12

Patient-Monitoring Systems

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Shortliffe/Perreault
Medical Informatics:
Computer Applications in Health Care (1st Edition)
Addison-Wesley Publishing Company – 1990

After reading this chapter,[1] you should know the answers to these questions:

- What is patient monitoring? Why is it done?
- What are the primary applications of patient-monitoring systems in the intensive-care unit?
- How do computer-based patient monitors aid health professionals in collecting, analyzing, and displaying data?
- What are the advantages of using microcomputers in bedside monitors?
- What are closed-loop and open-loop control systems?
- Why is integration of data from many sources in the hospital necessary if a computer is to assist in the majority of critical-care decisions?

[1]Portions of this chapter are based on Gardner, R. M., Sittig, D. F., and Budd, M. C. Computers in the intensive care unit: Match or mismatch? In Shoemaker, W. C., et al. (eds), *Textbook of Critical Care*, 2nd ed. Philadelphia: W. B. Saunders, 1989, p. 248.

12.1 What Is Patient Monitoring?

Frequent measurement of patient parameters (such as heart rate, respiratory rate, blood pressure, and blood-oxygen content) has become a central feature of the care of critically ill patients. When timely and accurate decision making are crucial for providing therapy, patient monitors frequently are used to collect and display physiological data.

We usually think of a **patient monitor** as something that watches for—and warns against—life-threatening events related to a critically ill patient. **Patient monitoring** can be rigorously defined as: "Repeated or continuous observations or measurements of the patient, his or her physiological function, and the function of life support equipment, for the purpose of guiding management decisions, including when to make therapeutic interventions, and assessment of those interventions" [Hudson, 1985, p. 630]. A patient monitor not only should alert health-care professionals to potentially life-threatening events, but also may control devices that maintain life.

In this chapter, we shall discuss the use of computers to aid health professionals in the collection, storage, interpretation, and display of physiological data. Although we shall deal primarily with patients who are in **intensive-care units (ICUs),** the general principles and techniques also are applicable to other hospitalized patients. For example, patient monitoring may be performed for diagnostic purposes in the emergency room, or for therapeutic purposes in the operating room. Techniques that just a few years ago were used only in the ICU are now used routinely on general hospital wards; some even are used by patients at home.

12.1.1 A Case Report

A case report will give you a perspective on the problems faced by the health-care team caring for a critically ill patient. A young man is injured in an automobile accident. He has multiple chest and head injuries. His condition is stabilized at the accident scene by skilled paramedics, using a microcomputer-based ECG monitor, and he is quickly transported to a trauma center. Once in the trauma center, the young man is connected via sensors to computer-based monitors that determine his heart rate, rhythm, and blood pressure. Because of the head injury, the patient has trouble breathing, so he is connected to a computer-supported ventilator. Later, he is transferred to the ICU. The results of clinical chemistry and blood-gas tests are soon transmitted from the laboratory to the ICU via electronic computer networks. The patient survives the early threats to his life and now begins the long recovery process.

Unfortunately, a few days later, the patient is beset with a problem common to multiple trauma victims—he has a major infection and develops problems with several vital organs. As a result, even more monitoring instruments are needed to acquire data and to assist with the patient's treatment; the detailed information required to care for the young man has increased dramatically. The computer provides suggestions about how to care for the specific problems, flags life-threatening situations, and organizes and reports the mass of data so the physicians can make prompt and reliable treatment decisions. Figure 12.1 is an example of a computer-generated ICU

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                L D S   H O S P I T A L   I C U   R O U N D S   R E P O R T
                                 DATA WITHIN LAST 24 HOURS

NAME:          , STEVEN                   NO.    10072      ROOM: E609                DATE: JAN 29 14:17
DR. STINSON, JAMES B.           SEX: M     AGE:  43   HEIGHT: 178   WEIGHT:  75.40   BSA: 1.93   BEE:  1697   MOF:     0
ADMT DIAGNOSIS: FEVER UNK ORIGN, S/P KIDNEY TR   ADMIT DATE: 14 DEC 88

CARDIOVASCULAR:  0                                                     EXAM: ____________
   -- NO CARDIAC OUTPUT DATA AVAILABLE
                  SP     DP     MP    HR  |  LACT         CPK         CPK-MB        LDH-1        LDH-2
 LAST VALUES      121    68     89    113 |
 MAXIMUM          194    97    126    124 |    (     )     (     )     (     )     (     )     (     )
 MINIMUM          101    58     72    83 .|

RESPIRATORY:  0
            pH    PCO2    HCO3    BE     HB    CO/MT   PO2   SO2   O2CT   %O2  AVO2  VO2   C.O.  A-a  QS/QT  PK/ PL/PP  MR/
29 06:21 A  7.43  27.3    18.0    -4.5   10.0   2/ 1   80    94    13.2   30                      66           0/   0/ 5  17/
          SAMPLE # 74, TEMP 38.4, BREATHING STATUS : ASSIST/CONTROL
          NORMAL ARTERIAL ACID-BASE CHEMISTRY
          SEVERELY REDUCED O2 CONTENT (13.2) DUE TO ANEMIA (LOW HB)

          ------- machine settings ------- | ------------------------- patient values -------------------------
          VENT   MODE   VR   Vt    O2%   PF   IP    MAP   PK   PL   PP   m-Vt   c-Vt   s-Vt   MR   SR   TR   m-VE   s-VE   t-VE   Cth
29 14:15  B-I    A/C    16   700   30    50               32   26   5    866    731           29             21.2                 34.8
29 06:05  B-I    A/C    16   700   30    50               22   20   5    830    745           19             14.2                 49.7
29 14:15   5/14:16   INTERFACE: TRACH TUBE;  ALARMS CHECKED; POSITION: SUPINE;  THERAPIST: DAVIS, TERIANNE,  CRTT
29 06:05  10/06:08   INTERFACE: TRACH TUBE;  ALARMS CHECKED; POSITION: SEMI-FOWLER;  PATIENT CONDITION: CALM;  SUCTIONED,
         HEMOPTIC;  THERAPIST: TARR, TED,  RRT

 DATE     TIME    HR   VR    VT    VC    VE    MIP   MEP   MVV   PK FLOW  THERAPIST           EXAM: ____________
01/29/89 07:15   109   20   600         12.0   -60                        DAVIS, TERIANNE            ____________

NEURO AND PSYCH:  0
   GLASCOW  6 (08:00) VERBAL ________   EYELIDS ________   MOTOR __________   PUPILS ________   SENSORY ________

   DTR ___________   BABIN. ________   ICP ____________   PSYCH __________

COAGULATION:  0
   PT:    14.2   (05:15    ) PTT:     50 (05:15    ) PLATELETS:   89 (05:15    )  FIBRINOGEN:   0(00:00) EXAM: ________
   FSP-CON:   0 (00:00     ) FSP-PT:   0 (00:00    ) 3P:              (00:00    )                              ________

RENAL, FLUIDS, LYTES:  0
   IN   3430 CRYST   1025  COLLOID   1035  BLOOD      NG/PO   1340 | NA       (     ) K         (     )  CL         (
   OUT  2689 URINE    800  NGOUT      500  DRAINS   25 OTHER  1364 | CO2 21.0 (05:15) BUN    51 (05:15)  CRE   4.2 (05:15
   NET   741 WT     75.40  WT-CHG          S.G.     1.015          | AGAP   16.7      UOSM               UNA       CRCL

METABOLIC --- NUTRITION:  0
   KCAL      2630   GLU  138    (05:15)  ALB    2.9 (05:15)  | CA   7.7 (05:15)   FE     .0 (00:00)   TIBC     0 (00:00)
   KCAL/N2   891    UUN     .0 (00:00)   N-BAL   .0          | PO4  1.9 (05:15)   MG    1.9 (05:15)   CHOL   228 (05:15)

GI, LIVER, AND PANCREAS:  0                                                                                  EXAM:
   HCT     29.4 (05:15)  TOTAL BILI   23.1 (05:15)  SGOT   73 (05:15)  ALKPO4  957 (05:15)  GGT     768 (05:15) ________
   GUAIAC         (     )     DIRECT BILI  17.4 (05:15)  SGPT   99 (05:15)  LDH     237 (05:15)  AMYLASE   0 (00:00) ________

INFECTION:  0
   WBC  5.2(05:15 ) TEMP  40.3 (28/06:00) DIFF  26 B, 70P,  3L,  1M,   E (05:15) GRAM STAIN: SPUTUM __________ OTHER ______

SKIN AND EXTREMITIES:
   PULSES ________  RASH ________  DECUBITI ____________

TUBES:
   VEN ________  ART ________  SG ________  NG ________  FOLEY ________  ET ________  TRACH ________  DRAIN ______

   CHEST _____________  RECTAL ______  JEJUNAL ________  DIALYSIS ________  OTHER ______________________________

MEDICATIONS:

MORPHINE, INJ                          MGM   IV      20   AMPHOJEL, LIQUID                             ML     NG
MEPERIDINE (DEMEROL), INJ              MGM   IV     150   DIPHENHYDRAMINE (BENADRYL), INJ              MGM    IV
PHENYTOIN (DILANTIN), SUSPENSION       MGM   NG     300   HYDROCORTISONE NA SUCCINATE (SOLU-CORTEF)MGM,  IV
MIDAZOLAM (VERSED), INJ                MGM   IV       5   AMIN-AID FULL STRENGTH, LIQUID               ML     NG D
AMPHOTERICIN B, INJ                    MGM   IV      40   TAP WATER, LIQUID                            ML     NG
CEFTAZIDIME (FORTAZ), INJ              MGM   IV    1000   MAGNESIUM SULFATE 50%, INJ                   GM     IV
SUCRALFATE (CARAFATE), TAB             MGM   NG    4000   POTASSIUM CHLORIDE, INJ                      MEQ    IV
FAMOTIDINE (PEPCID), INJ               MGM   IV      40   NOVOLIN REGULAR, INJ                         UNITS  IV
                                                                                                                  #087
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FIGURE 12.1 Rounds report used at LDS Hospital in Salt Lake City for evaluation of patients each day during teaching and decision-making rounds. The report abstracts data from diverse locations and sources, and organizes them to reflect the physiological systems of interest. Listed at the top of the report is patient-identification and patient-characterization information. Next is information about the cardiovascular system. Data for other systems follow. (*Source:* Courtesy of LDS Hospital.)

report produced by the HELP system (discussed in Chapter 7). This report summarizes 24 hours of patient data, and is used by physicians to review a patient's status during daily rounds (daily visits by physicians to their hospitalized patients).

12.1.2 Patient Monitoring in Intensive-Care Units

There are at least four categories of patients who need monitoring:

1. Patients with *unstable physiologic regulatory systems*; for example, a patient whose respiratory-control system is suppressed as a result of a drug overdose or anesthesia
2. Patients with a *suspected life-threatening condition*; for example, a patient who has findings indicating an acute myocardial infarction (heart attack)
3. Patients with a *high-risk status*; for example, a patient who has just had open-heart surgery, or a premature infant whose heart and lungs are not fully developed
4. Patients in a *critical physiological state*; for example, a patient with multiple types of trauma

Care of the critically ill patient requires prompt and accurate decisions so that life-protecting and lifesaving therapy can be appropriately applied. Because of these requirements, ICUs have become widely established in hospitals. Such units use computers almost universally for the following purposes:

1. To acquire physiological data, such as blood-pressure readings
2. To communicate data from distant laboratories to the ICU
3. To store, organize, and report data
4. To integrate and correlate data from multiple sources
5. To function as a decision-making tool that health professionals may use in the care of critically ill patients

12.2 Historical Perspective

The earliest foundations for acquiring physiological data date back to the end of the Renaissance period.[2] In 1625, Santorio, who lived in Venice at the time, published his methods for measuring body temperature with the spirit thermometer and for timing the pulse (heart) rate with a pendulum. The principle for both devices had been established by Galileo, a close friend. Galileo worked out the uniform periodicity of the pendulum by timing the period of the swinging chandelier in the Cathedral of Pisa, using his own pulse rate as a timer. The results of this early biomedical-engineering collaboration, however, were ignored. The first scientific report of the pulse rate did not appear until Sir John Floyer published "Pulse-Watch" in 1707. The first published course of fever for a patient was plotted by Ludwig Taube in 1852. With subsequent improvements in the clock and the thermometer, the temperature,

[2]This section has been adapted, with permission, from "Computer Monitoring in Patient Care" by D. H. Glaeser and L. J. Thomas, Jr., in the *Annual Review of Biophysics and Bioengineering*, Volume 4, ©1975 by Annual Reviews Inc.

pulse rate, and respiratory rate became the standard **vital signs.** In 1896, Scipione Riva-Rocci introduced the sphygmomanometer (blood-pressure cuff), which permitted the fourth vital sign, arterial blood pressure, to be measured. A Russian physician, Nikolai Korotkoff, applied Riva-Rocci's cuff with a stethoscope developed by the French physician Rene Laennec to allow the auscultatory measurement[3] of both systolic and diastolic arterial pressure. Harvey Cushing, a famous U.S. neurosurgeon in the early 1900s, predicted the need for and later insisted on routine arterial-pressure monitoring. Cushing also raised two questions familiar even at the turn of the century: (1) Are we collecting too many data? (2) Are the instruments used in clinical medicine too accurate? Would not approximated values be just as good? Cushing answered his own questions by stating that vital-sign measurement should be made routinely and that accuracy was important [Cushing, 1903].

