Computers as Monitors

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Concepts

Monitoring of critically ill patients with the aid of the computer has been explored intensively for more than a decade. However, the clinically successful projects have been so few that we must question whether the objectives have been realistic and the problems adequately defined. When viewed in the broader context of patient care, monitoring is only a part of the overall task. In appraising the value of the computer in this regard, other aspects of patient care must also be considered. These include the frequent acquisition of clinical measurements, record keeping, management of pharmacologic interventions, delivery of various modes of therapy, repeated analysis of patient status followed by decision-making regarding treatment, and the detection and reporting of clinically significant events.

A consensus regarding the definition of patient monitoring is difficult to obtain. However, minimal standards must be established to serve as a basis for critical appraisal. A working definition would certainly include patient surveillance and continuous display of physiologic signals. Since the measurements are essential for adequate assessment of the overall condition of the patient, their acquisition and recording may also be considered a monitoring function.

Automatic pattern recognition is the principal aim of computerized waveform monitoring. Unless very sophisticated pattern analysis schemes are utilized, however, only primitive patterns can be detected by computer techniques. Our working hypothesis has been that the computer can best utilize the acquisition of measurements, data storage and retrieval, medical record preparation, and structured analysis of the clinical data according to rules and logic, the latter allowing more accurate assessment of the status of the patient as well as decision-making regarding therapy. Some other definitions of computer monitoring have encompassed therapeutic intervention. As examples of the latter function, since 1967 we have utilized computer control of blood infusion to regulate left atrial pressure automatically, and recently the role of the computer has been expanded to include closed-loop control of hypotensive agents by employing feedback of mean arterial pressure.

The choice of bedside, central station, or remote monitoring is dictated by the type of patient monitored, the level of staffing in the particular intensive care unit, and the type of care delivered. Coronary-care systems have typically been oriented more toward the central station concept, whereas the majority of cardiothoracic surgical units have required bedside monitoring. In most instances these ideas have been carried over in the subsequent design of newer computer-based systems.

System Components

The computer-based system illustrated in figure 1 is composed of the ICU monitoring equipment, computer hardware, and the computer programs that operate the system. The computer programs can be divided into two categories: 1) programming systems for operating the computer's input/output devices and for compilation of the programs; 2) applications programs that tailor the computer to the particular monitoring duties and data manipulation desired.

Detection of the physiologic signal is the first of several steps crucial to the derivation of meaningful clinical data for monitoring purposes. The electrodes, cannulas, sensors, and sampling devices must be positioned with great care to obtain measurements with acceptable consistency and accuracy. Failure to properly prepare and maintain this inter-

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face severely diminishes the quality of the performance of the entire system and ultimately produces measurements of questionable reliability. The importance of meticulous technique in the application and maintenance of optimal function of the signal-acquisition devices cannot be overemphasized.

The second level in figure 1 consists of the electronics modules that are connected to the electrodes, thermistors, pressure transducers, densitometers, and other sensors and perform a variety of amplification and signal-processing functions (see fig. 2). This and subsequent phases of signal manipulation are so interdependent that the design possibilities are practically infinite. The range of capabilities includes: 1) preamplifiers that present raw or filtered waveforms for total processing by the computer; 2) analog preprocessing to follow peaks or troughs, to calculate rate, to differentiate, to integrate, to average, etc., for computer processing; 3) treatment of signals by hybrid techniques (analog and digital) that employ special-purpose digital circuits and/or microprocessor extraction of derived measurements for further processing by the main computer. It is imperative that electrically safe practices be followed in the intensive care unit to avoid microshock hazards. Noise-free transmission techniques need to be used to convey the signals to the computer.

The third element in figure 1 is the digital computer itself, with its input and output devices. In most instances, the signals transmitted by the preamplifiers and preprocessing electronics are of the analog type, i.e., time-varying voltage levels that correspond to the physiologic variables. Conversion of these signals to make them suitable for analysis is performed with an analog-to-digital converter at the computer in most systems, but can be done in the preprocessor so that the transmitted digital signals proceed directly to the computer.

