is operating within. As an example, within Baseline Assessment the nurse will be presented with a visual representation of items she/he can measure and fill in to form the Baseline Assessment for this patient. This may include items such as heart rate, body temperature, blood pressure, respiratory rate, etc. The interface process must also provide mechanisms for the nurses to seamlessly move between states already visited to reexamine pertinent patient information collected within their shift or to allow for the alteration of items erroneously entered.

The presentation engine consists of a graphical user interface (GUI) for presenting the different categories of decision tree traversal, customized for each patient assigned to the novice nurse, and allowing the nurse to perform data entry. A WinForm application on the PDA communicates with the server through a Web-service. In addition, a WebForm application that can be run on any browser allows maintenance of rules by an expert nurse. The Model View Controller (MVC) object model, as described in Allamaraju et al. [2000], is chosen for the design of the presentation tier's software architecture, which uses separate objects to represent the data, workflow, and presentation. A Model defines a set of objects that represent the business data of the application and are responsible for all state changes. A View performs screen presentation of model data to a user. A Controller reacts to user input and updates the model accordingly. Our implementation has a main controller which handles the details of application flow and navigation by choosing one of multiple application-specific request controllers to handle each request. A request controller produces no output but processes requests, initiates business operations and manipulates model states. Based on the model states, the main controller responds by choosing an appropriate view. When the nurse completes his/her actions on the PDA, the Controller component is invoked, which in turn calls the Model object to perform the communication with the server to get the necessary set of decision categories from the server (rule engine).

### **Extensibility Considerations**

First, we chose a thin client implementation, mainly for evolvability reasons; specifically if the nursing rules need to be updated or expanded, changes need to happen only in one central location. Second, using the MVC object model contributes to an extensible architecture, because each view can be replaced with another view that displays the same model differently, without significantly altering the application's behavior. It is possible to switch from one type of view technology to another, for example, from WinForm to ASP page, without significant change to the application logic. Overall, utilizing the MVC object model allows us to centralize and modularize the action and view management, centralize control, and enable evolvability by facilitating the addition of new views.

### **Security Considerations**

Security was addressed at the wireless communication level, which uses the Wi-Fi 802.11b standard. Specifically, the Wired Equivalent Privacy (WEP) protocol was used for data confidentiality and integrity and, based on the wireless service provider, 802.11 IPSec and Extensible Authentication Protocol (EAP) can be used to handle authentication and authorization. At the system level we provide a username/password (also specific roles for expert, nurse, and developer) to only allow authorized access to the system. Further, only appropriately formatted

XML (which only the valid client and server have knowledge of) are accepted by the server and client. Additionally, application level security can be implemented using SSL.

### Performance Considerations

*Asynchronous messaging:* For communication, we had to make a decision as to whether we would access the Web service at the computational logic tier, using a synchronous request-response mechanism, such as the one used in most RPC-oriented Web services, or a message-oriented one. In addition to adding flexibility and extensibility to the design, a messaging mechanism is more appropriate for our usability scenarios. Consider the scenario where a nurse clicks “Get Decision” on an assessment and would expect to get the suggested decision from the backend server in real time. If the server is busy with another request, the windows forms may appear frozen which will prevent the nurse from further interaction with the PDA until the server responds. Given the hectic nature of clinical environments, the N-CODES engineering team decided on a message-oriented type of communication with the Web service, which allows the PDA to send messages in an asynchronous fashion while keeping the PDA free for navigation.

*Implementation of the PDA as a smart client:* This means that the user interface, application logic, and data are dynamically deployed and updated from a centralized Web server. However, the smart client caches part of this functionality and maintains the connection with the central server in an intelligent way. As an example, a copy of the rule set for each category is saved locally in an XML file (as shown in Figure 4(c)) on the client PDA, which allows us to minimize the traffic sent by the server as we only need send the category name and timestamp of last update (as shown in Figure 4(b)) and not the details of these categories. The smart client verifies the freshness of its own copy and only when the local copy is obsolete is the category downloaded from the server via a call to another Web service method. Also, the XML document shown in Figure 4(b), is used by the client to build the graphical user interface for the nurse.