Since the 1920s, the four vital signs—temperature, respiratory rate, heart rate, and arterial blood pressure—have been recorded in all patient charts. In 1903 Willem Einthoven devised the string galvanometer for measuring the ECG, for which he was awarded the 1924 Nobel prize in physiology. The ECG has become an important adjunct to the clinician's inventory of tests for both acutely and chronically ill patients. Continuous measurement of physiological variables has become a routine part of the monitoring of critically ill patients.

At the same time that advances in monitoring were made, major changes in the therapy of life-threatening disorders also were occurring. Prompt quantitative evaluation of measured physiological and biochemical variables became essential in the decision-making process as physicians applied new therapeutic interventions. For example, it is now possible—and in many cases essential—to use ventilators when a patient cannot breathe independently, cardiopulmonary bypass equipment when a patient undergoes open-heart surgery, hemodialysis when a patient's kidneys fail to function, and intravenous (IV) nutritional and electrolyte (for example, potassium and sodium) support when a patient is unable to eat or drink.

12.2.1 Development of Intensive-Care Units

To meet the increasing demands for more acute and intensive care required by patients with complex disorders, new organizational units—the ICUs—were established in hospitals beginning in the 1950s; ICUs proliferated rapidly during the late 1960s and the 1970s. The types of units include burn, coronary, general surgery, open-heart surgery, pediatric, neonatal, respiratory, and multipurpose medical–surgical units. By the mid-1980s, there were an estimated 75,000 adult, pediatric, and neonatal intensive-care beds in the United States.

The development of **transducers** and instrumentation electronics during World War II dramatically increased the number of physiological variables that could be monitored. Analog computer technology was widely available, as were oscilloscopes—electronic devices used to picture changes in electrical potential on a cathode-ray tube (CRT) screen. These devices were soon used in specialized cardiac-catheterization[4] laboratories, and they rapidly found their way to the bedside.

Treatment for serious cardiac arrhythmias (rhythm disturbances) and cardiac arrest (abrupt cessation of heartbeat)—major causes of death following myocardial infarctions—became possible. As a result, there was a need to monitor the ECG of patients who had suffered heart attacks, so that these episodes could be noticed and treated immediately. In 1963, Day reported that treatment in a coronary-care unit of patients who had had a myocardial infarction reduced mortality by 60 percent [Day, 1963]. As a consequence, coronary-care units—with ECG monitors—proliferated. The addition of online blood-pressure monitoring quickly followed. **Pressure transducers,** already used in the cardiac-catheterization laboratory, were easily adapted to the monitors in the ICU.

With the advent of more automated instruments, the ICU nurse could spend less time measuring the traditional vital signs and more time observing and caring for the critically ill patient. Simultaneously, a new trend emerged; some nurses moved away from the bedside to a central console where they could monitor the ECG and other vital-sign reports from many patients. Maloney pointed out that this was an inappropriate use of technology when it deprived the patient of adequate personal attention at the bedside. He also suggested that having the nurse record vital signs every few hours was "only to assure regular nurse–patient contact" [Maloney, 1968, p. 606].

As monitoring capabilities expanded, physicians and nurses soon were confronted with a bewildering number of instruments; they were threatened by **data overload.** Several investigators suggested that the digital computer might be helpful in solving the problems associated with data collection, review, and reporting.

12.2.2 Development of Computer-Based Monitoring

Teams from several cities in the United States introduced computers for physiological monitoring in the ICU, beginning with Shubin and Weil in Los Angeles [Shubin and Weil, 1966], then Warner and colleagues in Salt Lake City [Warner et al., 1968]. These investigators had several goals: (1) to increase the availability and accuracy of data, (2) to compute derived variables that could not be measured directly, (3) to increase patient-care efficacy, and (4) to allow display of the time trend of patient data. Each of these teams developed its application on a mainframe computer system, which required a large computer room and special staff to keep the system operational 24 hours per day. The computers used by these developers cost over $200,000 each in 1965! Other researchers were attacking more specific problem areas in monitoring. For example, Cox and associates in St. Louis developed algorithms to analyze

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[3]In medicine, auscultation is the process of listening to the sounds made by structures within the body, such as by the heart or by the blood moving within the vessels.

[4]Cardiac catheterization is a procedure whereby a tube (catheter) is passed into the heart through an artery or vein, allowing the cardiologist to measure pressure within the heart's chambers, to obtain blood samples, to inject contrast dye for radiological procedures, and so on.

the ECG for rhythm disturbances in real time [Cox et al., 1972]. The arrhythmia-monitoring system, which was installed in the coronary-care unit of Barnes Hospital in 1969, ran on an inexpensive minicomputer.

As we described in Chapters 1 and 4, the advent of integrated circuits and other advances allowed computing power per dollar to increase dramatically. As hardware became smaller, more reliable, and less expensive, and as better software tools were developed, simple analog processing gave way to digital signal processing. Monitoring applications developed by the pioneers using large central computers now became possible using dedicated machines at the bedside.

The early bedside monitors were built around *bouncing-ball* or conventional oscilloscopes and analog computer technology (Figure 12.2). As computer technology has advanced, the definition of *computer-based monitoring* has changed. The early developers spent a major part of their time deriving data from analog physiological signals. Soon the data-storage and decision-making capabilities of the computer monitoring systems came under the investigators' scrutiny. Therefore, what was considered computer-based patient monitoring in the late 1960s and early 1970s (Figure 12.3) is now built into bedside monitors and is considered simply patient monitoring. Systems with database functions, report-generation capabilities, and some decision-making capabilities are usually called **computer-based patient monitors.**

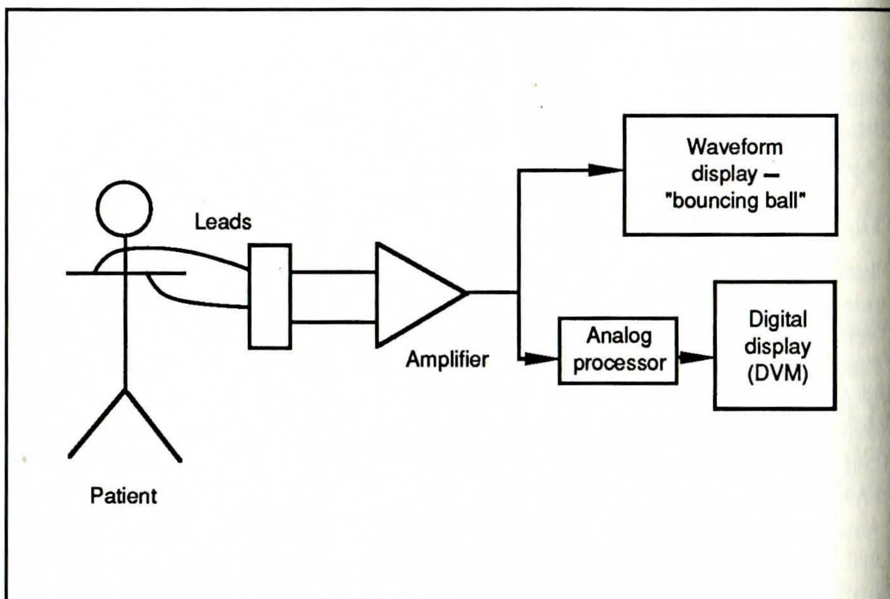


FIGURE 12.2 Block diagram of a typical analog monitor. These systems were developed in the early 1970s and are still in widespread use in hospitals today. [DVM = digital volt meter.]

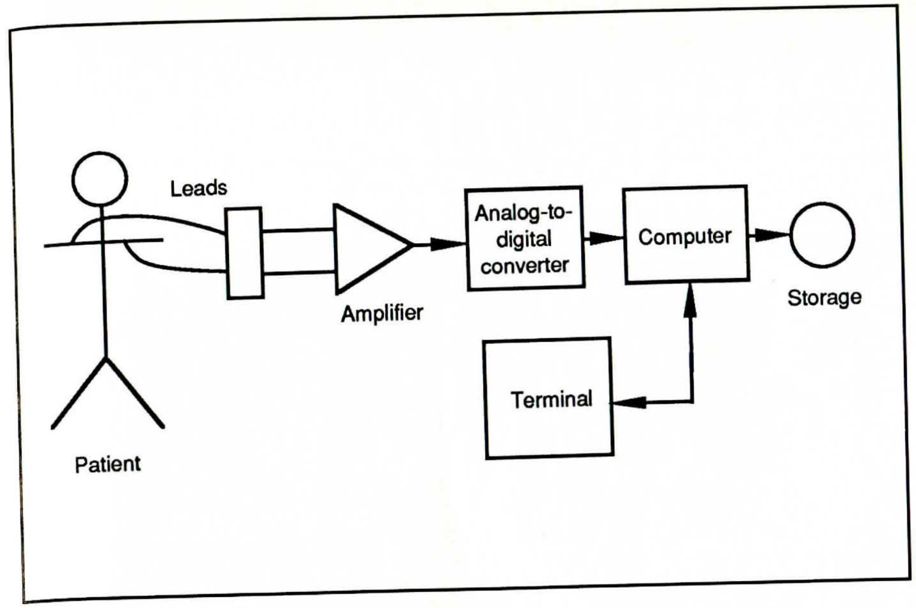


FIGURE 12.3 Analog monitor (see Figure 12.2) with a minicomputer attached. The system configuration is much like that used more than 1 decade ago by the developers of early computer-based monitoring systems.

12.3 Data Acquisition and Signal Processing

The use of microcomputers in bedside monitors has revolutionized the acquisition, display, and processing of physiological data.[5] There are few bedside monitors or ventilators marketed today that do not use at least one microcomputer. Figure 12.4 shows a block diagram of a patient connected to sensors and bedside monitors. Sensors convert biological signals (such as pressure, density, or mechanical movement) into electrical signals.

Some biological signals are already electrical, such as the currents that traverse the heart and are recorded on the ECG. Figure 12.5 shows a patient connected to ECG electrodes and an accompanying amplifier. The ECG signal derived from the electrodes at the body surface is small—only a few millivolts in amplitude. The patient is isolated from the electrical current of the monitor, and the analog ECG signal is amplified to a level sufficient for conversion to digital data using an analog-to-digital converter (ADC). Digital data then can be processed, and the results displayed (Figure 12.6).

[5]Portions of Sections 12.3 and 12.4 have been adapted with permission from Gardner, R. M. Computerized management of intensive care patients. *M.D. Computing*, 3(1):36–51, 1986.

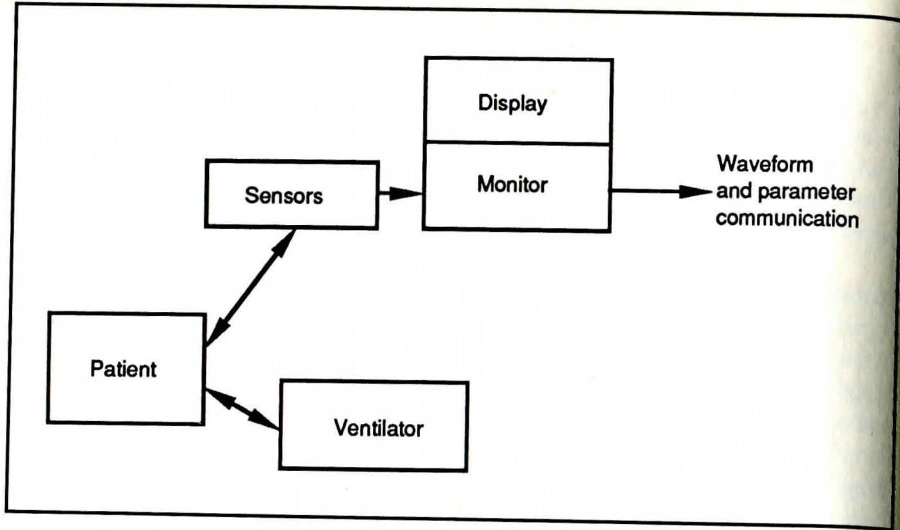


FIGURE 12.4 Block diagram of a simple bedside monitor with sensors attached to the patient. Signals are derived from the patient's physiological states and are communicated as waveforms and derived parameters to a central station display system.

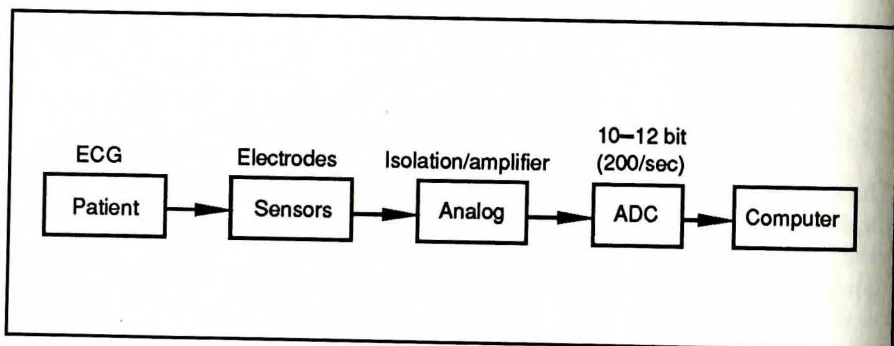


FIGURE 12.5 Front-end signal acquisition for a bedside monitor. The ECG signal is used as an example. The sensors (ECG electrodes) are attached to the patient. The resulting ECG signal is amplified by an electrically isolated analog amplifier, and is presented to an analog-to-digital converter (ADC). The signal is sampled at a rate of 200 measurements per second, with a 10- to 12-bit ADC; the resulting data are presented to the computer for pattern analysis.

