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Development of a Computerized Laboratory Alerting System

KAREN E. BRADSHAW, REED M. GARDNER, AND T. ALLAN PRYOR

Latter Day Saints Hospital, 325 8th Ave., Salt Lake City, Utah 84143 and University of Utah, Salt Lake City, Utah 84112

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Using the capabilities of the HELP medical information system at LDS Hospital, a Computerized Laboratory Alerting System (CLAS) was developed. CLAS monitors and alerts for the presence of life-threatening conditions in hospitalized patients which are indicated by laboratory test results. Alerts are posted on computer terminals on the hospital's nursing divisions, where they are reviewed and acknowledged by hospital staff so that appropriate treatment can be rapidly instituted. CLAS was evaluated to determine its effectiveness in relaying alerts to the clinical staff, and improvements were made to develop an effective user interface. Initial average alert response times on nursing divisions ranged from 5.1 to 58.2 hr. The average alert response time dropped to 3.6 hr when alert review was integrated with laboratory result review, and to 0.1 hr after installation of a flashing light to notify hospital staff of the presence of new alerts.

INTRODUCTION

The role of the clinical laboratory is primarily to provide physicians with patient data for use in clinical decision-making. Studies have shown that laboratory test results are the data most frequently used by physicians in decision-making (*1, 2*). For such decision-making to be effective, the clinical laboratory must provide accurate laboratory test results in a timely fashion, and physicians must identify and utilize important test results in making appropriate patient care decisions. Factors which make it difficult to achieve these goals are (1) problems in data communication, (2) unavailability of the attending physician, (3) information overload, and (4) human imperfectibility (*3*).

Over the past two decades, the number of laboratory tests performed by clinical laboratories has steadily increased, with laboratories in large hospitals performing several million tests per year (*4*). This increase has been due in part to advances in technology which allow batteries of tests to be run simultaneously at low cost, and in part to increased physician utilization of laboratory tests to aid in screening and early diagnosis of patients (*5*). As the number of tests performed by clinical laboratories has grown, so have the problems of data communication, information overload, and human error, both for the clinical laboratory and for the physician.

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Man is limited in his ability both to process large amounts of information (due to sensory overload) (*6, 7*) and to recognize important events which occur randomly and infrequently (*8*). Even physicians who have been trained, educated, and have the best intentions do err, especially when called upon to deal with large amounts of patient data (*9–13*).

How then can the computer help in providing physicians with important patient information generated by the clinical laboratory, and in ensuring the correct interpretation of that information by physicians? It has been suggested that computers are most helpful when they concentrate on areas in which physicians are known to be imperfect (*14*), and that they are most readily accepted when they are accessible, easy to use, and are perceived as enhancing the patient management capabilities of physicians (*15, 16*).

To date, laboratory information systems have been designed mainly to handle clerical, financial, and managerial functions including data acquisition, presentation, and storage (*17*). Some efforts have also been made to develop computerized decision aids to help in the interpretation of laboratory test results (*18–21*). However, little has been done to develop decision aids in the hospital setting which would automatically alert clinicians to laboratory information that needs their immediate attention. Such alerting systems would be most effective if they were integrated into a total hospital information system containing most or all of a patient's data available from such diverse sources as laboratory, pharmacy, radiology, and patient history (*22, 23*).

This paper describes the development of a new decision aid using the HELP medical information system at LDS Hospital (*24, 25*). The decision aid, called the Computerized Laboratory Alerting System (CLAS), monitors and alerts for the presence of life-threatening conditions in hospitalized patients, so that appropriate treatment can be more rapidly instituted. CLAS was designed to aid the clinical laboratory in the timely communication of important laboratory test results, to deal with the problems of physician absence, information overload, and human imperfectability, and to enhance the patient management capabilities of the physician in a way that is convenient and easy to use.

Methods

Background

LDS Hospital is a private 520-bed tertiary care facility which is part of the Intermountain Health Care (IHC) hospital system. It is a teaching hospital associated with the University of Utah College of Medicine, and has more than 300 private physicians on staff. The computer facilities at the hospital include 10 Tandem TXP central processing units, 18 minicomputers, and over 600 terminals and printers distributed throughout the hospital. At least four terminals and one printer are located on each nursing division. Intensive care units (total of 60 beds) and the 48-bed 8 West nursing division are equipped with a terminal at each bedside, and there are plans to place terminals at each bedside throughout the hospital in the near future (*26*).

