Computer-based ICU data acquisition as an aid to clinical decision-making

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The critically ill patient places tremendous mental challenges and crucial time demands on intensive care nurses and physicians. Computers can ease these demands by automatically acquiring, storing, and displaying patient data. However, the computer can more effectively serve the staff if medical-decision protocols are implemented. This paper describes the use of a computer system designed to optimize medical care for the acutely ill patient.

Perhaps in no other field of medicine are demands on time and intellect greater than in the care of the critically ill patient who requires prompt, accurate decisions and life-protecting and lifesaving therapy. Because of these requirements, ICUs have become widely established in hospitals throughout the United States. During the past decade increasingly more computer systems have been used in these units to: (1) acquire physiologic data, such as blood pressures, cardiac output; (2) communicate data from distant laboratories to the ICU; (3) present and report data in an organized way; (4) correlate data in limited circumstances; and finally and most importantly (5) function as decision-making tools in acute and critical care medicine.

Concurrent with the rapid development of computer methods and technology, there have been equally rapid and exciting developments in instrumentation, techniques for acquiring physiologic data, and the ability to use the information, especially in the treatment of patients with complex multiorgan failure. Monitoring of physiologic data in the ICU also has developed in the past decade. Physiologic measurements, previously performed as special procedures in the catheterization laboratory, are now commonplace in the ICU. During this same decade, computer technology has advanced so that we now have smaller, less expensive, and more powerful computers. It is, therefore, important to analyze the major elements of computer technology and intensive care in order to optimize data acquisition, reporting, and decision-making, which can benefit not only the critically ill patient but also other hospitalized patients.

Background

Computerized medical decision-making has become a major activity of the Department of Medical Biophysics and Computing at the Medical School of the University of Utah and the LDS Hospital in Salt Lake City. We first used computer techniques to monitor post-open-heart surgery patients, but have since expanded our application of the computer to all acute care and intensive care areas. A network of computers has been established for acquisition, communications, and the reporting of patient data and the interpretation of physiologic, x-ray, pharmaceutical, laboratory, and patient observations (Fig. 1). This network of 18 computers provides support to all phases of hospital care, but the most sophisticated application is for the care and monitoring of the critically ill. Six of these computers are used to acquire and store physiologic data from the ICUs; 6 Tandem computer processors are used for data acquisition, data base management, and decision-making; while the remaining 6 computers support laboratory and special procedure functions. Sixty-seven intensive care beds and surgical suites are served by our computer. There are 4 operating rooms (3 thoracic, 1 trauma), 14 thoracic surgery ICU beds, 10 shock-trauma beds, 12 coronary care beds, 8 respiratory ICU beds, 6 neurological beds, and 6 intermediate care beds. In addition, 12 surgical ICU beds are served at the University of Utah.

Data Sources

Major data sources for the computerized monitoring system are:

Physiologic: This includes measurements of systemic arterial blood pressure, pulmonary artery pressure, cardiac output, fluid intake and output data, laboratory results performed by unit nurses, and physical assessment data.

Clinical laboratory: This information is supplied by a communications link with Medlab Computer Services, Inc. The clinical laboratory computer system has its own patient data files and generates its own reports. When data are verified in the laboratory system, they are automatically transmitted to the HELP decision-making system for review, reporting, storage, and decision-making.
Blood gas laboratory: This laboratory processes all blood gas tests and disseminates the data to all hospital units. The ICUs are major users of the blood gas laboratory. This laboratory can measure pH, PCO₂, PO₂, hematoglobin, oxygen saturation, carboxy and met-hemoglobin, from which other variables are derived. Data from the blood gas laboratory are processed by the HELP system and the interpreted results are promptly transmitted to the ICU.

Pharmacy/Nutrition: All pharmacy orders are entered into the computer, at which time decisions about their suitability or whether there are contraindications are made. In the ICUs, all drugs and IV fluids administered are charted. Parenteral nutrition ordering and charting are also done with the computer.

Other operational units of the hospital: Examples are: (1) the admitting area, (2) x-ray, (3) multiphasic screening, (4) catheterization laboratory, (5) infectious disease department, (6) nutritional monitoring group, (7) medical records, and (8) patient history information which is also included in the patient's computer file.