As we discussed in Chapter 4, the sampling rate is an important factor that affects the correspondence between an analog signal and that signal's digital representation. Figure 12.7 shows an ECG that has been sampled at four different rates. At a rate of 500 measurements per second (part a), the digitized representation of the ECG looks like an analog recording of the ECG. All the features of the ECG, including the shape of the P wave (atrial depolarization), the amplitude of the QRS complex

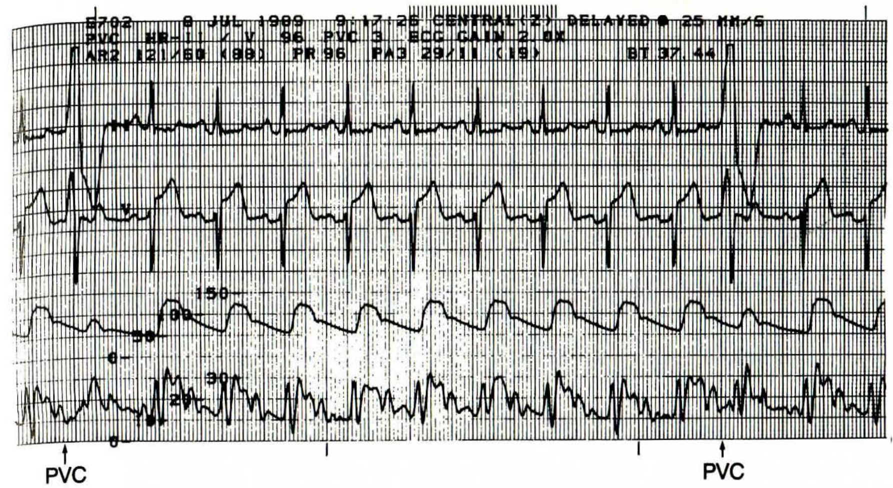


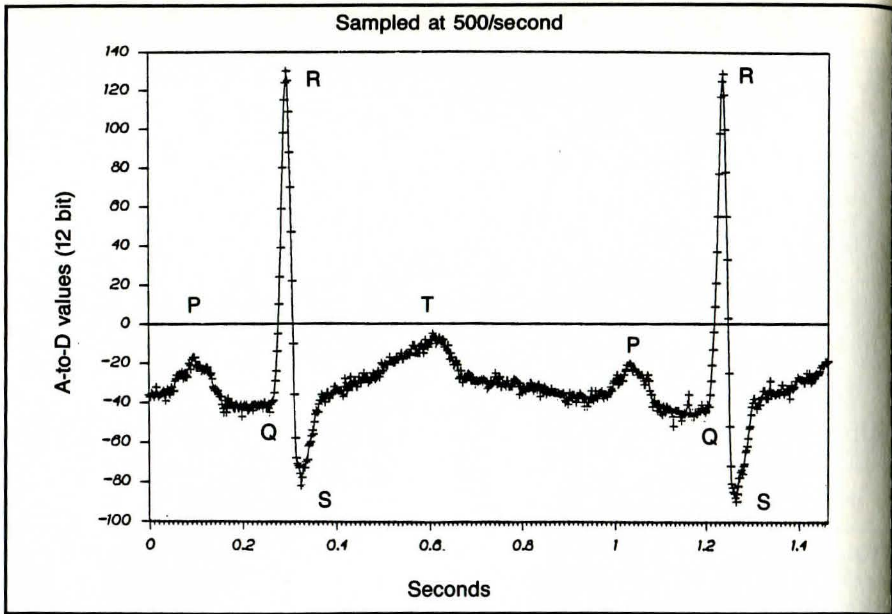
FIGURE 12.6 ECG (first [top] and second traces), arterial pressure (third trace), and pulmonary-artery pressure (fourth trace) recorded from a patient's bedside. Annotated on the recording are the bed number (E702), date (8 Jul 1989), and time (9:17:25). Also noted is regular rhythm, a heart rate from ECG (V) of 96 beats per minute, a systolic arterial pressure of 121, a diastolic pressure of 60, a mean pressure of 88 mm Hg, and a heart rate from pressure (PR) of 96. The patient is having premature ventricular contractions (PVCs) at a rate of three per minute; two PVCs can be seen in this tracing (the wide complexes noted at the beginning and near the end). The pulmonary-artery pressure is 29/11, with a mean of 19 mm Hg, and the blood temperature is 37.44° C. The self-contained monitoring system has determined the values and generated the calibrated graphical plot.

(ventricular depolarization) and the shape of the T wave (ventricular recovery) are reproduced faithfully. When the sampling rate is decreased to 100 measurements per second, however, the amplitude and shape of the QRS complex begin to distort. When only 50 observations per second are recorded, the QRS complex is grossly distorted and the other features also begin to distort. At a recording rate of only 25 measurements per second, gross signal distortion occurs, and even estimating heart rate by measuring intervals from R to R is problematic.

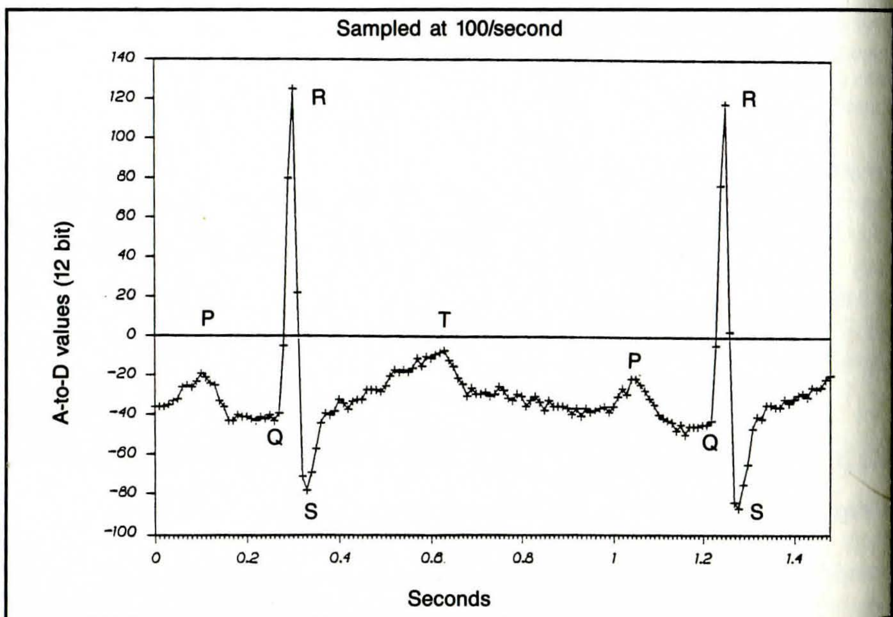
12.3.1 Advantages of Built-In Microcomputers

Today, the newest bedside monitors contain multiple microcomputers; they have much more computing power and memory than were available in systems used by the computer-monitoring pioneers (Figure 12.8). Bedside monitors with built-in microcomputers have the following advantages over their analog predecessors:

- The digital computer's ability to store patient waveform information such as the ECG permits sophisticated **pattern recognition** and **feature extraction.** The microcomputer uses **waveform templates** to identify abnormal waveform patterns, then classifies ECG arrhythmias. Analog computer technology allowed only a tiny

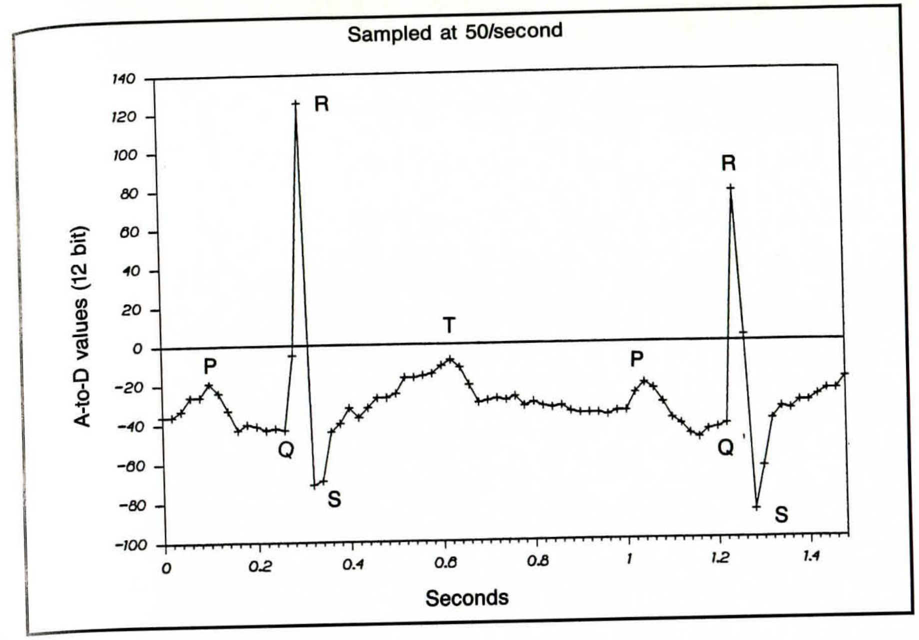


(a)

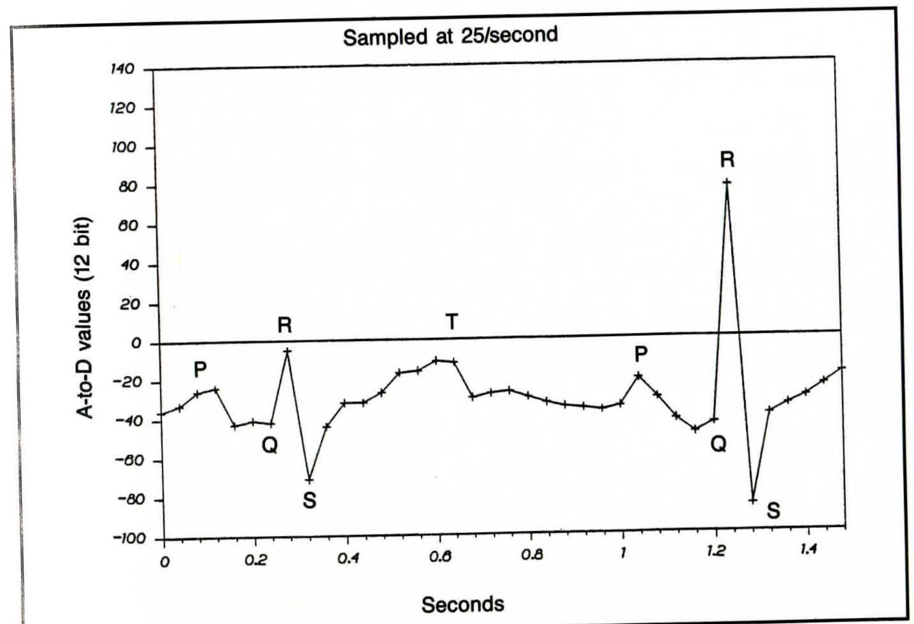


(b)

FIGURE 12.7 The sampling rate of the analog-to-digital converter determines the quality of the ECG recording. All four panels show the same ECG signal, sampled at different rates: (a) 500, (b) 100, (c) 50, and (d) 25 measurements per second. Note the degradation of the quality of the signal from (a) to (d).



(c)



(d)

FIGURE 12.7 *Continued.*

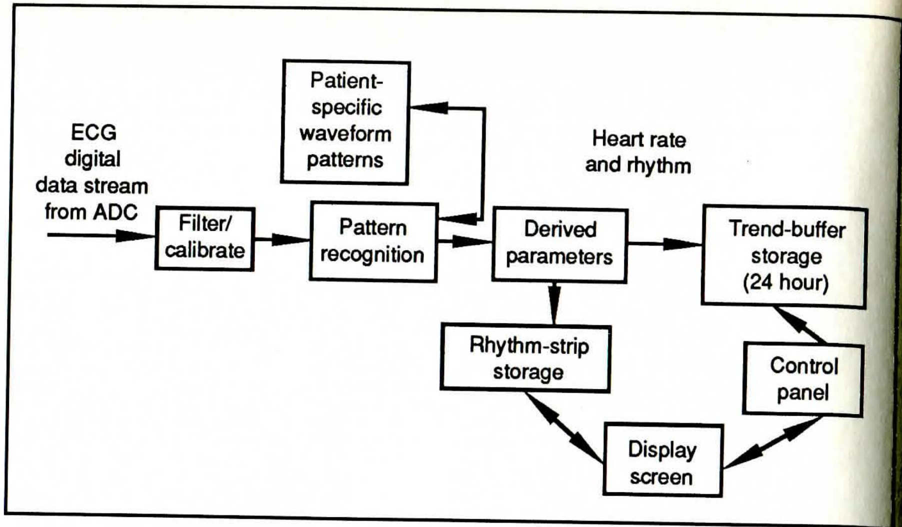


FIGURE 12.8 Block diagram of a microcomputer-based bedside monitor showing a digital data stream derived from an analog-to-digital converter (ADC), and how parameters are derived from the signal. First, the signal is calibrated, and unwanted signals are removed (such as the 60-Hz signal from the power line). Next, software pattern-recognition algorithms are applied. For ECG rhythm analysis, patient-specific waveform templates that the microcomputer-based system has learned are compared with each patient waveform. Once the signal characteristics are determined, derived parameters are generated and are stored in time-trend buffers. When arrhythmia events are detected by the pattern-recognition algorithm, the digitized signals also are transferred to a storage area for ECG recordings. Figure 12.9 shows an example of an ECG recording, or strip. The operator—usually a nurse or a physician—interacts with the monitor via a control panel and display screen.

segment of waveforms to be processed at one time, thereby permitting only a narrow view of the entire patient waveform.