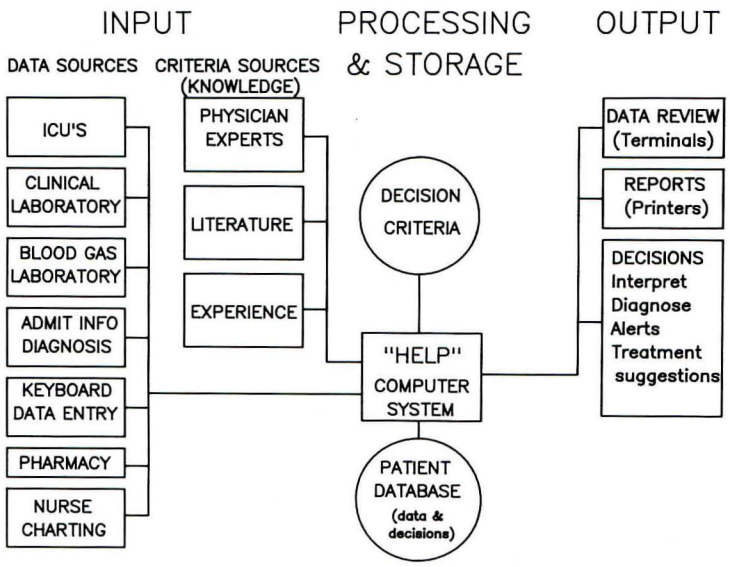

FIG. 1. The HELP System. Data from many sources are stored in the computerized patient database. The data are then available for review or for use in reports or computerized decision-making. The HELP knowledge base consists of decision criteria developed from expert opinion, the literature, and experience.

The hospital's computer facilities are used to provide a hospital-wide comprehensive medical information system called HELP (*24*). The HELP system has flexible medical decision-making capabilities and is able to evaluate data within specific time constraints. Medical knowledge is encoded into decision modules or frames which can then be evaluated by the HELP system. Frames can be automatically evaluated without human intervention (data driven) whenever a data item is stored in the computerized patient database. A diagram of the HELP system is shown in Fig. 1.

The laboratory information system used by the central laboratory at LDS Hospital is fully integrated into the HELP system so that as soon as laboratory tests are completed and verified, the results are transmitted to HELP and stored in the HELP computerized patient database. Laboratory test results are then available for use in evaluating computerized decision logic (frames), or for review at any terminal, both inside and outside the hospital.

Design of the CLAS System

The purpose of CLAS was to monitor and alert for life-threatening conditions in hospital patients. To achieve this purpose, it was necessary to develop a knowledge base defining the life-threatening conditions and an efficient method for transmitting alerts to the clinicians responsible for the patient's medical care. CLAS' medical knowledge base was developed in conjunction with phy-

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Title: Metabolic Acidosis (13:1:5)

Message:  |-<13 3 1 5 4~Metabolic Acidosis--CO2
          is (Val^CO2;##), BUN is (Val^BUN;##)-
          |

Author: Karen Bradshaw

Type: Diagnosis

Destination: Patient File, Nearest Terminal

Variable Declarations:
     CO2 which is |-13 1 1 1 4~CO2--SMA-7-|;
     BUN which is |-13 1 1 1 5~BUN--SMA-7-|;

Logic:    Val^CO2 = CO2;
          Val^BUN = BUN;
          If CO2 < 15 and BUN > 50
          or CO2 < 18 and BUN < 50
          or CO2 < 18 and Not Exist BUN
          then conclude true;
            end;

Evoke: If CO2 < 18;
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FIG. 2. Frame for the metabolic acidosis alert contained in the CLAS medical knowledge base. Frames in the knowledge base are data driven. This means that frames are automatically activated when pertinent laboratory data are stored in the HELP patient database.

sicians at LDS Hospital; it included alert criteria for hyponatremia, hypernatremia, falling sodium, hypokalemia, hyperkalemia, falling potassium, metabolic acidosis, hypoglycemia, hyperglycemia, and falling hematocrit (*27*). Once the alert criteria were developed, they were incorporated into decision modules called frames. These frames were "data driven" so that they were activated whenever pertinent laboratory data was stored in the computerized patient database. The frame for the metabolic acidosis alert is shown in Fig. 2.