The HELP Decision-making Computer System

Central to maintenance of the computerized data base and decision-making is a computer system called HELP, an acronym for Health Evaluation through Logical Processing. This system, initially implemented on 2 Control Data Corporation 3300 computers, recently has been transferred to a 6-processor Tandem computer system in order to:

(a) Increase reliability, because hardware and software of the Tandem system are designed to be fault tolerant; that is, no single failure will cause the entire system to fail. Patient files are stored in duplicate on magnetic discs (mirrors). Each disc has multiple pathways so that no single system component failure will cause the system to stop.

(b) Permit use of high-level software language to facilitate easier and faster programming and documentation.

(c) Allow expansion so other clinical and administrative functions could be added to the system. The admit/discharge/transfer (ADT) module was the first major administrative function added to our program. In addition, we have added order entry and charge capture modules to the system. Since the Tandem computer can be expanded to 16 processors, there is sufficient growth capability to perform most computerized hospital functions.

The HELP system software provides not only database management, data acquisition, and data review capabilities, but also has unique characteristics which allow convenient patient data retrieval for computerized decision-making, such as:

(1) Its ability to use key words to retrieve data from a patient's record. By referencing data using key words, the user does not need a directory of all patient information, but can select the appropriate item from a menu presented when a key word is entered, thus enabling physicians, engineers, and other technical people to learn the system easily.

(2) Its ability to retrieve data which is time-referenced. This is especially important for a critical care unit where the patient's rapidly changing physiologic conditions require a continual update of the time frame. Data can be retrieved in time frames with reference to: (a) the current time, or (b) the time relationship with other data elements or decisions. (All patient data are stored with a time reference indicating when the data were measured or when specimens were drawn.) In addition, once the appropriate time frame is chosen, various modifiers can be selected: (a) minimum, (b) maximum, (c) median, (d) mode, (e) average, (f) trend, (g) frequency, (h) first value, (i) last value, (j) time of the first value, (k) time of the last value, (l) closest to value, and (m) all values. Thus, the user can specify precisely which data are desired. As observers, we perform the time correlations and data selection functions for our own computation and data interpretation almost without thinking. The computer, however, must be given explicit instructions regarding which data to use. If data collection protocols and time limits are not established, the decision-making process can be ambiguous whether done by humans or by the computer. Thus, the computer's requirements have resulted in the establishment of more precise data collection protocols.

The types of decisions that can be made from patient data are categorized as follows: (1) interpretation of data: a good example is blood gas analysis, where the acid-base status and the oxygenation characteristics are determined. (2) Notification of alarm status: an example is.
notifying medical staff when laboratory data indicate that a life-threatening condition exists. (3) Suggestions for treatment: the computer can suggest treatment alternatives, such as changing a drip rate of a drug or changing the rate or volume of ventilator. These action-oriented suggestions are the ultimate state in computerized decision-making; at this level, change in medical care can best be initiated and consequently, evaluation of the computer can be assessed.

One underlying assumption with computerized decision-making systems is that computers can have a salutary effect on the patient's care. Supporting this assumption are 2 hypotheses: (1) there is an optimal treatment for each critically ill patient's condition, and (2) the application of the optimal treatment will have the desired salutary effect on the patient, and consequently, patient mortality and morbidity will decrease.

**Acquiring Accurate Data**

Early observations of computerized patient monitoring have shown that for a computer system to be truly effective, the patient data must be as complete as possible and that stored data should be free of artifact. We have found that the important factors in eliminating artifacts from the data base are: (1) comprehension of the measurement: optimal results are obtained only by knowing what accuracy is required and knowing how to minimize the sources of error in the measurement. (2) Use of only verified results in the laboratory and ICU: results should be verified by machine, and also by human operators, by having quality control features, range checks, running duplicate samples, and by having the capability of editing the computer results. (3) Implementation of carefully designed data collection protocols, so that accurate and current data are entered into the computer: this step also includes checking for obvious errors by the data entry program and paying close attention to the human engineering aspects of the data entry methods. (4) Employment of responsible people—nurses, physicians, technicians, and staff—who acquire and store the data. (5) Finally and most importantly, the rapid feedback of computerized data for patient care: in a typical situation, the physician orders a test and waits for the results. If the results are available promptly, they are compared with previous values and the patient's condition. If the results are not compatible, the sample may be double-checked. Thus, if this feedback loop can be closed rapidly, more rational decisions can be made and quality verification obtained. The computer accelerates the feedback process.