- Signal quality can now be monitored and maintained. For example, the computer can watch for degradation of ECG skin-electrode contact resistance. If the contact is poor, the monitor can alert the nurse and can specify which electrode needs attention.
- The system can acquire physiological signals more efficiently by converting them to digital form early in the processing cycle. The waveform processing (for example, calibration and filtering, as described in Chapter 4) then can be done in the microcomputer. The same principle simplifies the nurse's task of setting up and operating the bedside monitor, because it eliminates the need for manual calibration.
- Transmission of digitized physiological waveform signals is easier and more reliable. Digital transmission of data is inherently noise-free. As a result, newer monitoring systems allow health-care professionals to review a patient's waveform displays and derived parameters, such as heart rate and blood pressure, at a central station as well as at the bedside in the ICU.

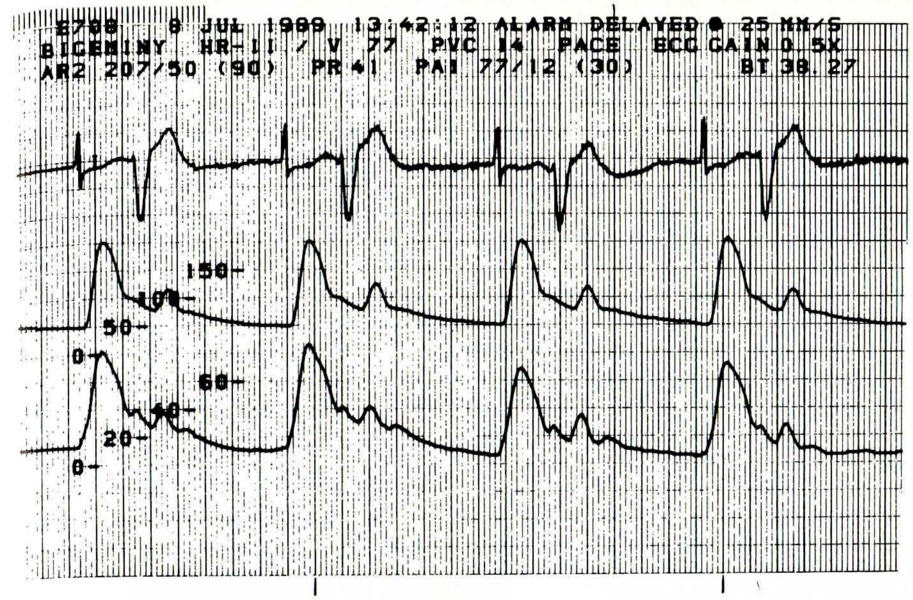
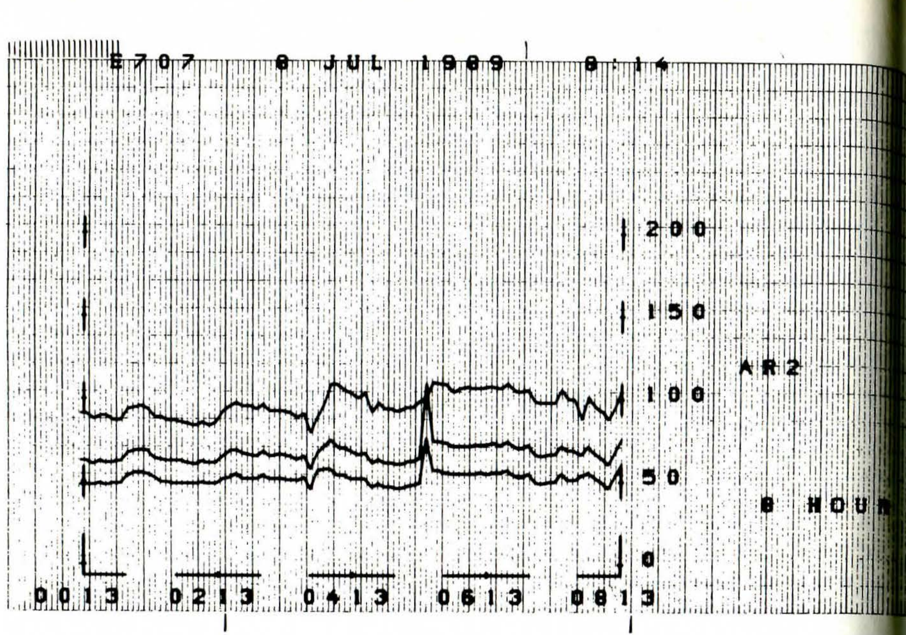
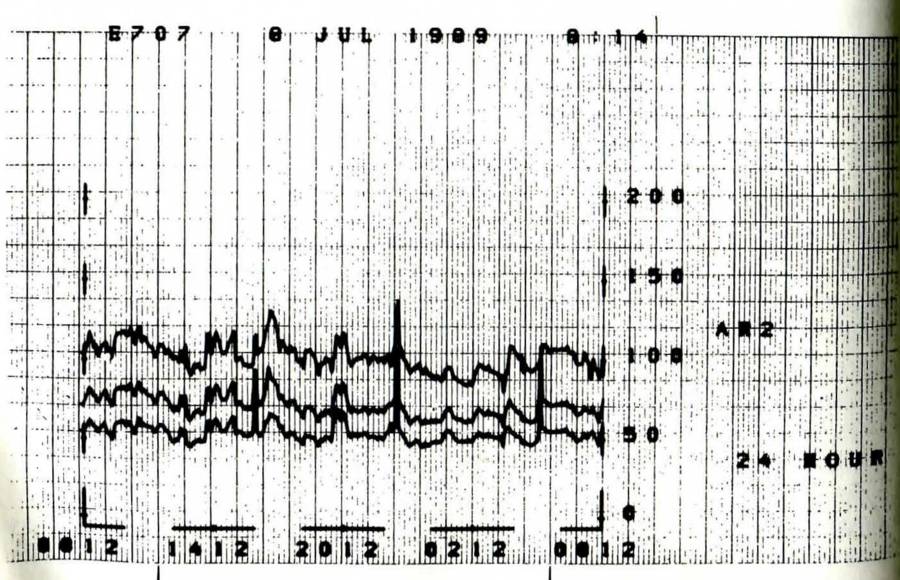


FIGURE 12.9 ECG strip showing a patient's ECG (upper trace) and arterial (middle trace) and pulmonary-artery (lower trace) pressure waveforms. The patient has a potentially life-threatening arrhythmia in which heart beats occur in pairs—a pattern called *bigeminy.* Note that, for the extra beats on the ECG pattern, the resulting pressure waveform pulsation is unusually small, indicating that the heart has not pumped much blood for that extra beat. The patient's heart rate, as determined from the ECG, is 77 beats per minute, whereas that determined from blood pressure is only 41 beats per minute. The heart is effectively beating at a very slow rate of 41 beats per minute.

- Selected data can be retained easily if they are digitized. For example, ECG strips reflecting interesting physiological sequences, such as periods of arrhythmias (Figure 12.9), can be stored in the bedside monitor for later review.
- Measured variables, such as heart rate and blood pressure, can be charted over prolonged periods to aid with detection of life-threatening trends (Figure 12.10).
- Alarms from bedside monitors are now much "smarter" and raise fewer false alarms. In the past, analog alarm systems used only high–low threshold limits and were susceptible to **signal artifacts.** Now, computer-based bedside monitors often can distinguish between artifacts and real alarm situations by using the information derived from one signal to verify that from another, and can confidently alert physicians and nurses to real alarms. For example, heart rate can be derived from either the ECG or the arterial blood pressure. If both signals indicate dangerous tachycardia (fast heart rate), the system sounds an alarm. If the two signals do not agree, the monitor can notify the health-care professional about a potential instrumentation or medical problem. The procedure is not unlike that performed by a human verifying possible problems by using redundant information from simpler bedside monitor alarms.



(a)



(b)

FIGURE 12.10 Two time-trend plots of systolic, mean, and diastolic pressure. The panel in (a) is for 8 hours; that in (b) is for 24 hours. Indicated across the bottom are the time of day at each of the tick marks. These plots show relatively stable blood-pressure trends over the time period.

- Systems can be upgraded easily. Only the software programs in read-only memory (ROM) need to be changed; in older analog systems, replacement of hardware was required.

12.3.2 Arrhythmia Monitoring—Signal Acquisition and Processing

Although general-purpose computer-based physiological monitoring systems have not yet been adopted widely, computer-based ECG arrhythmia-monitoring systems have been accepted quickly. ECG arrhythmia analysis is one of the most sophisticated and difficult of the bedside monitoring tasks. Conventional arrhythmia monitoring, which depends on people observing displayed signals, is expensive, unreliable, tedious, and stressful to the observers. One early approach to overcoming these limitations was to purchase an arrhythmia-monitoring system operating on a time-shared central computer. Such minicomputer-based systems usually monitor 8 to 16 patients and cost at least $50,000. The newest bedside monitors, in contrast, have built-in arrhythmia-monitoring systems. These computers generally use a 16-bit architecture, waveform templates, and real-time cross-correlation techniques to classify rhythm abnormalities. Figure 12.11 shows the output from a modern bedside monitor. There are four ECG

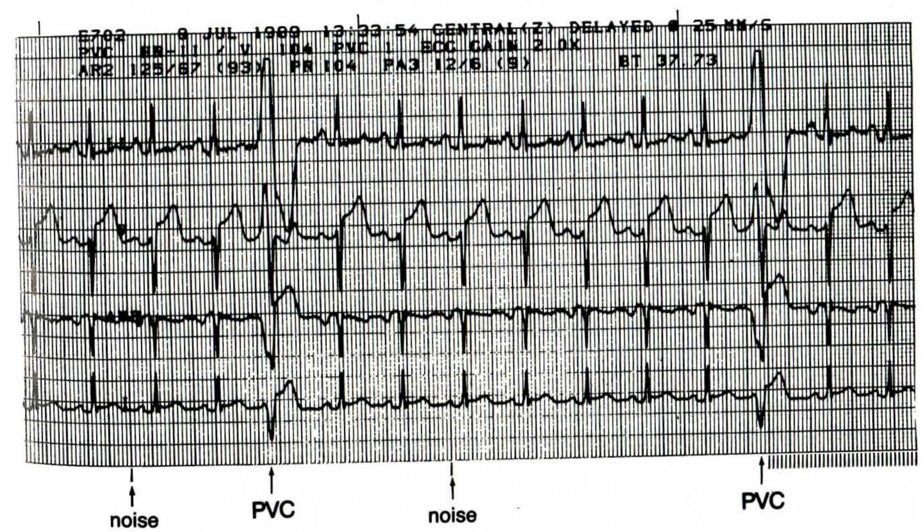


FIGURE 12.11 Four simultaneous lead tracings of ECG for a patient. The patient is having premature ventricular contractions (PVCs) at a rate of 1 per minute. (Two PVCs occur—one at the middle left and one at the right of the tracing.) The PVC is most apparent in lead II (top trace); it is much less apparent in lead V (second trace). Multiple-lead recording and computer access permit detection of a much wider variety of arrhythmias and also minimize the effect of artifacts (noise), which may occur in only one lead (as shown here in the bottom lead).

leads attached to the patient, and the computer has correctly classified a rhythm abnormality—in this case, a premature ventricular contraction (PVC). The bedside monitor also retains an ECG tracing record in its memory, so that at a later time a health professional can review the information.

Modern computer algorithms for processing ECG rhythms take sampled data, such as those shown in Figure 12.7, and extract features, such as the amplitude and duration of the QRS complex [Larsen and Jenkins, 1987]. The system performs feature extraction by searching the sampled data from beginning to end to locate the P wave, QRS complex, and T wave. A slope-detection strategy is often used to detect the quick upswing of the QRS complex—the rate of change in voltage (slope) is expressed as the difference between the values of two consecutive ECG data points. The algorithm compares the computed slope with a threshold value, and, if the threshold is exceeded, a trigger response signals the presence of a waveform edge. In some computer-based arrhythmia-monitoring systems, the user can adjust the threshold value, or QRS sensitivity.

Whereas the location of the QRS complex is relatively easy to detect using this slope-detection method, the P and T waves, because of their gentle slopes, are more difficult to recognize. Lack of reliable P-wave detection is one of the most serious limitations of computer-based arrhythmia monitors; the problem has not yet yielded to practical solution. Another major problem with automated waveform detection is attributable to noise in the signal. Movement of the patient frequently causes signal artifacts, which are seen on the ECG as steep slopes or transient spikes, both of which cause false trigger responses.

The Marquette 7700 series bedside monitor—from which waveforms shown in Figures 12.6, 12.9, 12.10, and 12.11 were derived—samples four leads simultaneously. Before performing the QRS detection step, the computer-based monitor searches for high-frequency noise or artifact. If the system finds artifact, the monitor displays the message "noise" on the screen and halts QRS detection for 2.5 seconds. Such processing helps to prevent the generation of many false alarms due to noise. When ECG monitoring begins, the computer-based bedside monitor initiates a *learning process* to determine which QRS waveform shape is seen most frequently. The learning process requires 16 beats from which to determine R–R intervals (the times between successive R waves) and to calculate the average interval. Waveforms are classified by shape. Of those waveforms with the most frequently occurring shape, the one having the longest R–R interval is designated the dominant shape. If at any time the dominant beat fails to occur within an interval of four beats, then the system seeks a new dominant beat by restarting the learning process.