The input/output capabilities vary considerably depending upon the size of the computer and the functions desired. Computer-derived measurements are generally displayed in the unit either at a central station, at the bedside as shown in figure 2, or both. Also shown in figure 2 is a keyboard, which is used for communication with the computer. This allows interaction with the display to enter data, select options, specify functions, initiate measurements, etc., manually. In a few systems, computer outputs directly control sampling valves, flushing systems, injection syringes, infusion pumps, and other devices. In addition to the special-purpose inputs and outputs, the computer may be equipped with a complement of conventional data-processing units such as a disk, line printer, paper tape, magnetic tape, card reader, and card punch, or it may be a satellite of a larger computer.

**System Designs**

A comprehensive review of system designs has been published by Gaeser and Thomas. Examples of various types of systems include the time-shared computer system, the process-control computer, multiple minicomputers, and the time-shared minicomputer.

**TIME-SHARED SYSTEM**

The intensive care unit at Latter Day Saints Hospital in Salt Lake City, Utah, is con-
nected to a time-shared computer system for intermittent processing of physiologic measurements. Manual entry of data and display of computer-derived data are performed at a central station.\(^\text{11}\)

**Process Control System**

The Cardiac Surgical Intensive Care Unit system at the University of Alabama Medical Center in Birmingham is structured around a process-control computer. The clinical measurements are automatically acquired at 2-minute intervals. Data display and manual entry are at the bedside. Closed-loop control of left atrial pressure by blood infusion and regulation of mean arterial pressure by automatic infusion of vasodilating agents are performed by the computer system.\(^\text{12}\)

**Multiple Minicomputers**

Continuous processing of the electrocardiogram to identify ventricular arrhythmias has been achieved with multiple minicomputers in the Coronary Care Unit at the Barnes Hospital—Washington University Medical Center in St. Louis. A special communication system is used to interconnect these minicomputers with a common mass-storage system for pro-
gram overlays and data storage. This design minimizes the memory requirements for the individual computers dedicated to each patient in the unit.1

TIME-SHARED MINICOMPUTER

In the thoracic surgical unit at the same hospital specially designed bedside monitoring devices, which employ microcomputers, time-share a minicomputer by means of a high-speed digital data bus. Bedside and central displays are used for presentation of data derived by continuous processing of the electrocardiograms (ECG), arterial pressures, and respiratory waveforms for five beds.13

Clinical Measurements

Fidelity of the ECG signal is dependent upon careful preparation of the skin and proper electrode placement to develop an acceptable impedance at the electrode/skin interface. R-wave detection for computation of average heart rate is usually an integral part of the preamplifier. However, in continuous monitoring of arrhythmias the amplified and filtered waveforms are transmitted to the computer for digitizing and analysis.

Intravascular and intraaortic pressures are obtained with indwelling cannulas connected to fluid-filled tubing, which transmits the hemodynamic pressures to the strain gauge or piezoelectric transducers for conversion to their electrical analogs. Continuous flushing devices help maintain patency by providing a slow infusion of heparinized physiologic solution.

The Swan-Ganz flotation catheter has significantly enhanced the measurement capabilities in non-surgical intensive-care units and coronary-care units. The ability to obtain cardiac output, pulmonary wedge pressure, and pulmonary arterial oxygen saturation frequently greatly aids in the analysis and decision-making regarding treatment and the effects of intervention. Russell and Rackley have described in detail the equipment requirements, computer processing, and clinical techniques required for the use of this important instrument.14

Intracardiac pressures obtained from small plastic catheters placed in the right and left atria are measured in patients following cardiac surgical procedures. By this means, cardiac function and the need for therapeutic interventions can be readily assessed. Catheter placement and signal-processing methods for these measurements have been described.20

The reliability of indirect (cuff) measurement of arterial pressure has been the subject of considerable debate. Our own experience, and that of others, indicate that intravascular measurement of pressure is necessary for optimum care of critically ill patients. Use of the invasive technique is justified, we feel, because of its greater sensitivity and lesser vulnerability to motion artifact, and because of the accuracy and reliability of the direct measurements, particularly in the patients who have diminished cardiac performance. Computer processing of the waveforms is sometimes used for the derivation of peak systolic, diastolic, and mean arterial pressures, but analog preprocessing is generally quite satisfactory.