It was decided that the best alert feedback mechanism would be one which functioned automatically, without the need for a human messenger, and one which notified appropriate health care personnel in a timely fashion (within minutes). This would allow CLAS to function effectively 24 hr a day, 7 days a week. The architecture of the CLAS alert feedback mechanism is shown in Fig. 3.

When laboratory tests are ordered for a patient, laboratory personnel perform the tests and enter the results into the laboratory computer system. Results are then transmitted to the HELP system, stored in the patient database, and evaluated by the data driver component of the HELP system to determine if alert decision logic should be invoked. Alert decision logic modules are invoked for sodium, potassium, carbon dioxide (pCO_2), glucose, and hematocrit laboratory values which fall within specified ranges or rates of change. The alert decision modules further evaluate laboratory values in conjunction with other patient data (e.g., past laboratory values or medications)

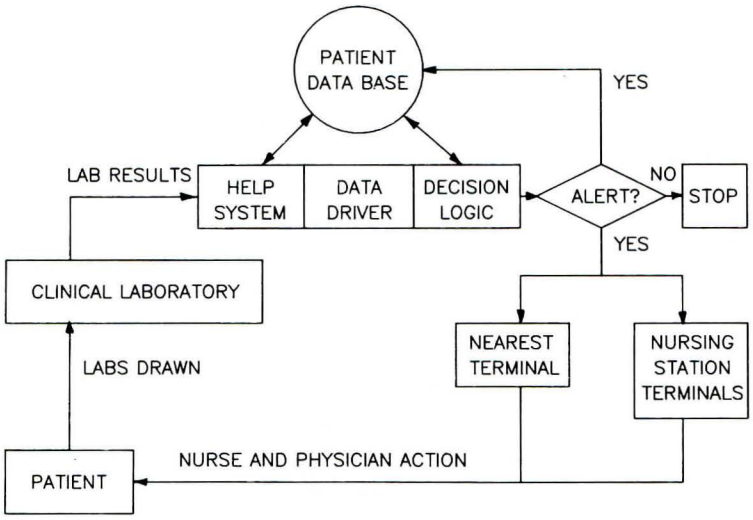

FIG. 3. Architecture of the Computerized Laboratory Alerting System (CLAS). Patient laboratory test values are evaluated by data driven decision logic to determine if a life-threatening condition is present. Resultant alerts are transmitted to the computer terminals on the nursing division where the patient is located. Alerts are reviewed by nurses and physicians and appropriate action is taken to treat the patient.

contained in the computerized patient database. If a life-threatening condition is detected, an alert is generated. The alert is stored in the patient database and is transmitted and displayed on computer terminals on the nursing division where the patient is located. The alert is transmitted to all the terminals at the central nursing station (usually four terminals), as well as to the terminal closest to the patient (bedside terminal or satellite terminal located closest to the patient's room). A nurse or physician can then review the alert on the computer terminal and use the alert information to help determine appropriate patient care.

The clinical staff were originally notified of the existence of an alert by having the patient's room number displayed in the lower left hand corner of the terminal screen. This method of alert notification was chosen because of practical limitations on where and how a message could be displayed on a computer terminal while it was in use, and because of concerns about alarming a patient's family or friends if a message containing the word "alert" appeared on the terminal at the patient's bedside. When a nurse or physician observed their patient's room number on the terminal, they selected the Lab Alert menu option on the terminal screen, specified the patient's room number, and the alert message was displayed on the screen. Once an alert was reviewed in this manner, the room number was cleared from the left hand corner of the terminal screen. The CLAS alert review program also allowed medical personnel to

review (via terminal or printed report) all alerts on an individual patient or all alerts on the patients of a specific nursing division.