As the system detects each new QRS complex, it performs classification by comparing the waveform with stored beats called *templates*; the cross-correlation process seeks beats of a similar shape. The first template stored is the dominant beat found in the learning process. Up to 15 template beats are stored and are used for cross-correlation. Series of beats are analyzed to classify rhythms. Once an abnormal rhythm has been identified, the system generates one of four levels of alarm, depending on the severity of the detected arrhythmia.

12.3.3 Commercial Development of Computer-Based Monitoring

Development of computer-based patient monitoring took place primarily in universities and medical schools and their affiliated hospitals. Later, as excitement about computer-assisted care in the ICU increased, commercial vendors became interested in marketing the technology. Several large, capable, and reputable manufacturers have supplied over 300 computer-based patient monitoring systems worldwide. These companies include Hewlett-Packard (which in 1987 controlled almost two-thirds of the market with its Patient Data Management System (PDMS)), Mennen Medical, Roche, Kontron, Siemens, Litton Datamedix, General Electric, Spacelabs, and EMTEK [Brimm, 1987]. Most products have tended to emphasize the acquisition and processing of physiologic data, without meeting the need to integrate relevant data from other sources in the hospital—the clinical laboratories, the radiology department, and the pharmacy. Currently, only a handful of successful integrated patient-monitoring systems is available commercially.

12.4 Information Management in the ICU

The goal of patient monitoring is to detect life-threatening events promptly, so that they can be treated before they cause irreversible organ damage or death. Care of the critically ill patient requires considerable skill, and necessitates prompt, accurate treatment decisions. Health-care professionals collect numerous data through frequent observations and testing, and more data are recorded by continuous-monitoring equipment. Physicians generally prescribe complicated therapy for such patients. As a result, enormous numbers of clinical data accumulate. Professionals can miss important events and trends if the accumulated data are not presented in a compact, well-organized form. In addition, the problems of managing these patients have been made even more challenging by economic pressures to reduce the cost of diagnostic and therapeutic interventions.

Continuity of care is especially important for critically ill patients, who are generally served by a team of physicians, nurses, and therapists, and whose data often are transferred from one individual to another (for example, the laboratory technician calls a ward clerk who reports the information to a nurse who in turn passes it on to the physician who makes a decision). Each step in this transmission process is subject to delay and error. The medical record is the principal instrument for ensuring the continuity of care for patients.

12.4.1 Computer-Based Charting

As we discussed in Chapters 2 and 6, the traditional medical record has several limitations. The problems of poor or inflexible organization, illegibility, and lack of physical availability are especially pertinent to the medical records of critically ill patients, due to the large number of data collected and the short time allowed for many treatment decisions.

having a unified medical record was demonstrated by a study conducted at Latter Day Saints (LDS) Hospital [Bradshaw et al., 1984]. Researchers kept detailed records of the data used by physicians to make treatment decisions in a shock–trauma ICU (Figure 12.12). The investigators were surprised to find that laboratory and blood-gas data were used most frequently (42 percent total), given that physiological bedside monitors are always present in the modern ICU. Clinicians' observations (21 percent) and drug and fluid-balance data (22 percent) also were used frequently. The bedside physiological monitor accounted for only 13 percent of the data used in making therapeutic decisions. These findings clearly indicate that data from several sources—not just those from the traditional physiological monitoring devices—must be communicated to and integrated into a unified medical record to permit effective decision making and treatment in the ICU.

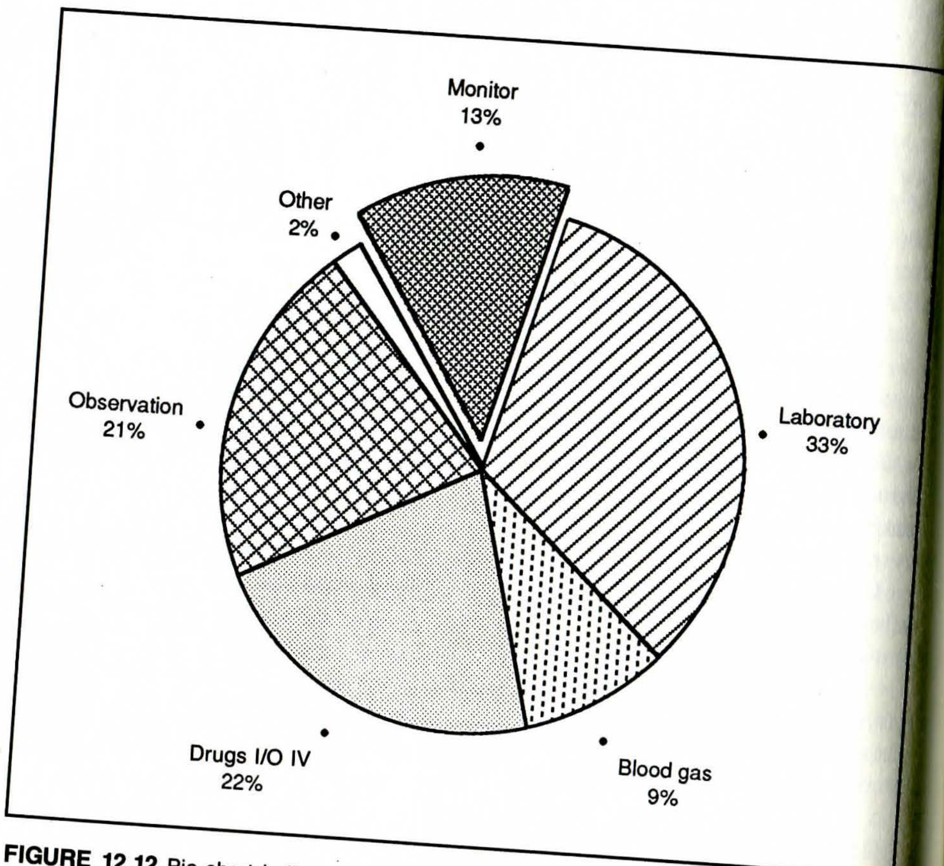


FIGURE 12.12 Pie chart indicating the variety of data physicians use when making treatment decisions in a shock–trauma intensive care unit. [I/O = input–output; IV = intravenous.] (*Source:* Reprinted with permission from Gardner, R. M., Sittig, D. F., and Budd, M. C. Computers in the intensive care unit: Match or mismatch? In Shoemaker, W. C., et al. (eds), *Textbook of Critical Care,* 2nd ed. Philadelphia: W. B. Saunders, 1989, p. 249.)

Effective computer-based charting in the ICU must support multiple types of data collection. As Figure 12.12 shows, a large percentage of the data is collected from typically manual tasks, such as administering a medication or auscultating breath or heart sounds. Furthermore, an instrument may present data in electronic form, yet require that a person note these data and write them in the chart. Thus, computer-based charting systems must be able to collect a wide variety of data from automated and remote sites, as well as from health-care providers at the bedside. Unfortunately, most computer-based charting systems have dealt with a limited subset (usually only the bedside monitoring) of the data that need to be charted.

Figure 12.13 illustrates the complexity of ICU charting. The chart must document the actions taken by the health-care staff, to meet both medical and legal requirements (items 1 and 2 in Figure 12.13). In addition, many of the data logged in the chart are used for management and billing purposes (items 3 and 4 in Figure 12.13). Many computer systems have ignored these requirements and thus have unwittingly forced the clinical staff to chart the same information in more than one place. Yet efficient

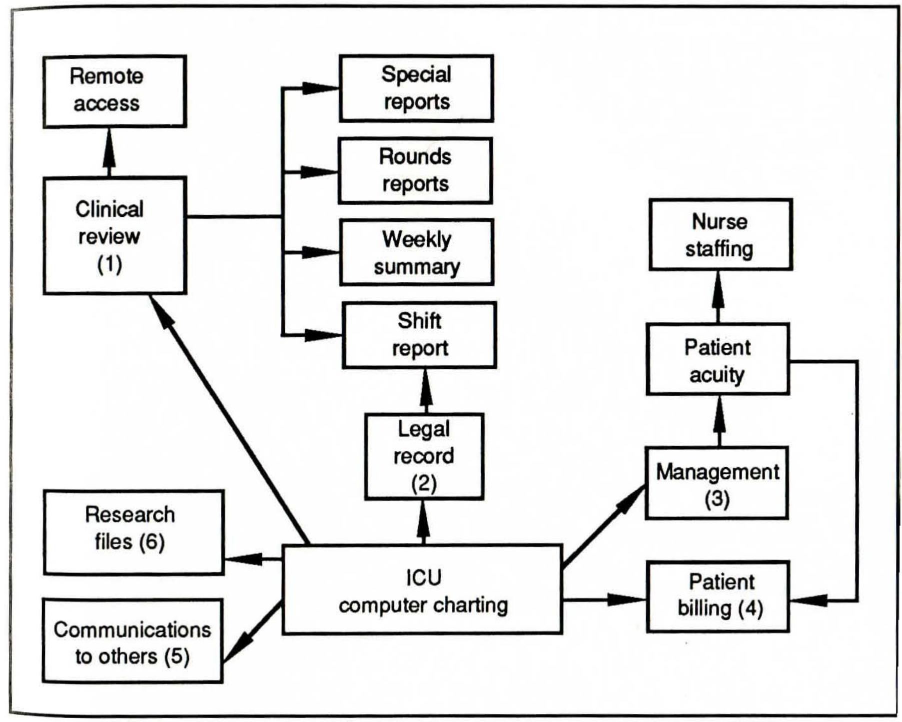


FIGURE 12.13 Block diagram showing the six major areas in which health-care professionals interact with computer-based ICU charting to make patient care more effective and efficient. See text for explanations of functions. (*Source:* Reprinted with permission from Gardner, R. M., Sittig, D. F., and Budd, M. C. Computers in the intensive care unit: Match or mismatch? In Shoemaker, W. C., et al. (eds), *Textbook of Critical Care,* 2nd ed. Philadelphia: W. B. Saunders, 1989, p. 249.)

management in hospitals is required, especially given the implementation of prospective-payment strategies (see Chapter 19). Hospitals now have strong incentives to evaluate and control the costs of procedures. As a result, it is necessary to know how ill the patient is, which in turn allows administrators to project nurse staffing needs and to account for the care of a patient by degree of illness. Communication (item 5 in Figure 12.13) with other departments within the hospital is mandatory. Access from office or home to clinical and administrative information is a great convenience to physicians. A computer-based record allows this type of communication. Because the computer-based ICU record is stored in the system, it is readily available for research purposes (item 6 in Figure 12.13). Anyone who has tried to retrieve data from manual patient charts for research purposes will recognize the value of this capability.

To meet the clinical management needs of critically ill patients, as well as to provide an adequate legal record, most patient data-management systems generate a variety of reports. At the LDS Hospital, in addition to the rounds report (shown in Figure 12.1), there is a variety of other reports. Figure 12.14 shows a nursing shift report for a patient. This 12-hour report documents the physiological data. The laboratory data are summarized in the upper section. A record of each drug given and each intravenous (IV) fluid administered is displayed in the lower section. The nurses who care for the patient are listed; the nurses place their initials next to their names to indicate that they have verified the data. Total fluid-intake data are derived from the IV data, and fluid-output data are summarized as well, allowing the system to calculate the net intake–output balance for the shift.

For the patient who is in the ICU for several days, a broader view of the course of the recovery process is essential. Thus, the system at LDS prepares weekly reports that summarize the data for each of the past seven 24-hour periods (Figure 12.15). The data already are stored in the computer, so no additional data entry is required to generate the report. A program abstracts and formats the data. Figure 12.16 shows a blood-gas report indicating the acid–base status of the patient's blood, as well as the blood's oxygen-carrying capacity. Note that, in addition to the numerical parameters for the blood, the patient's breathing status is indicated. Based on all these clinical data, the computer provides an interpretation. For life-threatening situations, the computer prompts the staff to take the necessary action. For example, if the level of a blood-gas measurement indicates that the patient is not getting enough oxygen, the system promptly notifies the laboratory staff, who are instructed to call the nurse or physician caring for the patient and to record whom they notified.

12.4.2 Calculation of Derived Variables

Increased sophistication of hemodynamic, renal, and pulmonary monitoring resulted in the need to calculate **derived parameters**; for the first time, ICU staff had to crunch numbers. At first, pocket calculators were used, with each step performed by a careful nurse. Then programmable calculators took over this task, making the computation simpler, faster, and more accurate. Soon these devices were replaced in turn by portable computers. Some of these systems provide graphical plots and interpretations.