In his excellent article, Gardner discusses the measurement procedures for the cardiovascular subsystem in the clinical environment. The desirable characteristics for instrumentation are outlined and the problem areas, especially with indirect methods of blood pressure estimation, are highlighted. Significant developments in intravascular pressure measurement system are also reviewed.14

The reliability of respiratory-rate measurements derived from thoracic impedance has been acceptable when the electrodes have been placed with great care. Extraction and processing of this low-level signal require electronics with adequate performance characteristics and sufficient quality of manufacture. Other respiratory measurements are much more difficult to obtain automatically because a custom-designed array of electromechanical devices, networks of tubing, and elaborate schedules for routing the flushing, calibration, and sampling streams to the electrodes and sensors are required. These complexities have prompted the use of manual sampling techniques followed by automatic measurement or keyboard entry of the measurements. Pulmonary monitoring by computers has been implemented at some centers to measure ventilatory rate and
volume, airway pressure, inspired oxygen concentration, and end-tidal carbon dioxide concentration. The derived values, too numerous to list here, are discussed by Glueser and Thomas, and in even greater detail by Osborn et al. Arterial and venous blood are usually sampled manually and introduced into the automated instrumentation for analysis. The measurements are transmitted to the computer automatically or by keyboard entry. A system for automatic sampling, measurement, display, and logging of arterial and venous blood gases has been developed.

Functions related to fluid and electrolyte balance and metabolic requirements include measurement of chest drainage and urinary output using load-cell weighing systems, infusion of blood with computer-controlled calibrated pumps, manual entry of intake of potassium and the serum level, calculation of base excess from blood-gas measurements, and measurement of core and extremity temperatures by rectal and surface thermists.

The previously discussed measurements and methods represent the presently available capabilities of those systems that have achieved moderate to excellent success in their respective hospitals. Since most of the measurements are acquired by invasive means, significant progress in computer-based monitoring will probably be limited to critically ill patients for some time to come. Development of reliable non-invasive techniques is progressing slowly, but may increase the potential number of patients that can be monitored in the future.

Monitoring of Arrhythmias

Common to nearly all monitoring systems are the display and processing of the electrocardiogram. This is done in the operating room, the recovery room, the cardiothoracic or general surgical intensive-care unit, and in coronary care and shock and trauma units. Since this readily available bioelectric signal can be acquired with electrodes placed non-invasively, many attempts to perfect systems for computerized monitoring of arrhythmias have been made. Unfortunately, special cunning was necessary to distinguish between patterns that should be detected and events that should be ignored.

Successful application of computer technology to the monitoring of biological signals such as the ECG derived from critically ill patients requires definitive, quantitative descriptions of waveforms that must be identified and conditions that must be detected. It is the explicit nature of programming the computer that imposes such demanding specifications. Therefore, the development of computer programs with sufficient sophistication to recognize patterns reliably has proven extremely difficult. The ability of the human observer to correlate an observed pattern with previous experience or training and identify the event is not understood well enough to allow precise description and quantitation of the pattern-recognition procedure and to allow computer programs to be written. Detection of P waves, for example, has been especially unreliable. Most arrhythmia-detection programs have therefore been designed to attempt to classify ventricular arrhythmias based on R-R intervals and the shape of the QRS complex.

The ARGUS™ arrhythmia-monitoring system deserves special mention since its widely accepted AZTEC™ preprocessing algorithm has been employed in many systems. Furthermore, ARGUS has been extensively evaluated, consistently detects QRS’s with an accuracy of 99 per cent, and correctly identifies 90 per cent of the premature ventricular beats. Despite these good results, clinical acceptance of the system has been slow. Harrison has speculated, and perhaps rightly so, that the lack of enthusiasm for commercially available systems results from inadequate validation of the system and the emphasis placed on premature ventricular contractions, with virtually no attention to detection of other premonitory arrhythmias or atrial activity. If only premature ventricular beats can be detected, we believe the impact of automated arrhythmia detection on patient care may not be sufficient to justify the relatively high cost of such a system.