User Education and Initial Evaluation

Once the alert feedback mechanism of CLAS was operational, efforts were made to educate the clinical staff about CLAS and to teach them how to use the system. These efforts included presentations to computer user groups, demonstrations to head nurses, written instruction sheets for individual users, memos to hospital staff, and a contest for the nursing division which achieved the best response (most alerts reviewed) to CLAS. These educational efforts were conducted over a 2-month period. At the end of the educational period, overall response to the CLAS was evaluated in terms of the number of alerts which were reviewed (acknowledged) on the computer terminal, and the length of time between alert posting (indication of an alert on the terminal) and alert acknowledgment. Acknowledgment of an alert consisted of review of an alert by a health care provider by displaying the full alert message on the terminal. In the initial evaluation of response to the CLAS, it was found that, though a large percentage of alerts were being acknowledged, the time between alert posting (on the terminal) and alert acknowledgment was often unacceptably long (several hr). Occasionally alerts for "life-threatening" conditions would not be acknowledged for several days. The average time before alert acknowledgment and the number of alerts acknowledged for each nursing division within the hospital are shown in Table 1 for the 2 weeks following the 2 month educational period.

Modification of the CLAS System

Because of the long acknowledgment time, two different methods were explored for improving the CLAS alert feedback system in the hope that alert response time could be shortened. First, a flashing yellow light was designed and installed on the West 8 nursing division. The alert feedback mechanism

TABLE 1

AVERAGE NUMBER OF ALERTS ACKNOWLEDGED AND AVERAGE ACKNOWLEDGMENT TIME AFTER EDUCATIONAL PERIOD APRIL 6, 1987 TO APRIL 19, 1987

Nursing unit	Date	# Acknowledged / # generated	%	Average time to acknowledge
Med/Surg ICU	4-6-87 to 4-12-87	5/11	45%	27.4 hr
Med/Surg ICU	4-13-87 to 4-19-87	0/8	0%	NA
Shock/ Trauma ICU	4-6-87 to 4-12-87	4/15	27%	39.0 hr

TABLE 1—*Continued*

Nursing unit	Date	# Acknowledged / # generated	%	Average time to acknowledge
Shock/ Trauma ICU	4-13-87 to 4-19-87	15/20	75%	33.6 hr
Coronary Care Unit	4-6-87 to 4-12-87	6/6	100%	15.4 hr
Coronary Care Unit	4-13-87 to 4-19-87	3/6	50%	35.6 hr
Thoracic ICU	4-6-87 to 4-12-87	0/8	0%	NA
Thoracic ICU	4-13-87 to 4-19-87	0/3	0%	NA
West 3	4-6-87 to 4-12-87	3/3	100%	16.1 hr
West 3	4-13-87 to 4-19-87	8/13	61%	15.1 hr
West 4	4-6-87 to 4-12-87	1/4	25%	14.9 hr
West 4	4-13-87 to 4-19-87	0/3	0%	NA
West 6 South	4-6-87 to 4-12-87	3/5	60%	13.2 hr
West 6 South	4-13-87 to 4-19-87	3/3	100%	39.0 hr
West 6 North	4-6-87 to 4-12-87	0/7	0%	NA
West 6 North	4-13-87 to 4-19-87	0/5	0%	NA
West 7	4-6-87 to 4-12-87	7/8	87%	43.2 hr
West 7	4-13-87 to 4-19-87	8/10	80%	33.6 hr
West 8	4-6-87 to 4-12-87	7/14	50%	49.4 hr
West 8	4-13-87 to 4-19-87	1/10	10%	5.1 hr
East 8	4-6-87 to 4-12-87	6/12	50%	58.2 hr
East 8	4-13-87 to 4-19-87	2/4	50%	38.7 hr
North 4	4-6-87 to 4-12-87	0/6	0%	NA
North 4	4-13-87 to 4-19-87	4/5	80%	23.3 hr
North 6	4-6-87 to 4-12-87	1/1	100%	21.1 hr
North 6	4-13-87 to 4-19-87	0/0	NA	NA

was modified so that a special code was transmitted along with the alert to terminals on the nursing division where the patient was located. The special code activated the flashing light so that health care personnel knew immediately when there was a new alert. After the alert was acknowledged, another code was transmitted which turned the light off. The flashing light was installed on one nursing division as a trial, and was found to dramatically reduce the time between alert posting and review (0.1 hr after vs. 28.0 hr before). Because the flashing light was successful in shortening alert acknowledgment time, plans were made to install flashing lights on all nursing divisions within the hospital. However, the unavailability of parts needed for constructing the lights caused a 2-month delay in the light construction. In the meantime, a second method for reducing alert response time was developed. The second method of reducing alert response time involved making modifications to the laboratory review component of the HELP system so that the terminal first displayed any unacknowledged alerts on a patient (along with appropriate laboratory data) whenever any of the patient's laboratory test results were reviewed.