### COMPUTATIONAL LOGIC TIER

The computational logic tier uses a Web service interface to communicate with the presentation tier. The reason for the use of the Web service is that Web services offer location transparency and platform independence and are based on prevalent technologies such as HTTP and XML [Mitsa and Joshi 2005].

### Extensibility Considerations

*The Web service as an interface:* As the data rules of any assessment category are defined by expert nurses and can be modified at any time, the Web service client must be isolated from these changes, assuring an extensible system architecture. Given this requirement, the Web service is designed as a generic interface to facilitate these inevitable altered implementations. This interface will maintain its definition by accepting the same set of parameters (including the returning values) for each service client. Specifically, the input and output arguments of the methods of the interface are encoded in XML as follows:

```
public XmlDocument exampleWebMethod(XmlDocument parameterXmlString) {
    //Method content
}
```

Using an XML format to encode the input and output parameters allows all our semantically similar methods to have the same signature and return type, independent of implementation. In this way, although some overhead is added, we decouple abstraction from implementation. For example, let us consider a `getDecision` Web method that is invoked by the smart client with the facts of current assessment (a category) passed as the input parameters, expecting a set of more refined assessments as the decision. Each category (Baseline Assessment, Refined

Assessment, etc.) has a different number of rules (and therefore a different number of facts). If we do not encode the parameters in XML format, then we need to use different Web methods for each category to achieve the same `getDecision` functionality, as each category may have different number of parameters (facts) to be passed to the server. If the expert nurses decide to add a new category or add/delete rules in an existing category without using the XML format, we need to create and publish a new Web method for this update. In the generic interface approach, we use a descriptive parameter inside the XML input argument document to describe which business process to invoke and, therefore, for the new category we just need to provide an additional value for the descriptive parameter.

### Performance Considerations

*Coarse-grained business interface:* Eliminating unnecessary data traffic in a service-oriented architecture is important. In traditional three-tier architectures, the class provides “accessors” (getters) and “mutators” (setters) for interaction with the business data. This type of multiple roundtrip `get/set` interaction is fine when the object is local, but it becomes a performance problem when interacting with objects across the network. The reason is due to the overhead associated with extra bytes in the Envelope of each SOAP message as well as the time required for name resolution and routing. Therefore, we decided to utilize a coarse-grained business interface to combine different method calls in a single method call as much as possible.

*Pattern matching using the Rete algorithm:* Rules in our system are expressed in the form “IF clause THEN implication.” As new facts about the patient arrive, we would like to know which rules apply and which do not. An obvious but very computationally expensive solution would be to continuously cycle through a list of all the rules. When matches are found, rules are triggered and fired, producing new implications (or removing implications). This issue is addressed by using the *Rete algorithm* [Forgy 1982], which remembers past facts and does incremental pattern matching, i.e., only on new facts.

### Reliability Considerations

Having decided on asynchronous communication, the next question to answer was the type of request/response model we would use. Reliability was addressed at the message level, by following each message, sent by either the server or the client, by an acknowledgment message. Specifically, the Web Services Description Language (WSDL) [McGovern et al. 2003; WSDL 2001] has four transmission primitives that can be supported by an endpoint:

1. One-way: The endpoint receives a message.
2. Request-response: The endpoint receives a message, and sends a message in response.
3. Solicit-response: The endpoint sends a message, and receives a message in response.
4. Notification: The endpoint sends a message.

Our application implements the request-response/solicit-response design pattern. Under this pattern, the initiate request is modeled as a request-response operation, while the response is modeled as a solicit-response operation. The client is responsible for creating the correlation ID and defining the reply-to address to indicate the service provider as to where the response of this correlation ID should be sent.