Data Management

The computer is unsurpassed at performing assigned tasks with persistent, indefatigable
diligence, no matter how menial these duties may be. Repetitive collection of the clinical measurements and transmission to the intensive-care unit is carried out automatically at intervals ranging from 2 to 15 minutes. Manual entry of information with the keyboard is managed on a demand basis. Organization of the data and frequent logging to auxiliary storage units such as a disk allow for subsequent computer processing. Data retrieval and display are executed quickly to allow a structured review of the automatically and manually entered measurements and assessment of the current status and progress of the patient.

Some systems use the computer to perform complex computations for derivation of information. Examples of this include calculation of base excess and oxygen saturation from blood-gas measurements, cardiac output from a thermodilution or dye-dilution curve, body surface area from height and weight, drug dosages, and respiratory indices from airway gas and flow measurements. Glaeser and Thomas properly caution that the reliability of derived values is subject to the validity of the underlying assumptions. The alluring, sophisticated indirect methods must be approached reservedly with a full understanding of the fundamental principles so that the model applied is rigorous and appropriate.

The data management potential of computers has been applied to the preparation of the hospital record by plotting or tabulating the patient's clinical data. Confidence in the information obtained is absolutely essential because no time will be saved if the nurse continues parallel measurement and charting by hand.

**Clinical Decision-making**

As patient management protocols are developed, the care of critically ill patients becomes more structured. This trend toward decision-making on a logical basis from data analyzed according to rules has made it possible to use the computer to assess the condition of the patient and select an appropriate therapeutic intervention. The application of multivariate techniques in the development of prognostic indices is evolving at some centers.

Latter Day Saints Hospital has implemented computer programs for logical evaluation of a broad data base derived from many sources, including real time monitoring and investigative procedures. Decision criteria are established through interactive dialog with the system from a computer terminal. A problem-oriented record is created for each patient and updated through on-line analysis of the data as they are acquired by the system.

At the University of Alabama Medical Center patient management programs for the cardiovascular subsystem in postoperative cardiac surgical patients have been computerized (table 1) to assist in the detection of diminished cardiac performance, the decision to intervene, and the selection of the appropriate intervention. Rules for the analysis of the volume of chest-tube drainage and the necessity for reoperation have also been developed.

Multivariate analysis of physiologic data has been applied to patients, primarily in shock and trauma units. Classification of patients according to measurements that have been combined to yield maximum discrimination is one of the goals of these investigations. Further distillation of the data to compute a single-valued numerical representation of the patient's prognosis has been evaluated as well. If these methods can be applied successfully, less physiologic insight will be needed than for automation of patient-care protocols that demand definitive models. The lack of orderly rules and logic is the chief obstacle to employing the computer as a decision-making tool.

**Computer-controlled Interventions**

Involvement of the computer in therapy by closed-loop, feedback control is slowly gaining acceptance, but only a few clinical applications exist. Physicians may be reluctant to adopt these techniques because of an unwillingness to acknowledge that many aspects of care can be structured sufficiently to be automated.

Maintenance of left atrial pressure by infusion of blood has been performed automatically in 6,400 cardiac surgical patients since October 1967. The computer-programmed rules developed by Kirklin, Kouchoukos and
### Table 1. Logic for Analysis and Treatment of Impaired Cardiac Performance Early after Operation