Data Collection and Final Evaluation

At the time CLAS was implemented, a special computer file was set up to capture pertinent information for each alert generated including patient number, type of alert, time of alert, time of acknowledgment, hr till acknowledged, and patient room. The information captured on each alert allowed tracking of user response to CLAS, and aided in determining the success of modifications (flashing light, etc.) which were made. Six months after CLAS implementation, the computer file was further modified to capture information on CLAS users by type (nurse, physician, ward clerk or other). Data captured in the special computer file were downloaded to a personal computer, edited using WordPerfect, and analyzed using Lotus 123.

RESULTS

Table 1 shows the percentage of alerts which were reviewed and acknowledged on each nursing division for a 2-week period after CLAS had been implemented for 2 months. The average time between alert posting (on the terminal) and alert acknowledgment for this period ranged from a low of 3.1 hr to a high of 72.7 hr. After installation of the flashing light on the West 8 nursing division, data were again collected and analyzed to see if the flashing light had any effect. The results of the analysis are shown in Table 2.

For the "pre" flashing light period, from March 24, 1987 to May 3, 1987, the 686 alerts generated hospital wide had an average acknowledgment time of 38.7 hr. For the West 8 nursing division, 70 alerts were generated, and the average acknowledgment time was 28.0 hr. After the flashing light was installed on the West 8 nursing division, the average West 8 acknowledgment time dropped to 0.1 hr or about 6 min (103 alerts). Before the flashing light was installed on

TABLE 2

RESULTS OF EFFORTS TO IMPROVE CLAS FEEDBACK AND ACKNOWLEDGMENT SYSTEM—FLASHING LIGHT (PRE-LIGHT—3/24/87 TO 5/3/87; POST LIGHT—5/28/87 TO 8/10/87)

Location	Pre/post	Average hr till acknowledged	Percent of alerts acknowledged
Entire Hospital	Pre	38.7 ± 31.8	41.4
West 8	Pre	28.0 ± 28.1	28.6
West 8	Post	.1 ± 0.2	100.0

West 8, 28.6% of the alerts generated were acknowledged. After the light was installed, the percentage of alerts acknowledged on West 8 rose to 100%.

A similar analysis of average acknowledgment time and number of alerts acknowledged was performed on data collected for two weeks before (July 28 to August 11, 1987) and after (August 14 to August 28, 1987) the integration of alert review and acknowledgment with the HELP laboratory review program. The data from the analysis are summarized in Table 3. During the "pre" period (118 alerts generated), the average alert acknowledgment time for the hospital, excluding the West 8 nursing division, was 64.6 hr, with 71.2% of the alerts acknowledged. Data collected during the "post" period (149 alerts generated) showed that the average acknowledgment time for the hospital, not including West 8, had fallen to 3.6 hr, with 94.6% of the alerts acknowledged. The distribution of alert acknowledgment times for the first 220 min after alert posting during the "post" period is shown in Fig. 4. After alert/laboratory review integration, 29% of the alerts were reviewed within 20 min of posting, 47% were reviewed within 1 hr of posting, and 78% of the alerts were reviewed in the first 220 min after posting.

TABLE 3

RESULTS OF EFFORTS TO IMPROVE CLAS FEEDBACK AND ACKNOWLEDGMENT SYSTEM—ALERT/LAB REVIEW INTEGRATION (PRE-INTEGRATION—7/28/87 TO 8/11/87; POST INTEGRATION—8/14/87 TO 8/28/87)

Location	Pre/post	Average hr till acknowledged	Percent of alerts acknowledged
Hospital except West 8	Pre	64.6 ± 67.1	71.2
Hospital except West 8	Post	3.6 ± 6.5	94.6