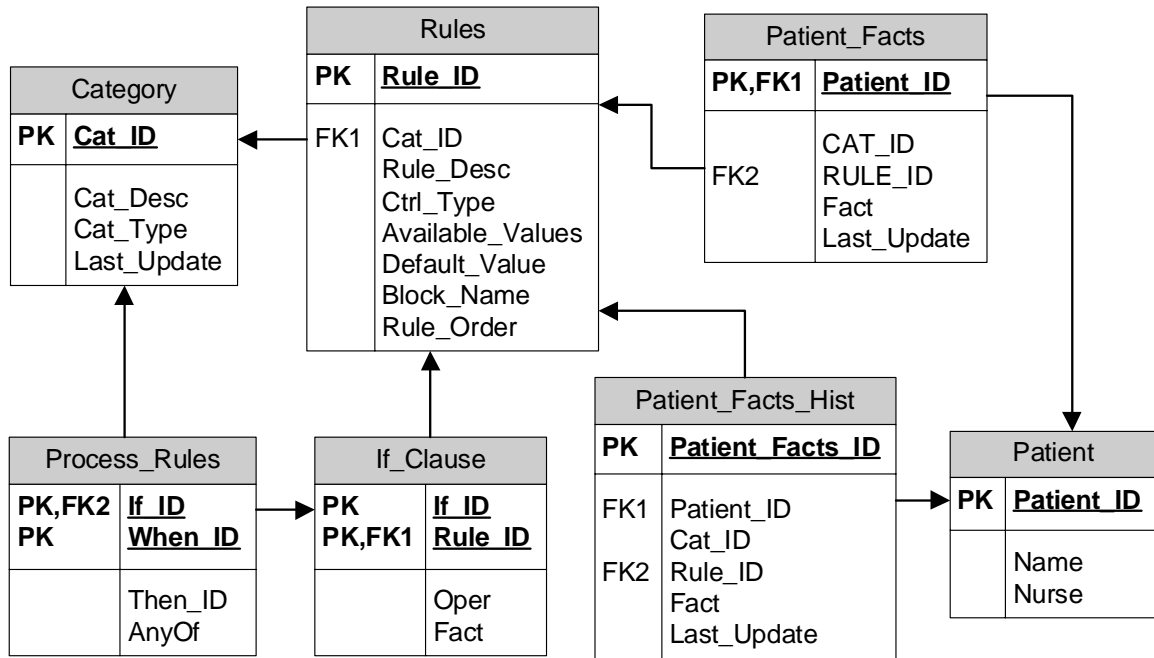


Figure 5. N-CODES Database Schema

**DATA TIER**

The data tier contains the repository for the patients’ history and current states in the form of temporal facts. In addition, it contains the nursing knowledge base, which is the key component of this tier. Seven tables are used to store the rule knowledge base of the nursing domain and the patient specific facts. Figure 5 shows a part of the database schema for the N-CODES database. We briefly examine some pertinent attributes of each table.

1. **RULES:** This table contains the data rules, such as temperature, blood pressure, etc. *Rule\_ID* is the primary key assigned to each specific rule. *Rule\_Desc* is the rule’s description, while *Ctrl\_Type* represents the type of user interface control (scrollbar, combobox, textbox, etc) used in the WinForm on the hand-held device. *Available\_Values* is a comma-separated string of available values for the rule. *Default\_Value* is the default value for the rule. The *Block\_Name* is the unique name assigned to represent a specific block. The set of rules in a category with the same *Block\_Name* are grouped together in the iPAQ display. For example, Systole and Diastole data rules are grouped under the block name “Blood Pressure.” *Cat\_ID* is the foreign key to the CATEGORY the rule belongs to. *Rule\_Order* defines the display sequence of rules within a category.
2. **CATEGORY:** This table contains the details concerning how the data rules are categorized, for example Baseline Assessment contains rules such as temperature, pain, etc. *Cat\_ID* is the primary key and identifies the category each data rules belongs to. *Cat\_Desc* labels each category (Baseline Assessment, Respiratory Assessment, etc). *Cat\_Type* specifies the display strategy (data entry, information) that each category type (assessment, intervention) uses. *Last\_Update* identifies when the category was last updated.
3. **PATIENT\_FACTS\_HIST:** This table stores the temporal history of all the facts assessed on the patients. *Patient\_ID* identifies the patient being monitored. *Cat\_ID* and *Rule\_ID* identify the data rules and *Fact* identifies the value assessed by the nurse. The *Last\_Update* field gives the time the data rule was assessed.