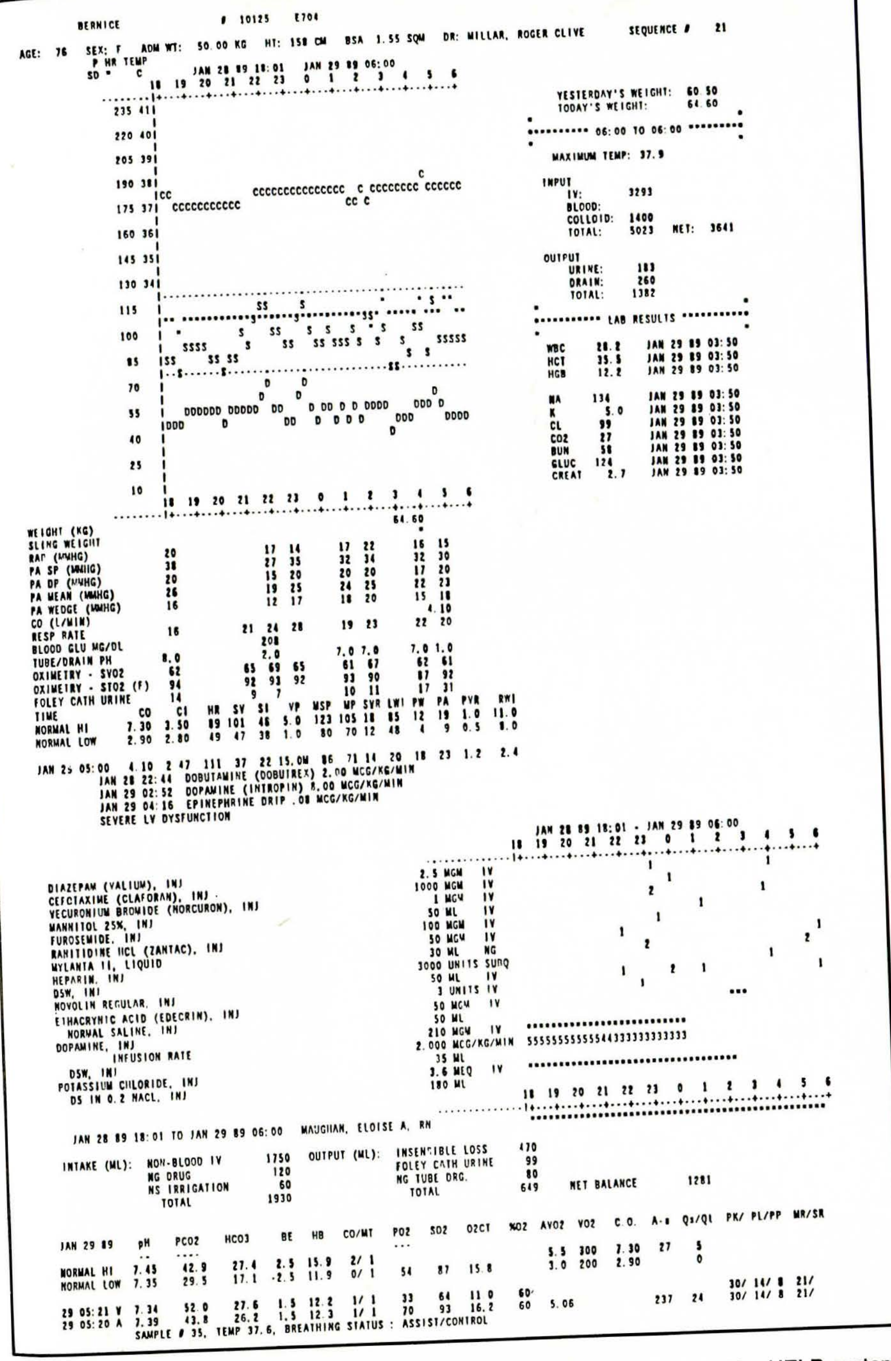


FIGURE 12.14 Shift report for a 12-hour ICU nursing shift produced by the HELP system at LDS Hospital. The report displays vital signs, laboratory-test results, and other patient data collected over a 12-hour period. (*Source:* Courtesy of LDS Hospital.)

12.4.3 Decision-Making Assistance

One mark of a good physician is the ability to make sound clinical judgments. Medical decision making traditionally has been considered an intuitive, as well as scientific, process. In recent years, however, formal methods for decision making have been applied to medical problem solving (see Chapter 3), and computer-assisted medical decision making has gained wider acceptance. Indeed, discussion of artificial intelligence (AI) is commonplace in medicine today (see the discussions of decision-support systems in Chapter 15). We now have the opportunity to use the computer to assist staff in the complex task of medical decision making in the ICU. For example, the HELP computer system at the LDS Hospital in Salt Lake City has been used effectively to assist in ICU decision making. The system collects and integrates data for the ICU patient from a wide variety of sources. The data are processed automatically by the HELP decision-making system to determine whether the new information, by itself or in combination with other data in the patient record (such as a laboratory result or a previously generated decision), should lead to a new medical decision. These computer-generated medical decisions are based on predefined criteria stored in the system's knowledge base.

The HELP decision-making system has been used in the following areas:

- *Interpretation of data;* for example, interpretation of breathing status based on blood-gas reports and hemodynamic parameters
- *Alerts;* for example, notification that a drug is contraindicated, at the time the drug is being ordered

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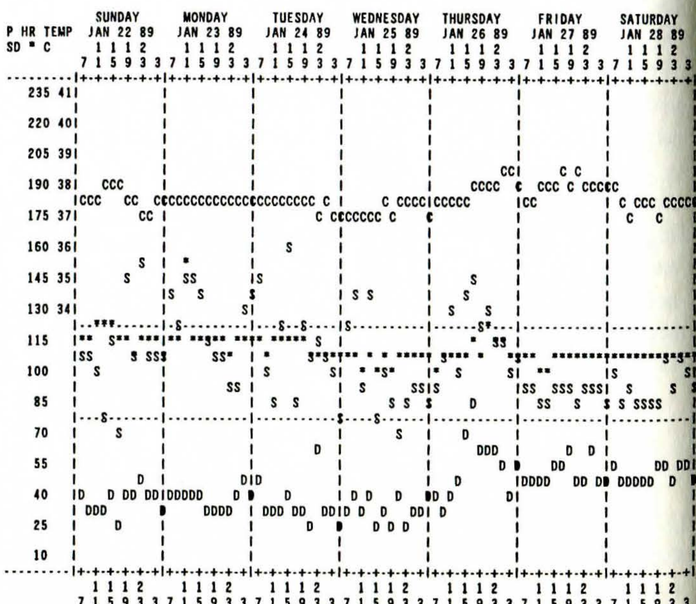

(a)

FIGURE 12.15 Two portions of a weekly (7-day) ICU report produced by the HELP system at LDS Hospital. The report provides a daily weight, fluid-balance, drug, and physiological-data summary for an individual patient. (*Source:* HELP System, LDS Hospital.)

			JAN 22	JAN 23	JAN 24	JAN 25	JAN 26	JAN 27	JAN
MORPHINE, INJ	MGM	IV	37.0	21.0	2.0			7.0	6.
ACETAMINOPHEN, SUPP	MGM	RECT					1300	650	
DIAZEPAM (VALIUM), INJ	MGM	IV						10.0	5.
CEFOTAXIME (CLAFORAN), INJ	MGM	IV							10
GENTAMICIN, INJ	MGM	IV						60.0	60.
CEFUROXIME (ZINACEF), INJ	MGM	IV	3000	3000	3000	3000	3000	3000	
DOBUTAMINE (DOBUTREX), INJ	MGM	IV	732	582	792	810	270	87	2
EPINEPHRINE DRIP, INJ	MGM	IV	22.20	11.46	3.96	0.00			1.
VECURONIUM BROMIDE (NORCURON), INJ	MGM	IV	39	26	18	13	10	3	
DOPAMINE, INJ	MGM	IV	648	492	420	396	522	864	7
METOLAZONE (ZAROXOLYN), TAB	MGM	NG					5.00		
NITROPRUSSIDE (NIPRIDE), INJ	MGM	IV	0						
AMRINONE (INOCOR), INJ	MGM	IV	0						
FUROSEMIDE, INJ	MGM	IV	80	80	80	80	120	80	21
MANNITOL 25%, INJ	ML	IV							[illegible]
ETHACRYNIC ACID (EDECRIN), INJ	MGM	IV							[illegible]
ACETAZOLAMIDE (DIAMOX), INJ	MGM	IV			250	250		250	
RANITIDINE HCL (ZANTAC), INJ	MGM	IV	150	100	150	150	150	150	1
MYLANTA II, LIQUID	ML	NG		60	30	120	90	60	11
MYLANTA, LIQUID	ML	NG			30	60			
HEPARIN, INJ	UNITS	SUBQ						3000	60
HEPARIN FLUSH, INJ	UNITS	IV	400	300		300	500	200	1
ARTIFICAL TEARS (LACRIL), SOLUTION	GTTS	OPTH	6	4					
PLASMANATE 5%, INJ	ML	IV						250	14
PACKED RBC	ML	IV					500		
ALBUMIN 25%, INJ	ML	IV	100	50	50	150			
PLATELETS (RANDOM DONOR)	ML	IV	400		150				
AMINOSYN 8.5%, INJ	ML	IV	311	621	472	529	608	1079	6
POTASSIUM	MEQ	IV	25.2	50.3	38.2	59.7	73.0	131.0	94.
CALCIUM	MEQ	IV	3.1	6.2	4.7	5.3	5.7	9.9	5.
MAGNESIUM	MEQ	IV	14.9	35.0	28.3	31.7	12.7	17.3	9.
ZINC	MGM	IV	3.4	6.8	5.2	5.8	6.7	11.9	6.
COPPER	MGM	IV	0.7	1.4	1.0	1.2	1.3	2.4	1.
MANGANESE	MGM	IV	0.3	0.6	0.5	0.5	0.6	1.1	0
CHROMIUM	MCG	IV	6.8	13.7	10.4	11.6	13.4	23.7	12
CHLORIDE	MEQ	IV	20.8	41.6	31.6	35.4	35.0	50.6	47
ACETATE	MEQ	IV	24.9	49.7	37.8	42.3	41.5	69.7	52
PHOSPHATE	MEQ	IV	14.9	29.8	22.7	25.4	65.8	138.5	45
SULFATE	MEQ	IV	9.9	25.1	20.8	23.3	10.1	17.3	7
GLUCONATE	MEQ	IV	3.1	6.2	4.7	5.3	5.7	9.9	5
FAT EMULSION 10% (LIPOSYN), INJ	ML	IV							5
NORMAL SALINE, INJ	ML	IV	6	2		2	154	10	
FAT EMULSION 20% (LIPOSYN), INJ	ML	IV	200	200	200	200	200	66	1
POTASSIUM CHLORIDE, INJ	MEQ	IV	67.9	78.0	183.7	51.9	51.6	104.3	17
D5W, INJ	ML	IV	410	215	25	150	5	10	
HETASTARCH (HESPAN), INJ	ML	IV				250	0		
MAGNESIUM SULFATE 50%, INJ	GM	IV	2.00						
NOVOLIN REGULAR, INJ	UNITS	IV	18	15					
INTAKE (ML): BLOOD			400		150		500		
COLLOID			100	50	50	150		250	14
NON-BLOOD IV			2783	3046	2707	2395	2254	3145	32
NG DRUG				60	60	180	90	60	1
TOTAL			3313	3216	2967	2815	2874	3485	50
OUTPUT (ML): INSENSIBLE LOSS			937	946	943	873	1016	1077	
FOLEY CATH URINE			360	740	210	902	2950	895	
NG TUBE DRG.			50	200	80	125	40	75	
WATERSEAL DRG, 1			180	50					
TOTAL			3918	3936	4023	2512	5226	2470	1
NET BALANCE (ML):			-605	-720	-1056	303	-2352	1015	3
WEIGHT (KG)			61.2	61.4	60.8	62.2	60.4	60.5	6
NUTRITIONAL: NP ENERGY	KCAL	(IV)	1468	2143	1784	1803	1953	2813	2
TOTAL ENERGY	KCAL	(IV)	1573	2354	1944	1982	2160	3181	2
PROTEIN	GM		26	53	40	45	52	92	
FAT	GM		40	40	40	40	40	13	
CHO	GM		315	513	407	413	456	789	
NP ENERGY/N2	KCAL/GM		367	238	254	257	244	200	
N2 IN	GM		4	9	7	7	8	14	

BERNICE # 10125 E704

PROCESS TIME: 00:18

TIME OUT: JAN 29 89 13:53

(END)

(b)