<table>
<thead>
<tr>
<th>Mean Left Atrial Pressure (mm Hg)</th>
<th>Mean Arterial Pressure (mm Hg)</th>
<th>Cardiac Index (ml/min/m²)</th>
<th>Less than 2.0</th>
<th>2.0–3.0</th>
<th>More than 3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 or less</td>
<td></td>
<td>Blood</td>
<td>Blood</td>
<td>Blood</td>
<td></td>
</tr>
<tr>
<td>7–14</td>
<td></td>
<td>Blood</td>
<td>Blood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15–18</td>
<td>Less than 100</td>
<td>Epinephrine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than 100</td>
<td>Epinephrine, dopamine, or isoproterenol</td>
<td>Trimethaphan or nitroprusside</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 18</td>
<td>Less than 100</td>
<td>Epinephrine, dopamine, or isoproterenol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than 100</td>
<td>Epinephrine, dopamine, or isoproterenol plus trimethaphan or nitroprusside</td>
<td>Trimethaphan or nitroprusside</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Tabulation of criteria that have been programmed for computer-aided analysis and treatment of impaired cardiac performance in the University of Alabama Hospital Cardiac Surgical Intensive Care Unit.

Sheppard are utilized to actuate computer-controlled infusion pumps when left atrial pressures are not at desired levels. For the past year, regulation of mean arterial pressure in hypertensive patients by computer-controlled infusion of hypotensive agents has been performed in patients during the first 24 to 48 hours after operation. Morgan et al. have evaluated automated infusion of blood, and Robins et al. have reported the successful clinical implementation of automated fluid infusion, as well as infusion of blood, using the rules developed by us. Pluth et al. have performed the most critical evaluation of automatic infusion of blood. Their results show that the average total volume of blood infused automatically was half a unit less per patient than when blood was infused manually.

Sheppard et al. developed a computer-controlled infusion pump in 1967, and Bisera et al. in 1974, but these have only recently become available commercially. Several nontechnological factors have impeded the application of automatic-control techniques to intensive care. The facility with which the variable to be controlled can be accurately and reliably measured determines the feasibility of closed-loop feedback techniques. In some instances a related measurement can be fed back if the primary variable cannot be measured conveniently, reliably, or with acceptable frequency. Physiologic response to the intervention as well as potentially undesirable side effects must be quantitated. Furthermore, translation of this knowledge into proper computer-programmed control procedures (algorithms) is absolutely essential. When acceptable solutions to these problems have been developed, the system can be gainfully employed in direct patient care to achieve significant improvements over manual techniques by improved physiologic subsystem stability, earlier completion of therapy, smaller quantity of agent used, less erratic and more intense control, and therapy uninterupted by the need to perform other duties.

**Impact on Staff, Care and Costs**

Computerized intensive-care monitoring systems relieve nurses of many time-consuming tasks such as routine measurement and charting, enabling them to devote much more of their time to those aspects of patient care that can only be done manually by skilled personnel. Further support of the nurses is provided by biomedical instrumentation technicians, who clean and sterilize the transducers, set up and calibrate the clinical measurement subsystems, connect the newly arrived patient to the measurement devices, collect arterial blood samples and perform the
blood-gas analyses, and carry out the steps necessary for measurement of cardiac output by the dye-dilution method. These paramedical personnel are essential to the smooth operation of the system, providing expert technical support and continuity.

Opinions vary widely regarding the value of computer systems in patient care. The availability of objective data on this important issue, however, is limited. Quite properly, success demands acceptance by nurses and physicians, which in turn depends on how well the system has been integrated into the intensive-care unit and whether it performs useful clinical functions in a reliable fashion. Even if acceptance of the system is obtained, specific improvements in patient care as a result of the computer system have eluded quantitation. The difficulty lies in separating the effects of the automated system from the effects of other variables on modalities such as mortality, morbidity, quality of care, bed utilization, cost, and staff efficiency.