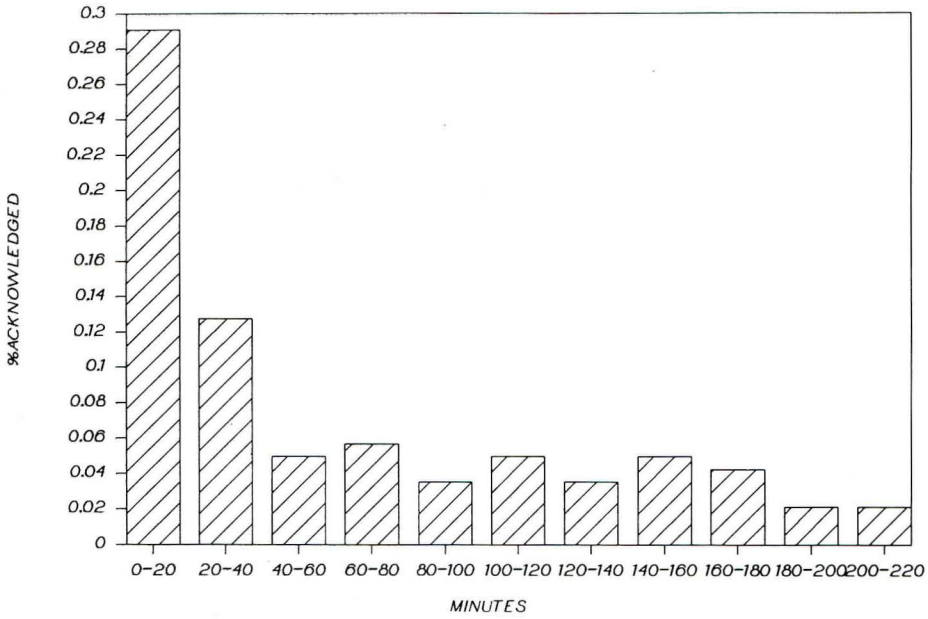

FIG. 4. Graph of the distribution of alert acknowledgment times following integration of alert acknowledgment and laboratory review (8/14/87 to 8/28/87). During this period, 149 alerts were generated (not including alerts for patients on the West 8 nursing division), and 78% of these alerts were acknowledged within 220 min of posting (on the terminal).

Data on users of the CLAS system were collected for $2\frac{1}{2}$ months after CLAS implementation. Each time an alert was acknowledged, the user was asked to indicate whether they were a ward clerk, nurse, M.D., or "other" hospital personnel. The data gathered on users of the CLAS system are shown graphically in Fig. 5. The percentage of users in each user group did not vary greatly between the general nursing floors and the ICUs. The largest difference was for ward clerks, who acknowledged alerts 15.9% of the time on the floor and 7.5% of the time in the ICUs. Physicians acknowledged alerts 32.0% of the time in the ICUs, and 25.9% of the time on the floors. Nurses acknowledged alerts 53.8% of the time in the ICUs and 51.9% of the time on the floors. "Other" personnel acknowledged alerts 7.7% of the time in the ICUs and 6.3% of the time on the floors.

DISCUSSION

For physician decision-making to be effective, the clinical laboratory must provide accurate laboratory test results in a timely fashion, and physicians must identify and utilize important test results in making appropriate patient care decisions. The CLAS decision-aid was designed to help accomplish both of these goals. In its original implementation, however, few of CLAS' alerts