FIGURE 12.15 *Continued.*

```
                         L D S   H O S P I T A L   B L O O D   G A S   R E P O R T

          STEVEN                                    NO.  10072    DR. STINSON, JAMES B.            RM E609
                              SEX: M  AGE: 43

JAN 05 89      pH    PCO2    HCO3     BE    HB   CO/MT   PO2   SO2   O2CT  %O2  AVO2  VO2   C.O.   A-a  Qs/Qt  PK/ PL/PP  MR/
               --    ----                                ---
NORMAL HI     7.45   40.6    25.9    2.5  17.7   2/ 1                                5.5  300   7.30    22    5
NORMAL LOW    7.35   27.2    15.7   -2.5  13.7   0/ 1     64    91   18.5            3.0  200   2.90          0

05 04:36 V    7.43   34.5    22.7    -.4  11.5   2/ 1     42    76   12.3   40
05 04:35 A    7.48   29.3    21.7         11.6   2/ 1    128    96   15.9   40   3.43                    75   12   30/ 28/ 5  20/
              SAMPLE # 37, TEMP 37.3, BREATHING STATUS : ASSIST/CONTROL                                          30/ 28/ 5  20/
              MILD ACID-BASE DISORDER
              MODERATELY REDUCED O2 CONTENT
              SUPRA-NORMAL PO2
              PULSE OXIMETER SO2  96.0

04 04:20 V    7.45   36.1    24.9    1.9  10.2   2/ 1     37    72   10.4   40
04 04:19 A    7.49   31.6    24.0    2.0  10.2   2/ 1     90    95   13.7   40   3.36 353  10.50   111   18   26/ 20/ 5  21/
              SAMPLE # 36, TEMP 37.5, BREATHING STATUS : ASSIST/CONTROL                                          26/ 20/ 5  21/
              MILD ACID-BASE DISORDER
              SEVERELY REDUCED O2 CONTENT (13.7) DUE TO ANEMIA (LOW HB)
              PULSE OXIMETER SO2  93.0

03 06:05 A    7.44   35.8    24.1    1.0  11.7   2/ 1     91    95   15.7   40                          105        26/ 22/ 5  23/
              SAMPLE # 35, TEMP 37.0, BREATHING STATUS : ASSIST/CONTROL
              NORMAL ARTERIAL ACID-BASE CHEMISTRY
              MODERATELY REDUCED O2 CONTENT
              PULSE OXIMETER SO2  93.0

02 04:16 V    7.46   37.4    26.4    3.4   9.1   1/ 1     35    71    9.1   40
02 04:15 A    7.51   32.4    25.8    3.9   9.5   2/ 1     91    95   12.8   40   3.29 237   7.20   109   17   32/ 25/10  20/
              SAMPLE # 34, TEMP 37.1, BREATHING STATUS : ASSIST/CONTROL                                          32/ 25/10  20/
              MODERATE METABOLIC ALKALOSIS
              SEVERELY REDUCED O2 CONTENT (12.8) DUE TO ANEMIA (LOW HB)
              PULSE OXIMETER SO2  95.0

01 10:53 A    7.47   37.0    26.8    4.0  11.1   1/ 1     77    94   14.7   60                          238        36/ 27/10  20/
              SAMPLE # 33, TEMP 37.7, BREATHING STATUS : ASSIST/CONTROL
              MILD ACID-BASE DISORDER
              MODERATELY REDUCED O2 CONTENT
              PULSE OXIMETER SO2  93.0

01 03:59 V    7.41   46.2    29.0    4.5  10.0   1/ 1     42    73   10.2   80
01 03:58 A    7.46   39.2    27.7    4.5   9.9   1/ 1    146    97   13.7   80   3.64 331   9.10   287   23    /   /12  20/
              SAMPLE # 32, TEMP 38.4, BREATHING STATUS : ASSIST/CONTROL                                           /   /12  20/
              MILD ACID-BASE DISORDER
              SEVERELY REDUCED O2 CONTENT (13.7) DUE TO ANEMIA (LOW HB)
              SUPRA-NORMAL PO2

01 00:39 A    7.44   42.2    28.4    4.7  10.0   1/ 1    104    95   13.5   90                          386         /   /10  20/
              SAMPLE # 31, TEMP 38.9, BREATHING STATUS : ASSIST/CONTROL
              MILD ACID-BASE DISORDER
              SEVERELY REDUCED O2 CONTENT (13.5) DUE TO ANEMIA (LOW HB)
              PULSE OXIMETER SO2  91.0

31 23:35 A    7.42   42.4    27.2    3.2  10.1   1/ 1     63    87   12.3   65                          276         /   / 5  20/
              SAMPLE # 30, TEMP 39.0, BREATHING STATUS : ASSIST/CONTROL
              MILD ACID-BASE DISORDER
              MODERATE HYPOXEMIA
              SEVERELY REDUCED O2 CONTENT (12.3) DUE TO ANEMIA (LOW HB)
              PULSE OXIMETER SO2  83.0

31 16:00 A    7.49   34.4    26.1    3.8   9.7   1/ 1     87    95   13.1   40                          111         /   / 5  21/
              SAMPLE # 29, TEMP 37.8, BREATHING STATUS : ASSIST/CONTROL
              MILD ACID-BASE DISORDER
              SEVERELY REDUCED O2 CONTENT (13.1) DUE TO ANEMIA (LOW HB)


PRELIMINARY INTERPRETATION -- BASED ONLY ON BLOOD GAS DATA.  ***(FINAL DIAGNOSIS REQUIRES CLINICAL CORRELATION)***
KEY: CO=CARBOXY HB, MT=MET HB, O2CT=O2 CONTENT, AVO2=ART VENOUS CONTENT DIFFERENCE (CALCULATED WITH AVERAGE OF A &V HB VA
 VO2=OXYGEN CONSUMPTION, C.O.=CARDIAC OUTPUT, A-a=ALVEOLAR arterial O2 DIFFERENCE, Qs/Qt=SHUNT, PK=PEAK, PL=PLATEAU, PP=P
 MR=MACHINE RATE, SR=SPONTANEOUS RATE.          *** SPECIMEN IDENTIFICATION: BLOOD (A=ARTERIAL, V=VENOUS, C=CAPILLARY, W=WE
                                                FLUIDS (P=PLEURAL, J=JOINT, B=ABDOMINAL, S=ABSCESS); E=EXPIRED AIR;
                                                ECCo2R (I=INFLOW, M=MIDFLOW, O=OUTFLOW)

KEEP FULL PAGE FOR RECORDS
(END)
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FIGURE 12.16 A blood-gas report produced by the HELP system at LDS Hospital. The report shows the patient's predicted values, as well as the measured values. The computer provides a decision-making interpretation and alerting facility. Note that this report summarizes, in reverse chronological order, the patient's blood-gas status over the course of 1 week. (*Source:* Courtesy of LDS Hospital.)

- *Diagnoses;* for example, detection of hospital-acquired infections
- *Treatment suggestions;* for example, suggestions about the most effective antibiotics to order, when the microbiology laboratory reports a positive culture result

The ICU component of HELP is the most mature of the system's clinical applications. The basic requirements for data acquisition, decision support, and information reporting are similar for patients in the ICU and on the general wards of the LDS Hospital. The number of variables and the volume of observations that must be integrated, however, are much greater for patients in the ICU.

12.4.4 Response by Nurses and Physicians

Currently, bedside terminals are functioning in all ICUs at LDS Hospital, and nurses use a computer-based system to create nursing care plans and to chart ICU data. The goals of automation were (1) to facilitate the acquisition of clinical data, (2) to improve the content and legibility of medical documentation, and (3) to increase the efficiency of the charting process so that nurses could devote more time to direct patient care. Studies demonstrated that the number and quality of nursing care plans increased, and that the content and quality of nursing charts improved markedly [Bradshaw et al., 1988]. To date, however, the studies have not shown improvements in the efficiency of information management by ICU nurses (time savings) that could be credited to use of the system.

The failure to demonstrate time savings may be a result of several factors. First, the new system affected only selected aspects of the nursing process. For example, physiological and laboratory data were already acquired automatically, so the effects of these computer-based systems were not included in the analyses. Second, the computer-based charting system is not yet comprehensive; nurses still must perform some manual charting. Third, nurses do not always take advantage of the capabilities of the charting system. For example, they sometimes reenter vital signs that have already been stored in the computer. Fourth, the intervals of time saved may have been too small to be measured using the work-sampling methods employed in the studies. Fifth, these small savings in time are easily absorbed into other activities. Despite the lack of demonstrated improvement in efficiency, however, the nursing department at LDS is enthusiastic about using computers; surveys of the nursing staff have shown that nurses favor the prospect of using computers throughout the hospital.

Physician members of the LDS staff are also heavy users of the computer system. The information in the computer is more current and more readily available than information in the paper charts. Now, when physicians want to review laboratory and other data, they use a computer terminal, rather than searching for the paper record.

12.5 Current Issues in Patient Monitoring

The future of computer-based ICU monitoring systems is bright. Developments in bedside monitors have recently accelerated because of the availability of the microcomputer. Nonetheless, some important areas of research in patient monitoring have not yet been addressed effectively.

12.5.1 Data Validation

A major problem is how to ensure that the data entered into ICU data-management systems are valid representations of patient state, and are not the product of noise or errors in data collection or data processing. A system must provide feedback at various levels to verify correct operation, to carry out quality control, and to present intermediate and final results. As we discussed earlier, some **cross-validation** between signals is possible, but this process is performed by few of the bedside monitors used today. Some of the newer patient-monitoring devices, such as pulse oximeters that attach to the ear or finger and direct pressure-measuring systems, have built in noise-rejection algorithms to improve the quality of the data presented [Gardner et al., 1986]. Data validation, however, is one area of patient monitoring that still offers much opportunity for technological development and improvement.

12.5.2 Invasive Versus Noninvasive Monitoring

Physiological and biochemical parameters commonly used in monitoring can be measured by instruments and devices that are either invasive (require breaking the skin or entering the body) or noninvasive. After several decades of development of **invasive techniques,** the recent trend has been to design **noninvasive methods.** Much of the development of noninvasive technology can be attributed to the availability of microcomputers and solid-state sensors.

The development of inexpensive light-emitting diodes (LEDs), small solid-state light detectors, and new computer methods, for example, made possible the development of the pulse oximeter, an exciting example of noninvasive monitoring technology. By alternately shining red and infrared light from the LEDs through a finger or an ear, the device can detect the pulsations of blood and determine arterial oxygen saturation and heart rate [Severinghaus and Astrup, 1986]. Pulse oximetry is one of the most significant technological advances ever made in monitoring. The technology is reliable yet inexpensive; also, because it is noninvasive, it does not subject the patient to the discomfort, expense, and risks of invasive techniques (infection and blood loss, for example).

12.5.3 Continuous Versus Intermittent Monitoring

One of the persistent questions facing people who monitor patients is "Should I measure a parameter continuously, or is intermittent sampling enough?" A related question is, "How often do I make the measurement?" These questions have no simple answer. If we want to display an ECG signal continuously, we must sample the signal at a rate of at least twice the rate of the maximum frequency of interest in the signal (the Nyquist frequency; see Chapter 4). For an ECG, the sampling rate should be at least 200 measurements per second.

When **intermittent monitoring** (periodic measurement of blood pH value, for example) must be performed, the overriding concerns in determining sampling rate are how rapidly the parameter can change, and how long before a dangerous change will result in irreversible damage. Sudden heart stoppage or severe dysrhythmias are the most frequent causes of sudden death. Therefore, heart-rate and heart-rhythm monitors must function continuously and should sound alarms within 15 to 20 seconds after detecting a problem. Other physiological parameters are not as labile and can be monitored less frequently. For the most part, medical measurements are made intermittently, and even continuously measured parameters are displayed at intervals. For example, heart rate can change with each beat (by 0.35 to 1 second). To provide data that a human can interpret, however, a bedside monitor usually updates its display of the rate every 3 seconds.

12.5.4 Integration of Patient-Monitoring Devices

Most bedside patient-support devices, such as IV pumps, ventilators, and physiological monitors, are microcomputer-based. Each has its own display and, because each comes from a different manufacturer, each is designed as a standalone unit. As a result, it is common for a nurse or therapist to read a computer display from one of these devices and then to enter the data through a terminal into a different computer. The need to integrate the outputs of the myriad devices in the ICU is apparent. The absence of standards for medical-device communications has stymied the acceptance and success of automated clinical data-management systems. Because of the large number and variety of medical devices available, and the peculiar data formats, it is impractical to attach the growing number of bedside devices to computers by building special software and hardware interfaces. For these reasons, an IEEE committee (P1073) has been organized to write standards for the **Medical Information Bus (MIB)** [Gardner and Hawley, 1984; Franklin, 1988; Shabot, 1989].

Pilot work underway at LDS Hospital [Hawley et al., 1988] has shown that the use of a common bus system facilitates data acquisition from bedside devices such as pulse oximeters, ventilators, infusion pumps,[6] pH meters, and mixed venous oxygen-saturation monitoring systems. The MIB data-communications system tested at LDS Hospital permits connection of up to 255 devices on a network, and will be able to communicate with each of these devices every few seconds. The communications technology being developed will allow the connection of a variety of bedside devices to the computer, and the recording of these devices' data will be almost continuous (Figure 12.17). The potential for improvements in the accuracy and timeliness of data acquisition, as well as for labor savings, is enticing. We shall discuss the MIB in Chapter 20, when we consider major issues that affect the future of medical informatics.

12.5.5 Closed-Loop Control Systems

