An Expert System for Culture-Based Infection Control Surveillance

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Hospital-acquired infections represent a significant cause of prolonged inpatient days and additional hospital charges. We describe an expert system, called GERMWATCHER™, which applies the Centers for Disease Control's National Nosocomial Infection Surveillance culture-based criteria for detecting nosocomial infections. GERMWATCHER has been deployed at Barnes Hospital, a large tertiary-care teaching hospital, since February 1993. We describe the Barnes Hospital infection control environment, the expert system design, and a predeployment performance evaluation. We then compare our system to other efforts in computer-based infection control.

INTRODUCTION

Hospital-acquired infections represent a significant cause of prolonged inpatient days and additional hospital charges. Studies by the Centers for Disease Control (CDC) estimate that in 1992, two million patients acquired nosocomial infections at a cost of more than $4.5 billion. The same studies document that 19,000 deaths nationally could be directly attributed to a nosocomial infection and that an additional 58,000 deaths could be indirectly attributed to the complications associated with a nosocomial infection[1, 2]. In assessing the impact of infection control surveillance programs, these national studies also documented that 30-50% of nosocomial infections were preventable, that aggressive infection control programs could reduce nosocomial infections by up to 36%, and that a 6% reduction in the nosocomial infection rate paid the full cost of an infection control program [3].

Key infection control activities include hospital-wide infection surveillance, outbreak investigations, and personnel education. Our work focuses on the surveillance activities. Surveillance is performed using a combination of three methods: review of microbiology culture results, chart review, and self-reporting. In comparing the three surveillance methods, we find self-reporting to be the least expensive but least sensitive, and concurrent chart review to be the most expensive but most sensitive. However, it is microbiology culture review which is used most often, because it provides a reasonable compromise between cost and sensitivity. Typically, trained infection control personnel, usually nurses, review positive microbiology culture results, determine which cultures represent potential problems, and maintain historical tallies of problematic cultures to detect progressive temporal changes in the rate of various infections. Although many hospitals use local definitions, the CDC's National Nosocomial Infection Surveillance System (NNIS) provides explicit culture-based and clinical-based definitions for the most significant nosocomial infections [4].

GERMWATCHER is an expert system which applies both local and NNIS culture-based criteria for detecting potential nosocomial infections. GERMWATCHER has been deployed at Barnes Hospital, a large tertiary-care teaching hospital, since February 1993. We describe the Barnes Hospital infection control environment, the expert system design, and a predeployment performance evaluation study. We compare our system to other efforts in computer-based infection control.

BARNES HOSPITAL INFECTION CONTROL

Barnes Hospital is a 1000 bed tertiary-care medical center associated with the Washington University School of Medicine. The microbiology laboratory processes 900 positive cultures per day. Each morning, the infection control unit receives a hardcopy report on these cultures. This report is divided among the three infection control nurses (ICNs) according to hospital floor; each nurse is responsible for reviewing the culture reports and for marking only those cultures which are potential nosocomial infections. The process of reviewing the positive culture reports occupies approxi-

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mately 6 person-hours each day. A data-entry person transfers data from the paper report into a departmental infection control database. A faculty member from the Division of Infectious Diseases reviews the infection control data and coordinates investigations when outbreaks occur in the hospital.

SYSTEM ARCHITECTURE

Goals

The acceptance of the GERMWATCHER system required that three key goals be addressed in an acceptable manner: culture classification, results review, and data downloading.

Classification The criteria used by the ICNs for identifying significant, reportable infections are based on the CDC's NNIS guidelines and modified by Barnes Hospital infection control policy. There are numerous rules and some are so complex that more than one interpretation is possible. Both of these factors make it very difficult for the ICNs to apply the rules uniformly. Therefore, the program's primary goal is: *apply the set of rules in a consistent manner to the finalized, positive microbiology cultures, classifying them according to whether or not they meet the criteria.* A maximum acceptable error rate of 15% was established.

ICN Review and Approval Expert systems which can perform monitoring or assisting functions without requiring a great deal of user interaction are more likely to be accepted. Therefore, a second goal was established: *avoid introducing excessive changes to the way the nurses perform this task, unless those changes would result in a definite improvement.* For example, we decided to present the expert system results as a single line of already-familiar, coded, mnemonic text. This would allow the ICNs to quickly view several results at a glance.

Automatic Database Download Since the culture data would now be available in electronic format, a third goal was adopted: *eliminate the tasks of manual data entry and ICN review of the entered data.*

Design Issues

The most challenging portions of the system's design were the interfaces between the microbiology laboratory information system, the development system, and the users' workstation, each of which runs on a different hardware platform and operating system.