One of the salient factors for implementation of a computerized decision-making scheme for the care of the critically ill is to have the computer data become the primary record. The computer record should be used as the official patient record, for hardcopy records, and for billing functions. That is, there must be "nonparallel" charting; if there are 2 charts (manual and computer), then neither chart will be complete nor accurate. Unless, and until, the computer record becomes the primary vehicle for patient care and for logging of results, it will never contain sufficient or accurate data required for computerized decision-making.

**Clinical Application**

The system described above has been developed over 15 years. Initially it was only a physiologic data gathering system, but in recent years complete recording of patient information, communication, and decision-making capabilities have been added. The system is in routine daily use and during 1981, the computer system was used at LDS Hospital to: (a) monitor 1235 surgical procedures, (b) monitor physiologic pressures for 5456 patient days (44% of the ICU patients, average 15 patients/day), and (c) generate nurses' charting for 12,447 patient days (average 34 patients/day).

Physicians, nurses and paramedical staff utilize the computer system for most data inquiries. For example, if the latest laboratory data are wanted, these people all go to the computer terminal to review the data. If a staff member desires a printed copy, it is printed easily and promptly with one key stroke.

Several clinical applications will illustrate the record keeping and decision-making capabilities of the HELP system.

**Pharmacy.** The pharmacy module of our computerized intensive care monitoring system illustrates the use of the computer concepts to enhance data entry as well as decision-making (Fig. 2A). The physician writes an order (prescription) for a drug (or iv fluid) in the conventional way. The drug order then is entered promptly into a computerized schedule by a pharmacist, nurse, or ICU technician. As the drug order is entered into the computer, several processes occur: (1) the drug order is stored in the patient's data file and is available for review on the computer terminals; (2) the drug schedule is entered on the patient's computer record. At 12-h intervals, a printout of drugs ordered for the patient (with time and dose) is made; and (3) each new drug is processed through the computerized pharmacy decision criteria to determine if drug-drug interactions exist, to determine if the patient is allergic to the drug, or to determine if there are other contraindications, such as clinical laboratory findings. When a drug is administered to the patient, a similar process is initiated: the patient's file is reviewed for the appropriate drug order by a nurse or technician; the time the drug was given is logged by the system. The computer notes that the drug was given and executes the pharmacy decision criteria for any decisions. The "given" status is charted into the computerized patient's record and becomes a part of the permanent care documentation (Fig. 2B). In addition, information is sent to a patient billing file. Outputs from this computerized
order-entry and charting system are: (1) charting of given drugs to the nearest minute; (2) 12-h reports and 7-day summary report; and (3) automatic billing for drugs given. By utilizing this system, the entire clinical data base is recorded, and the billing information is available as a byproduct of the clinical recording task, thereby reducing the paper handling, saving the nurse time, and reducing lost charges. By providing this type of service, which saves the nurse time and effort, the computer system makes the nurses much more amenable to entering patient data promptly into the computer.

**Blood Gas.** Blood gas results are an important part of the ICU patient's record. Once samples are drawn, they are taken to a central laboratory and analyzed. During the data input process there are checks to help eliminate erroneous entries. Then the results are interpreted by the computer and are usually available in less than 1 min in the appropriate ICU (Fig. 3). In addition to the patient's identifying information, normal high and low values are given. The most recent blood gas (Time 05:35) is an arterial sample (the 316th arterial sample on this ICU patient) taken while the patient was on an assisted/controlled ventilator with 20% oxygen at 30 breath/min with 10 cm H2O of PEEP. The acid-base status is normal, the right-to-left shunt was estimated for 3 different arteriovenous oxygen content differences (C(a-V)O2). The arterial oxygen content is severely reduced due to anemia. When arterial and venous samples are taken at about the same time, C(a-V)O2 and pulmonary shunt (Qs/Qt) are calculated. If a cardiac output is measured at the same time, the Fick principle is used to estimate oxygen consumption. (For example, see 23 April 05:25 sample in Fig. 3.) Other comments are made in the interpretative statements warning of severe hypoxemia and indicating the patient's ventilatory status.