Closed-loop control devices use a computer to sense and control a physiological variable; they alter therapy directly without human intervention. A nonmedical example of a closed-loop control system is the thermostat on a heater. A sensor continuously measures the temperature of the air. When the temperature drops below the setpoint,

[6]An infusion pump is a device used to control the rate of delivery of intravenous drug so as to maintain a constant level of drug in the body.

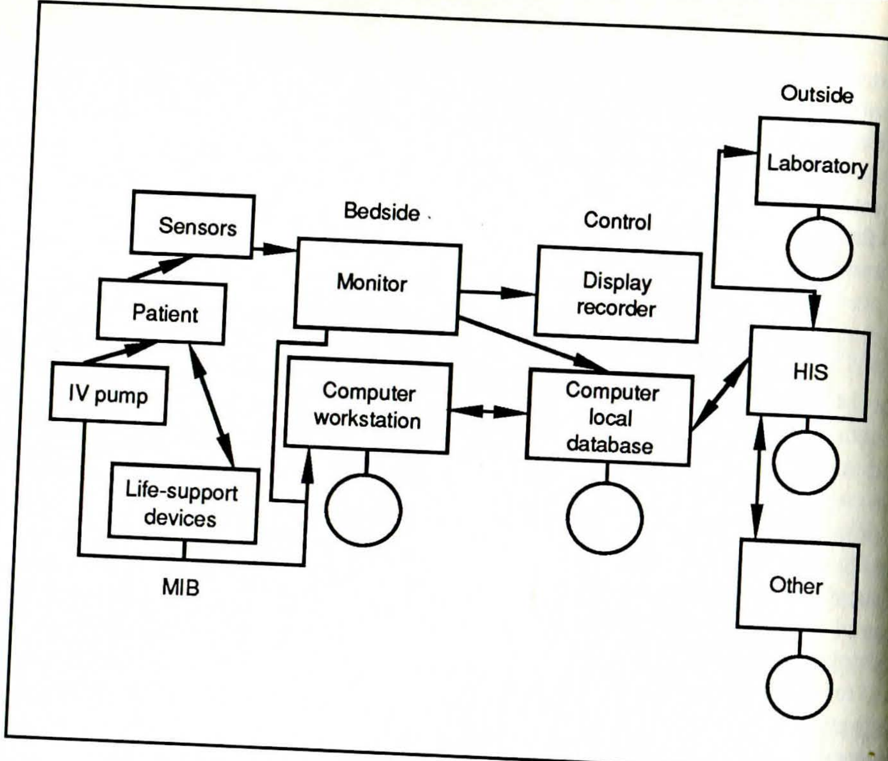

FIGURE 12.17 Block diagram of a distributed-database ICU system with networking. The database has been distributed to improve response time and reliability; the communications network has been implemented to enhance the integration function needed to care for the critically ill patient. [MIB = medical information bus, HIS = hospital information system, IV = intravenous.]

the heater turns on. When the temperature rises sufficiently, the heater shuts off. Sheppard and associates at the University of Alabama have shown the effectiveness of this type of device in controlling physiological parameters. They used a computer-controlled infusion pump to control the administration of sodium nitroprusside, a drug used to regulate blood pressure [Sheppard and Sayers, 1977; Sheppard, 1980]. These investigators have shown that the controller performed more effectively than did a nurse in regulating a constant blood pressure. The system works well under a wide range of clinical situations, and is designed with several fail-safe features. Closed-loop drug-delivery systems now are commercially available for controlling the infusion of oxytocin (a labor-inducing drug) and insulin and dextrose (used to control the level of glucose in the blood). In the future, closed-loop systems will control the delivery of other drugs and fluids, the administration of anesthesia, and the management of patients on ventilator therapy. Application of this type of technology is exciting because the computer may be able to provide more effective patient care while saving nursing time.

12.5.6 Open-Loop Treatment Protocols

The use of protocols—standardized plans for patient management—in the treatment of critically ill patients is not new. Protocols have been used for numerous applications, such as to guide therapeutic dosing so as to prevent adverse drug reactions, to suggest fluid management, to improve cardiac management of surgical patients, and to suggest therapy based on hemodynamic information. If these plans are encoded in the logic of a computer, the computer can analyze the patient data and recommend appropriate treatment. In a closed-loop system, as we discussed, the computer determines the appropriate action and acts directly to implement that action. However, given the complexity and inherent uncertainty of many medical decisions, the incompletely solved problem of data validation, and the dire consequences of error, it may be undesirable or impossible to relinquish complete control to the computer. Nonetheless, we should not ignore the superior computational ability and memory of the computer. Consequently, there is growing interest in the use of computers in **open-loop control systems,** in which the computer collects and analyzes data and generates recommendations or instructions, but human decision makers—such as physicians and nurses—evaluate the appropriateness of the advice before acting on it.

The Ventilator Manager (VM) program was an experimental system designed to interpret quantitative data collected in the ICU and to aid in managing the care of postoperative patients who were receiving mechanical ventilatory assistance [Fagan, 1985]. VM applied AI techniques to detect possible errors in data measurement and to suggest adjustments to therapy based on the patient's status over time and on long-term therapeutic goals. Developed as an experimental prototype, VM was not used to manage actual patients in the ICU. More recently, researchers at LDS Hospital implemented a program to manage the therapy of patients who have acute respiratory distress syndrome (ARDS) and who are enrolled in a controlled clinical trial [Sittig, 1987]. The system automatically generates therapeutic instructions to health-care providers from data input by the laboratory and by physicians, nurses, and respiratory therapists. The system has been used successfully to manage the care of several patients. The researchers' hypothesis is that the system can reduce the time required to initiate correct therapy, and can assist in managing the clinical trial.

12.5.7 Demonstration of the Efficacy of Care in the Intensive-Care Unit

ICU care is expensive. Given the current pressures to control health-care spending (see Chapter 19), there is growing concern about the cost-effectiveness of such care. In a 1984 study prepared for the Office of Technology Assessment, one researcher estimated that 15 to 20 percent of the nation's hospital budget, or almost 1 percent of the gross national product, was spent for ICU care [Berenson, 1984]. Unfortunately, the problems of assessing the benefit of each element in the ICU are many; to date, no definitive studies have been performed. It is difficult to identify and isolate all the factors in the ICU setting that affect patient recovery and outcome. Furthermore, as we mention in our discussion of technology assessment in Chapter 19, the ethical implications of withholding potentially beneficial care from patients in the control group of a randomized clinical trial make such studies difficult to perform. For the moment, we do not know what incremental benefit even the bedside monitor has for a patient. The value of a computer-based data-management system used in conjunction with monitoring devices is even more difficult to assess. One study from LDS Hospital reported that the implementation of a computer-based record-keeping system resulted in a 15-percent increase in the productivity of respiratory therapists [Andrews et al., 1985]; often, however, medical and nursing staff acceptance is the only clear indicator of value we have.

Another study that evaluated how nurses spend their time in caring for patients who have undergone open-heart surgery provided insight about how the computer may assist in improving nursing efficiency [Tolbert and Pertuz, 1977]. The authors concluded that automated patient monitoring should relieve nurses of some routine tasks, such as checking and charting vital signs. The extra time then could be used to provide more direct patient care, if necessary, or could be channeled into other productive tasks. A striking finding of both this study and an unpublished study conducted at LDS Hospital (Figure 12.18) was that nurses spend less than one-half of their time performing direct patient care.

In one attempt to assess the differences in patient outcome among major medical centers and with different treatment modalities, Knaus and associates developed an Acute Physiology and Chronic Health Evaluation (APACHE) scoring system [Knaus et al., 1986]. Scores assigned to patients are intended to stratify them prognostically by risk, so that different treatment programs can be compared more accurately. Fortunately, the data needed to derive the APACHE score are already available from computer-based monitoring systems [Shabot et al., 1987]. By using such systems to simplify data acquisition, we may be able to analyze variations in care and to determine optimal treatment strategies for critically ill patients.

12.5.8 Consensus Conference on Critical-Care Medicine

We can gain a perspective on what should be done to improve data management in critical-care medicine from a 1983 consensus conference organized by the National Institutes of Health (NIH) [Ayers et al., 1983]. Conclusions of the conference pointed out areas in treatment of critically ill patients that needed improvement. Many of these problems are amenable to computer assistance. Technical difficulties, errors in data interpretation, and increased interventions caused by continuous monitoring are potential nosocomial[7] hazards for ICU patients. Based on the findings of the conference, we identify eight areas in which computers can assist in the practice of critical-care medicine.

[7]Nosocomial hazards are dangers related to hospital care itself. A nosocomial infection, for example, is caused by exposure to infectious agents in the hospital environment.

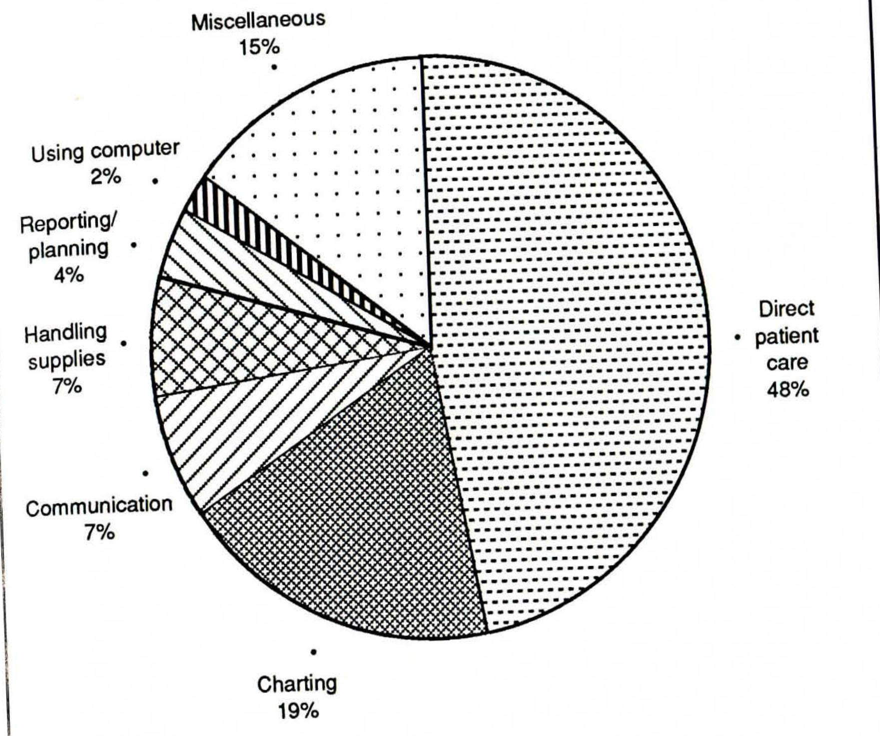

FIGURE 12.18 Pie chart indicating how nurses in a surgical ICU at LDS Hospital allocate their time among patient care, charting, communication, and other activities. Nurses spend only one-half of their time performing direct patient care. (*Source:* Reprinted with permission from Gardner, R. M., Sittig, D. F., and Budd, M. C. Computers in the intensive care unit: Match or mismatch? In Shoemaker, W. C., et al. (eds), *Textbook of Critical Care,* 2nd ed. Philadelphia: W. B. Saunders, 1989, p. 256.)

1. All ICUs should be capable of arrhythmia monitoring. Bedside physiological monitors using microcomputers now provide excellent arrhythmia monitoring.
2. Invasive monitoring should be performed safely. Computer-stored data on invasive events such as the insertion of an arterial catheter, analyzed in combination with data from the microbiology laboratory, can help to avoid infection (a major complication of invasive monitoring).
3. Generated data should be correct. The computer can check data as they are entered to verify that they are reasonable. Also, computer-based data communication and calculation are less subject to error than is work performed by human beings.

4. Derived data should be interpreted properly. The computer can assist in the integration of data from multiple sources. In addition, the computer can derive parameters and also can provide prompt, accurate, and consistent interpretations and alerts. For example, note in Figure 12.16 that oxygen consumption (VO_2) is calculated and displayed when data on arterial and venous blood gases and cardiac output are available (oxygen consumption was 353 ml/minute on 4JAN89 at 04:19).
5. Therapy should be employed safely. The computer can assist physicians by suggesting therapy, calculating appropriate drug doses, and flagging combinations of interacting drugs.
6. Access to laboratory data should be rapid and comprehensive. Computer networking provides fast access to all laboratory data, and can even interpret the results and provide alerts.
7. Enteral (tube-feeding) and parenteral (IV) nutritional support should be available. There are interactive computer programs that help physicians to prescribe care by assisting with the complex task of determining the appropriate volume and content of nutritional supplements.
8. Titrated[8] therapeutic interventions that use infusion pumps should be available. Closed-loop systems for controlling the administration of fluids and intravenous drugs can facilitate patient care and can provide an accurate record of the therapy.

The availability of microcomputers has greatly enhanced the ability to generate and process the physiological data used in patient monitoring. The use of computers in the ICU is still in its infancy, however. Many challenges remain in the exploration of ways with which the computer can be used effectively to integrate, evaluate, and simplify the complex data used in caring for critically ill patients.

Suggested Readings

Ginzton, L. E. and Laks, M. M. Computer aided ECG interpretation. *M.D. Computing,* 1:36, 1984.

This article summarizes the development of computer-based ECG interpretation systems, discusses their advantages and disadvantages, and describes the process by which a typical system obtains and processes ECG data.

Shoemaker, W. C., et al. (eds). *Textbook of Critical Care,* 2nd ed. Philadelphia: W. B. Saunders, 1989.

This handbook will be of interest to the medical computer scientist who is exploring the use of computers in critical-care settings. It includes a chapter that summarizes the current status of medical practice in the ICU.

Westenskow, D. R. Automating patient care with closed-loop control. *M.D. Computing,* 3:14, 1986.

This article provides an understandable discussion of closed-loop control theory and a brief summary of the medical applications of closed-loop systems.

[8]Titration is a method for adjusting the concentration of a dissolved substance by observing a resulting effect. It is used as a method for adjusting the concentration of a drug to achieve the desired effect; for example, a nitroprusside infusion may be adjusted to control blood pressure within prespecified limits.

Wiederhold, G. and Clayton, P. D. Processing biological data in real time. *M.D. Computing,* 2:16, 1985.

This article summarizes the logical elements of real-time data acquisition and analysis. It contains a detailed discussion of signal acquisition, sampling frequency, and analog-to-digital conversion.

Questions for Discussion

1. Describe how the integration of information from multiple bedside monitors, the pharmacy, and the clinical laboratory can help to improve the sensitivity and specificity of the alarm systems used in the ICU.
2. Discuss three factors you must consider when deciding when and how often a physiological, biochemical, or observational variable should be measured and stored in a computer's database.
3. You have been asked to design part of an electronic exercise bicycle. Sensors in the handgrips of the bicycle will be used to pick up transmitted electrical signals reflecting the rider's heart activity. Your system then will display the rider's heart rate numerically on a liquid crystal display (LCD).
   a. Describe the steps your system must take in converting the heart's electrical signals (essentially a single ECG lead) to the heart rate displayed on the LCD.
   b. The resistance of the pedals can be controlled electronically by a microprocessor. Design a simple closed-loop system that dynamically adjusts (increases or decreases) the work for the cyclist based on heart rate. Draw a flowchart for how you might use the calculated heart rate to control the pedal resistance.
   c. How is the accuracy of your data affected by a rider's failure to maintain constant contact with the handgrips? What would happen if your algorithm were used with these inaccurate data? Suggest a second type of data you could collect to verify the accuracy of the handgrip heart-rate data.