Legacy System Linkage The Microbiology Daily Positive Report (MDPR) is generated each day by a COBOL program running on the IBM mainframe-based microbiology laboratory information system. The MDPR is a single, formatted ASCII text file which is transmitted to the development system, a SUN SPARCstation running UNIX. In analyzing the MDPR, we found, as did Nussbaum [5], that the report is a structured document, assembled from a list of coded phrases which are maintained in tables called *dictionaries.* Thus the same dictionary of terms was required by the expert system. These identical dictionaries allowed the expert system to use a very simple pattern-matching algorithm to identify each of the key elements (organisms, culture locations) in the reports.

Database Integration A full-featured SQL-compliant relational database was required to handle the storage and reporting requirements of the large volume of culture data. Because our expert system needed access to culture information in the database and the expert system shell we used did not provide an integrated database interface, we developed that interface ourselves [6].

Client-server Architecture Simultaneous remote access to the expert system results on the UNIX development system was needed from the interactive user interface running on the nurses' workstation, a PC running Microsoft Windows. The user interface is a "Windows" application implemented in C++ using a platform-independent graphical user interface development tool. In addition to the user interface we developed, Paradox (a commercial PC-based graphical database query and reporting tool) gives the nurses transparent access to all the databases from their PC.

System Design

Figure 1 shows the system architecture, including both the hardware and software configuration. There are three processing components: (1) the preprocessor, (2) the expert system and (3) the user interface.

Preprocessor Early each morning, the MDPR is transferred from the mainframe to the UNIX development system, is *parsed* using a text manipulation language, and is uploaded into a commercial relational database. High-level parsing is done at this stage (e.g., cultures are separated from each other, page breaks are handled, etc.). Parsed cul-

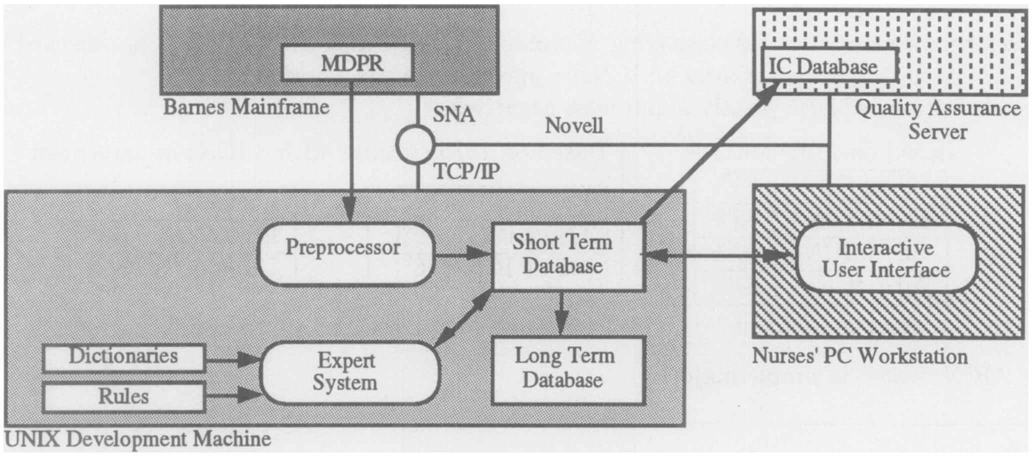

Figure 1: System Architecture

ture data are uploaded into the "short-term" database, where they remain until they are reviewed and approved by the nurses.

Expert System The expert system component, which classifies the cultures, was implemented with CLIPS, a forward-chaining expert system shell.

Since the NNIS criteria were already published, the development of most of the rule base was fairly straightforward. We sought the collective consensus of expert opinion for the difficult, ambiguous cases [7].

The expert system runs non-interactively during the early morning hours, classifying all positive cultures finalized during the previous day. It asserts its results, which consist of the assigned classification and the reason that classification was chosen, into the short-term database.

User Interface From their workstations, the nurses use an interactive user interface to review and approve all culture results. If they disagree with the expert system's result, they can override it and assign their own. They can view the original microbiology culture reports, perform various queries which display summary listings of cultures, and print either the reports or the summary listings.

Once approved, the data are automatically *exported* (or "copied") from the short-term database to two other databases intended for high-volume, long-term storage. The "long-term" database supports other projects and ongoing research activities. The "IC database" is the infection control departmental PC database, from which the monthly, quarterly, and annual reports are generated.

EVALUATION

Evaluation Methodology

The three Barnes Hospital ICNs, one Infectious Disease (ID) faculty member, and the GERMWATCHER expert system each classified the same 2161 final microbiology reports into one of two categories: Keep (culture meets NNIS criteria) or Discard (culture does not meet NNIS criteria). Any culture that did not elicit unanimous agreement among the five classifiers was resubmitted for reconsideration to the ID faculty member who was not told the source of the disagreement. The results of this second review defined the "Gold Standard" classification for that culture.

Evaluation Results

Table 1A presents the rate of agreement between the expert system (ES), the infection control nurses (ICNs), and the gold standard (GS). There was agreement if both entities (ES v. GS, ICNs v. GS, ES v. ICNs) either "kept" or "discarded" a culture result. For the comparison between the infection control nurses (ICNs v. ICNs), agreement was present when *all three* nurses either kept or discarded a culture.