**Hemodynamic Report.** Many seriously ill patients have thermodilution pulmonary artery balloon flotation catheters. For these patients, the computer prompts the injection of iced saline, plots the curves, and calculates the cardiac output. After at least 3 acceptable curves are available, the data are transferred from the minicomputer in the ICU to the HELP system. The HELP system then automatically calculates derived variables, such as

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**Fig. 2. A (top):** Flow chart of data entry and decision-making for drug/iv orders. When a drug order is entered into the computer, it is processed for contraindications using the stored decision logic to evaluate information in the patient record in relationship to the drug ordered. Outputs from this process are decisions and a drug schedule. B (bottom): Flow chart of data entry and information flow when a given drug is "charted" as given. Outputs include computerized medical decisions, logging in the medical record, and generation of billing information.

**Fig. 3.** Blood gas report with the most recent data shown at the top. Day of the month, time the sample was drawn, and sample type are printed on the left. Data derived from measurement and computations are shown next (see key at bottom for abbreviation definitions). Note also the computer-generated interpretations.
vascular resistance, from the data already in the computer database, independent of whether they were determined automatically or manually entered. A time window of ±15 min is used to recover the appropriate data. In addition to derived values, decisions about the condition of the heart and circulation are made and displayed (Fig. 4). Because many of these patients are being given drugs orally, by injection, iv, or otherwise which will affect the contractility of the heart, the drug and its rate of administration are also printed on the report. Because the drugs are charted as a part of the computer record, the information is made available to help the staff interpret the results.

Twelve-Hour Reports. The patient's medical record is an important document which is used by the medical staff to provide information from which to make diagnostic or therapeutic decisions. It also serves a legal purpose by giving an accurate accounting of drugs administered, procedures executed, and variables measured. The record also can serve the billing function. This latter function is seldom actually accomplished with manual systems; instead, a separate form usually is sent for billing purposes. With our computer system, the medical, legal, and administrative functions are integrated into a single computerized record. An example of a 12-h report is shown in Figure 5. The upper section of the report is a plot of "vital sign" data (heart rate, systolic and diastolic blood pressure, and temperature). Below, in time phase with the vital signs, are additional variables (physiologic pressures, cardiac output, respiratory rate, and laboratory data measured in the ICU). After this segment are the hemodynamic data for the 12-h period. The second section of the report lists the drugs and iv solutions given (amount, route, and time given). For iv solutions where infusion rate determines the physiologic effect, the rate of infusion also is indicated.

The next section of the report gives an intake/output balance from the data entered. Insensible loss is estimated from the patient's body temperature and body surface area. Finally, the blood gas data for the 12-h period are also reported. The hemodynamic and blood gas data have been a recent addition to the report to minimize paper in the medical record and also make it easier to correlate data. The report becomes the permanent medical record. The information in the machine also is transmitted to the billing computer for use in billing the patient.

Seven-Day Report. In addition to the 12-h report which gives information in detail, a 7-day report is produced for each patient at 06:00 each day (Fig. 6). This long-term report summarizes physiologic data at the top, similar to the 8-h report, but at 2-h intervals. These reports give the medical staff a quick overview if the patient has been in the ICU for more than a day or so. A summary of the drugs, iv, and blood product information for each 24-h period is given. In addition, fluid balances and weights, and nutritional balances are summarized. The 7-day report format is very useful to the medical staff because it helps them to look at long-term trends in addition to familiarizing them with a referral patient.

Problems and Concerns about the Use of Computerized Decision-Making in ICUs

The following concerns have been raised about the use of computers for medical decision-making:

A. Physicians may feel threatened. However, because the computer provides timely feedback to physicians, helps them to prevent errors, and alerts them of life-threatening situations when corrective action can be taken, we have had enthusiastic support from our medical staff.

B. Patients may receive "inhuman treatment" because they are connected to the computer. We have not found this to be true. Since the advent of computers in the ICU, the nurse and physicians, rather than having to take care of the bookkeeping and paperwork, have had quicker access to patient data and have had more time for the "human" elements of care.

C. Malpractice insurance might be required for the computer. At this point, we have not provided comput-
Fig. 5. Twelve-H Report: detailed report of 12-h of patient care. *Top section* shows "vital" signs, at 15-min intervals. Hemodynamic values for the same 12-h period are reported. Then drug and iv data are reported. A summary of intake and output is reported, then finally the blood gas data for the 12-h period are summarized.