4. *PATIENT\_FACTS*: This table contains only the latest values (facts) of each data rule for rule-based reasoning. *PATIENT\_FACTS\_HIST* contains all temporal facts that can be used to build cases for case-based reasoning, which is our future work.
5. *PROCESS\_RULES*: This table stores the state-transition process rules of the knowledge base. The *When\_ID* gives the *Cat\_ID* of the CATEGORY which, when assessed, triggers this process rule. The *Then\_ID* identifies the set of decision categories. The *If\_ID* is used as foreign key into the *IF\_CLAUSE* table and specifies the set of conditions/conjuncts of the process rule. *Any\_Of* specifies the minimum number of matching conditions in the *IF\_CLAUSE* to fire the process rule.
6. *IF\_CLAUSE*: A set of the same *If\_ID* identifies the set of conditional conjuncts of a corresponding process rule. Each condition is represented by *Rule\_ID*, *Operator* (=, NOT IN, WITHIN), and the *Fact* value.
7. *PATIENT*: This table stores the profile of the patients with *Patient\_ID* as the primary key to the table. It also identifies the nurse involved in patient care.

**V. USER TRIAL**

The goals of the user trial were to evaluate usability, navigation, and nurse satisfaction of the N-CODES prototype.

**TESTING PROTOCOL, PARTICIPANTS, AND DATA COLLECTION PROCEDURES**

The NCODES nursing team developed the protocol to guide the usability trial. The protocol consisted of eight tasks (Table 2) requiring the participants to navigate screens to enter information and/or locate screens to obtain specific information [Chin 2006].

Table 2. Selected Tasks from the N-CODES Study Protocol

Your patient has a history of asthma, has been wheezing, short of breath, and coughing intermittently. What refined assessment does the N-CODES program suggest you perform?
Enter the following data: recent exposure to environmental trigger, decreased PEF, and history of asthma. What interventions does the N-CODES program suggest you perform?
Your patient has been confined to bed for one week following a major car accident. He had multiple bone fractures. He just returned from surgery on his leg. The patient was alert and oriented, denied pain, and resting comfortably when you left him one hour ago. When you go back to check on him, he appears uncomfortable, and is complaining of cough, dyspnea and pleuritic pain on the right side of his chest. Vital signs are: 98.8- 110- 30 150/81, O2 sat 89%. What does the program identify as the problem?
What type of extraneous heart sound does the program indicate might be present when you suspect pulmonary emboli?

Ten acute care nurses with varying levels of education and experience were recruited for the user trial. The mean age of the participants was 32.2 years, with a range of 24-47 years. The mean length of clinical experience was 8.9 years, with a range of 2-25 years. Regarding computer and specifically PDA experience, four of the ten nurses regularly used a PDA, while all participants had a computer at home, used a workplace computer and consulted decision support resources online.

The user trial was conducted at a university site. Two data collection tools, an observation data recording sheet and a usability questionnaire were developed by the investigators to collect both

quantitative and qualitative data. The observation data recording sheet was used by the investigator to track each participant's progression through the series of tasks. Specifically, the investigator recorded the time to complete tasks and any difficulties encountered in navigating screens. In addition, the investigator recorded participant comments and non-verbal behaviors, such as evidence of frustration. The second data collection tool, the usability questionnaire, was made up of questions with a five-grade Likert-type scale to answer each question, ranging from Strongly Disagree to Strongly Agree (Table 3). In addition, respondents were asked to list the most positive and most negative aspects of the N-CODES program.