Detailed studies of computerized monitoring systems have been conducted at several hospitals by Arthur D. Little, Inc. Their investigations serve to further emphasize the problems in attempting definitive evaluation of the computer in the ICU. Though some benefits were cited overall, the degrees of success varied among the units from minimal in some to total integration and acceptance in others. In one hospital, work-sampling studies obtained during normal system function were compared with data acquired while the computer was being relocated. Without the system the time the nurses spent taking measurements tripled to 16 per cent and the charting time doubled to 16 per cent. This increased workload was managed at the expense of patient observation, which was reduced from 21 per cent with the computer to 2 per cent without.29

In a study that compared similar groups of patients in computerized and non-computerized surgical ICU's Pluth et al. observed that 24 per cent of the patients in the computerized unit received antiarrhythmic drugs, compared with 17 per cent in their standard unit. The incidence of serious arrhythmias was 37 per cent higher in the standard unit, mortality 50 per cent higher, and three times as many of the deaths had an arrhythmic component than in the computerized unit. They speculated that more prompt recognition of arrhythmias led to earlier treatment, preventing development of more serious arrhythmias, in the computer unit.20

The investment required for adding the computer and arrhythmia-monitoring programs to an existing eight-bed coronary-care unit already equipped with the normal complement of oscilloscopes and preamplifiers is $58,000. Included in this cost are central station, minicomputer, keyboard and display, chart recorder, signal-recall memory, computer programs, one year of hardware service, two years of software service, and in-service training. System hook-up is included, but the cost of installation, material, and labor for site preparation is not included. Similarly, the investment required for computerizing a four-bed surgical intensive care unit already equipped with the signal-acquisition devices is $97,000. Bedside terminals and automatic blood and fluid infusion are included as well. However, the total installed cost and cost of operation depend on numerous factors such as the number of beds and the type of patient being served. Without doubt, initial costs are higher when systems are first implemented, but the eventual integration into the routine operation of the unit results in enhanced nursing efficiency, increased bed utilization from shorter ICU stays, and other benefits that accrue to such an extent that the cost per patient decreases in the long run. Implementation of the automated system in our own unit has resulted in our being able to transfer patients from the unit to a regular nursing floor one to two days sooner than was possible previously. We have observed that most patients are hemodynamically stable by the morning after operation and can be returned to their hospital rooms within 24 hours after operation. The resulting cost reductions are more than sufficient to offset the added cost of the automated system (less than $100 per day per patient) in the surgical unit.29

Summary and Conclusions

The value of the computer in monitoring has been mainly in the automation of measurement acquisition, display, storage, retrieval, and charting for the medical record. Computer control of therapy has not been widely
accepted despite successful implementation in a few centers. Arrhythmia monitoring with the aid of the computer has fallen short of expectation because of the difficulties encountered in developing reliable waveform-recognition techniques. The economics of computerized monitoring are not clearly established because the dollar values of many of the derived benefits are difficult to quantify. Objective analysis of the impact of the computer has been accomplished to a modest extent. However, each reported application of a computerized system must be judged on its own merits, because not every problem lends itself to computerization, and the style of care in some units may not benefit from computer monitoring.

Clinical successes have been confined primarily to those systems addressing well-defined problems that were sufficiently rigid in structure to employ the computer productively. The system analysis that emphasizes the clinical needs instead of the capabilities of the computer is more likely to yield effective solutions to patient-care problems.

Achievement of clinical results depends upon determining in advance whether the computer is needed. Intensive system analysis must be performed before the computer is implemented as part of the monitoring activity. A complete understanding of the role of the computer is absolutely essential in order to know which expectations are realistic and which are impractical. Problems that are ill-defined before computerization are likely to remain so afterwards. The computer itself is not the issue. The following principles should be applied to avoid producing a system in which the computer does not function optimally:

Identification of the clinical needs.
Definition of the problem.
Establishment of specific objectives.
Design of relevant solutions.
Implementation of robust technology.
Integration of the system into the operation of the unit.
Follow-through with training, maintenance, evaluation, revision, and updating.

The belief that computers can be programmed to perform patient-care functions that human beings are unable to perform is unrealistic. Basically, the system should be used to amplify human endeavors. By this means personnel efficiency can be enhanced to such an extent that patient care is improved and/or productivity is increased. Repetitive tasks that require speed of response, consistency, and frequent execution of involved procedures are performed better by an automated system than by manual means.

References