Fig. 6. Seven-Day Report: formatted similar to the 12-h report. "Vital" signs are reported at 2-h intervals. Drug and iv data are summarized for each 24-h period (06:00 to 06:00). Intake and output fluid balances and daily weights are reported. Finally, a daily nutritional summary is calculated and presented from the fluid and iv data previously entered into the machine.

The "closed-loop" control of patient therapy as others have. Because of this and the fact that disclaimers are put on patient's reports, the physician and medical staff are in complete control. There is hence no need for malpractice insurance for our computer.

D. The cost outweighs the benefits. Because computers
are expensive, there is concern that the benefits may not be worth the cost. Recently, we looked at the benefit of one element of our system (pharmacy module) and found there was a benefit-to-cost-ratio of about 4:1. Evaluation of benefit is difficult and perhaps our best barometer is the fact that each new computer service, and its cost, must be approved by our medical staff.

E. Patient care is endangered if the computer system fails. Anyone who has worked with computers in the clinical setting realizes that this can be a traumatic problem. As previously mentioned, we have installed Tandem computers which have built-in redundancies in the hardware and the software intelligence to continue operating even if there are hardware failures. For example, if a disc drive stops, there is an identical "mirror" which stays operational. Since our transfer to the Tandem computer system, we have had stoppages which average less than 3 min/day (99.8% uptime).

CONCLUSION

Our ICU physicians and nurses have recognized the benefit of the ICU computerized decision-making system in the following 8 areas:

(1) Computer data are better organized for review and decision-making.

(2) Automated computer decision-making provides valuable data interpretation and alarm functions.

(3) Computer reports and alarms focus attention of personnel on the treatment and management of the most critical problems.

(4) Computerized data manipulation and the availability of derived variables enhance patient care. Having all data/variables available in the computer is convenient and stimulates thought-provoking inquiry about patient management.

(5) The computer system accelerates data availability because of the online computer communications network, allowing physicians to work in real-time with their decision-making process.

(6) The computerized decision-making provides an excellent basis to teach logical decision-making skills.

(7) The quantitative structure of the computer causes physicians to think more quantitatively and as a consequence, is also an excellent educational tool.

(8) Having most all the patient data in the computer database: (a) eliminates redundant charting, (b) defines charges with clinical data entry, (c) allows transfer of patients anywhere in the hospital without data loss, and (d) allows data review on ICU patients from multiple locations.

Problems in applying computers to decision-making in the ICU can be categorized into three areas: (1) data collection, (2) computer interaction, and (3) development of interpretative and therapeutic protocols.

In the data collection area, computer and monitoring systems are seriously lacking in observational ability, such as those available to a physician who examines a patient (visual, palpation, auscultation). Convenient and efficient methods must be designed to acquire and enter this type of data into the computer. Mechanisms for acquiring key data values must be developed. For example, if an arterial pH could be made available in a certain situation, this value might provide the vital piece of information which would permit the computer to make a therapeutic suggestion. Perhaps when situations like this arise, the computer could "ask" for the data. A persistent problem that the physician continually lives with is inaccurate or erroneous data. The computer can do many things to prevent data errors, but it does not as yet have the insight of a good physician's instinct. Data collection protocols need to be established so that data can be collected in a quick and organized way and can thereby be used for decision-making. Whereas free-format data collection has been the practice in the past, strict protocols required by computers sometimes seem unwarranted to our staff.

There is major need for improvement in solving the problems of man-to-computer communication. Computer terminals need to be more "user-friendly." Advances in terminal hardware capability and the improvements in software should help in this area. Also, most of the current generation of physicians and nurses have had considerable experience with computer terminals, and their entertainment "cousins"—video games. There should, therefore, be no problem in getting this generation of users to "interact" with computers. In fact, we are concerned that we might not be ready for their expectations.

The development of interpretative and therapeutic protocols is the greatest challenge of all. To this point, medicine has not been taught or applied as a strictly quantitative science. Thus, the development of more quantitative medical methods which could be transferred to computer protocols must be developed and validated. This is an area in which very creative and exciting developments no doubt will be made in medical computing in the years to come.

We expect that use of computers in medicine will expand, especially in the critical care areas where data management, decision-making, and therapeutics are so urgent. We feel confident that the problems outlined previously will be solved and that the decision criteria developed and implemented in computer format will greatly improve the educational and operational aspects of intensive care medicine.

REFERENCES