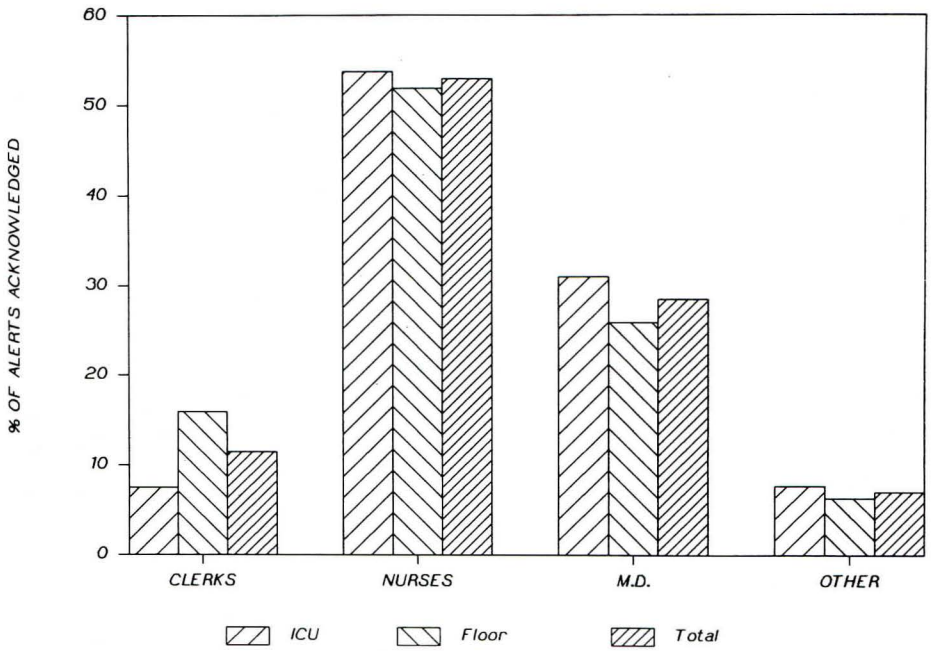

FIG. 5. Graph showing relative proportions of use by different categories of hospital staff for the floor, ICU, and hospital as a whole.

were actually reviewed by the clinical staff, and those that were were often so delayed as to be of little value. CLAS was initially unsuccessful in meeting its design goals because it required clinicians to develop new habits (checking the computer terminal for alerts, accessing a special alert review menu option), and because the alert acknowledgment process required several steps and was time consuming (3–4 min).

For CLAS to be truly effective in relaying important laboratory results to physicians in a timely manner, the alert feedback and acknowledgment system had to be modified to more nearly meet the needs and habits of the users. The two methods used to improve alert acknowledgment were successful to different extents and for different reasons.

The flashing light on the West 8 nursing division caused an immediate and marked improvement in the speed and completeness of alert acknowledgment because it made the presence of an alert obvious and because the light was bright enough and obnoxious enough to make people want to respond. On the other hand, incorporation of alert acknowledgment within the laboratory result review component of HELP was effective because it was logical (as alerts were based on patient laboratory test results) and because it used a mode of access to patient information which was both familiar to and frequently used by nurses and physicians. Although both methods greatly reduced the alert acknowledg-

ment time (28.0 hr before vs 0.1 hr after the flashing light and 64.6 hr before vs 3.6 hr after integration) and increased the number of alerts reviewed (28.6% before vs 100% after the flashing light and 71.2% before vs 94.6% after integration), average acknowledgment time using alert/laboratory integration was still several hr, with only 29% of the alerts reviewed within 20 min.

Since CLAS was designed to warn of life-threatening conditions, a 3 to 4 hr average response time was unacceptable. On the other hand, our experience showed that constant use of the flashing light was not desirable, as it was distracting and somewhat irritating to hospital staff. For these reasons, we elected to combine the two methods, so that alerts could still be acknowledged at the time of laboratory data review, and so that the flashing light was activated whenever alerts were not reviewed and acknowledged within 20 min of posting on the terminal. The combination of alert/laboratory review integration and flashing light then became an effective and accepted method for alert feedback and acknowledgment.

During the development of CLAS, physicians were asked their opinion of the best method of alert feedback. They responded that the alerts should first be relayed to nurses who could then evaluate them and use their judgment as to whether to notify the physician. Data collected on CLAS users showed that the most frequent users of the system were in fact nurses (nurses acknowledged 53.0% of all alerts). An unexpected result was that a large portion (28.5%) of the alerts were acknowledged by physicians. This result reflects a high degree of physician involvement in review of laboratory data using the computer terminal. As more physicians make use of a recently available option to review laboratory data on terminals in the physician's home or office, the percentage of physicians acknowledging alerts may increase.

Now that CLAS has been tested and modified so that it effectively meets design goals and is accepted by clinicians, further evaluation can be carried out to determine CLAS' effect on the patient care process and on patient outcome. Such evaluation will allow us to judge whether the CLAS system truly improves the quality of the patient care process, and whether its associated costs are justified. If CLAS does have a positive impact on patient care, the system can then be expanded to meet additional data communication and decision-making needs within the hospital.

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