Table 3. Evaluation of Various Aspects of the N-CODES System by User Trial Participants

(Notations in columns indicate number of responses to each survey item)

	Strongly disagree	Disagree	Uncertain	Agree	Strongly agree
It was simple to use this system.		1	1	6	2
I feel comfortable using this system.			1	8	1
The information provided is clear.			1	6	3
It was easy to find the information that I needed.				5	5
The information is effective in helping answer the questions.				5	5
The screens are easy to read.				4	6
The system had the capabilities that I expected it to have.			1	5	4
The system prompted me to consider the right problem.			3	3	4
The terminology was NOT familiar.	2	6		2	
The system helped me to consider more aspects of the problem.				7	3
The system provided options that I did not know.			2	6	2
The system did not help me answer the questions.	5	5			
If this system handled clinical problems in a similar way, I would use it in clinical practice.				2	8

**RESULTS**

The average time to complete the eight patient-related tasks was 30.4 minutes, with a range of 21 to 48 minutes. Seven participants completed all tasks, two completed seven tasks, and one

participant completed five tasks. The participant who completed only five tasks had the least computer experience and had not used a PDA previously.

In listing the most positive aspects of the program the participants stated it was easy to navigate and informative. The average task completion time of 30.4 minutes, which was less than the time estimated by the investigators, also supports the ease of navigation. There were few negative comments, with the most serious one being the potential to enter assessment data on the wrong patient. This issue will be addressed in future versions of the tool's software. In addition, there was one comment that the tool was too difficult for users that are not computer-literate, one comment about the over-sensitivity of the screen and one comment regarding the time-consuming nature of the program. The following adjectives appeared frequently: informative (9), helpful (7), thought-provoking (7), useful (7) and user-friendly (5), where the number in parentheses indicates number of times each appeared. Participant nurses discussed several potential outcomes of using the N-CODES program, such as improved nurse-MD communication, increased nursing knowledge, and reduced stress levels [Chin et al. 2006].

## VI. CONCLUSION AND FUTURE WORK

We presented a novel PDA-based Clinical Decision Support System for the novice nurse that utilizes specific patient information and evidence-based nursing knowledge to offer real-time guidance to the novice that mimics that of an expert nurse. The system's architecture was presented from two different viewpoints: a dynamic one and a static one. In the dynamic description, we utilized the Enterprise Communication Framework model to describe how the inference engine and patient data drive the actions of the user. In the static system description, particular emphasis was placed on describing the steps we took to assure the system's extensibility, reliability, security, and performance, which are all important considerations in the design of a clinical DSS.

The first usability trial of N-CODES yielded important data. Overall, nurse satisfaction was very positive, while ease of navigation and usability were highly ranked. Our future work will focus in the following directions:

- *Standardization of language:* First, we will use a standardized language to express the rules of the inference engine. We will specifically explore the use of GELLO and PROforma. Second, we will use standardized languages to express the nursing knowledge practice maps, such as NIC, NOC, and NANDA.
- *Standardization of patient database interface:* As we plan to deploy the N-CODES system in heterogeneous environments with different types of patient databases, we will explore the use of a vMR as a way of standardizing the DS system-database interface.
- *Inference engine:* We will explore integration of case-based reasoning (CBR) with rule-based reasoning (RBR) in the inference engine, where the case-base knowledge will be extracted from a database of patient cases.
- *Software architecture:* To enhance the effectiveness of N-CODES as an educational tool, we will create a mentor mode in the PDA device. In this mode, the mentor will be able to assess the students' actions and compare them with those of expert nurses under similar circumstances. In addition, we will add safeguards that ensure that all steps are performed on the correct patient, such as display the name of the current patient on each screen.
- *Nursing practice maps:* Practice maps for the cardiac and gastrointestinal areas will be developed.

## ACKNOWLEDGEMENTS

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