Table 1A shows that the agreement among nurses was 84%. In actual practice, the three nurses do

Table 1: Performance statistics for classifying microbiology cultures as either "keep" or "discard."
GS = gold standard; ES = expert system; ICNs = infection control nurses
See text for definitions of false positives and false negatives.

Based on 2161 cultures

ES vs GS	84%
ES vs ICN*	88%
GS vs ICN*	90%
All 3 ICNs	84%

(A) Agreement

*ICN "vote" is simple majority

Based on 1815 cultures with 3 ICNs in agreement

ES vs GS	12%
ES vs ICN	9%
GS vs ICN	6%

(B) False Positives

ES vs GS	4%
ES vs ICN	3%
GS vs ICN	4%

(C) False Negatives

not review the same cultures; each nurse is responsible for specific hospital floors and locations. This result illustrates the potential impact of nurses substituting for each other — during a prolonged absence, significant changes in apparent infection rates could be caused by culture-selection criteria differences used by two nurses.

Using only the subset of cultures where all three Infection Control nurses agreed, Tables 1B and 1C show the false positive and false negative rates. A false positive occurred when either the expert system or the ICNs kept a culture that the gold standard discarded. A false negative occurred when either the expert system or the ICNs discarded a culture that the gold standard kept. For the comparison of the expert system and the ICNs (last column in Tables 1B and 1C), the nurses were considered the gold standard.

The expert system kept 114 cultures that were discarded by all three nurses and the gold standard. We call these cultures "strong" false positives. The analogous situation where all three infection-control nurses discarded a culture that was kept by the gold standard occurred in 103 cultures. More worrisome, the expert system discarded 32 cultures that were kept by all three nurses and the gold standard. We call these cultures "strong" false negatives. The analogous situation where all three infection-control nurses discarded a culture that was kept by the gold standard occurred in 64 cultures. We describe the etiology and implication of these strong false positive and strong negative cases in the Discussion section.

DISCUSSION

Evans has written extensively on the development of a computer-based surveillance system for nosocomial infections [8, 9, 10]. Linked to the HELP hospital information system at LDS hospital, this surveillance system has been extended to monitor antibiotic usage and consultation, to monitor drug utilization, and to detect adverse drug reactions [11].

Our system differs from the LDS system in two significant features. Our architecture is only loosely coupled to the Barnes Hospital Information System. The key components of our system (the preprocessor and expert system) were constructed from readily available public-domain or low-cost software which runs on generic computer platforms – only the translation of data files from a Barnes Hospital-specific export format into a program-specific internal format is site-dependent. However, because of the loose coupling, we do not have ready access to the depth of patient-specific clinical information available to the LDS system. The second key distinction is our use of the CDC's NNIS definitions as the basis for classifying cultures as potential nosocomial infections. Evans describes using criteria derived from the earlier SENIC study combined with local infectious disease experts to define their computerized knowledge base [9]. Our criteria, while based on the newer NNIS definitions, also includes some local modifications to NNIS.

Our criteria do not take into account the difference between the time of the patient's admission and the time the culture was taken. Most NNIS criteria require at least a 48 hour delay to increase the likelihood that the infection was hospital-acquired. Instead, we keep the date of admission and date of positive culture with each result. Studies which seek to use only those cultures obtained 48 hours after admission can be obtained using a SQL query specification. In a future study, we intend to examine the sensitivity and specificity of culture results obtained at various time intervals from the date of admission.

The performance evaluation demonstrates that the expert system agrees with the Gold Standard almost as often as do the three infection control nurses (Table 1A), that the program is conservative (it keeps cultures that should be discarded – Table 1B), and that the program's false negative rate (it discards cultures that should be kept – Table 1C) is no greater than that of the infection control nurses. Of particular note is the 16% disagreement rate among the three ICNs (Table 1A). For long-term rates to be comparable, the criteria used to generate the statistics must be consistent. A computerized system enforces a level of consistency that can be measured and monitored. Thus, statistics generated using our program are likely to remain consistent over long periods of time.

In examining the sources of the 114 strong false positive and 32 strong false negative cultures, we noted that 3 new rules and 4 rule modifications accounted for the vast majority of erroneous classifications. These changes are being implemented; a second performance evaluation on a different data set is planned.

Two additional evaluation studies are planned. Although we have examined the predeployment efficacy of the expert system's classifications, we have initiated a predeployment/postdeployment economic and work-flow impact study. In addition, we are designing a cross-validation study which will examine the cost-effectiveness of our microbiology culture-driven expert system to detect nosocomial infections compared to concurrent patient chart reviews. With these studies, we will be able to quantify the differences in infection rates as determined by both computer-based and manual surveillance methods.

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