New developments in ICU monitoring systems within the past two years rival the impact of the original systems designed for this purpose.

COMPUTERIZED MANAGEMENT OF INTENSIVE CARE PATIENTS

REED M. GARDNER, Ph.D.

Say "intensive care monitoring," and the picture that pops into most physicians' minds involves blood-pressure or ECG monitoring. These measurements were certainly the focus of the initial monitoring systems introduced 20 years ago; but newer systems dealing with a much broader class of information are now becoming available. The following fictitious scenario illustrates the kinds of things that can be done with today's technology.

Larry, a 30-year-old man critically injured in an automobile accident, is admitted to a trauma center. Using a computer, medical emergency staff order and receive the results of laboratory tests at electronic speed. Once doctors have determined the extent of his serious head, chest, and abdominal injuries, the patient is brought to surgery, then later moved to a shock/trauma intensive care unit (ICU). There, a computer monitors Larry's heart rate, rhythm, and blood pressure. A computer-controlled ventilator supports his breathing, and a computerized "closed-loop" infusion pump titrates a vasoactive drug into one of his veins. For the moment, he is stable.

After two days of improvement, however, computer reports from X-rays and the laboratory indicate that Larry has pneumonia. Worse, he has multi-organ failure. To sustain his metabolism, his doctors prescribe total parenteral nutrition (TPN) and medications through the computer, which warns the pharmacist about drug interactions or the existence of laboratory tests that might influ-

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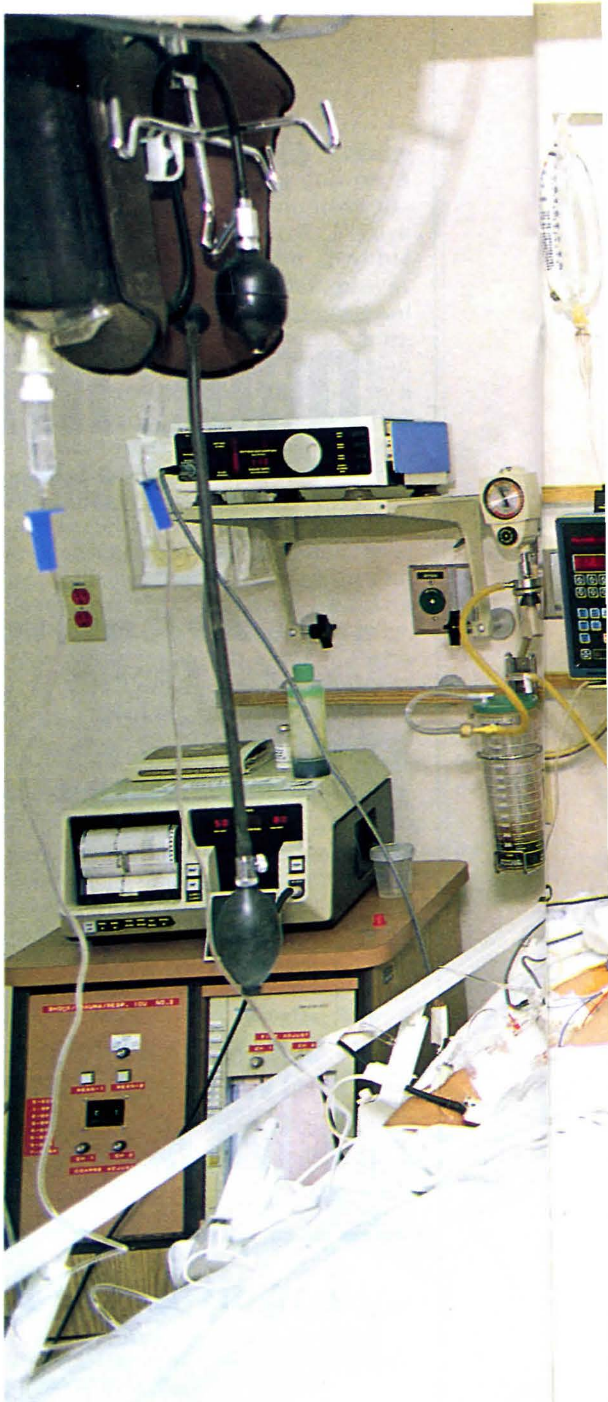


Photograph of a patient bedside, showing the complex setup of monitoring equipment. The following devices are visible, from left to right: mixed venous (pulmonary artery) oxygen saturation recorder; finger-pulse oximeter for noninvasive arterial saturation; IV pump #1; bedside physiological monitor measuring four channels of ECG, arterial pressure, pulmonary artery pressure, and cardiac output; volume ventilator; IV pumps #2 and #3; bedside computer workstation; IV pump #4; and IV (TPN) pump #5.


PUMP

```
                          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:                                  NO.                ROOM: 4S30                              DATE: FEB 21 06:
DR. PRICE, RICHARD R.         SEX: M   AGE:  30   HEIGHT: 178   WEIGHT:  81.00   BSA:  1.99   BEE:  1862   MOF:    6
================================================================================================================
CARDIOVASCULAR: 1                                                             EXAM: ______________________________
TIME               CO     CI    HR  SV   SI    VP  MSP  MP SVR LWI PW  PA  PVR   RWI    ______________________________
FEB 21 04:53  11.84  5.95    95 125  63 12.0M  97  83  6  72  13  33  1.7  18.0
         LV PARAMETERS ARE WITHIN NORMAL LIMITS
                     SP     DP    MP    HR  ¦ LACT          CPK          CPK-MB        LDH-1         LDH-2
  LAST VALUES       153     84   112    98  ¦
  MAXIMUM           231    219   228   136  ¦  1.9 (05:00)     (    )      (    )      (    )      (    )
  MINIMUM            83     44    61    79  ¦
  HEART RATE =         QRS =         PR =        QRS AXIS =
  -- NO ECG DECISIONS AVAILABLE --
================================================================================================================
RESPIRATORY: 3
FEB 21 84     pH     PCO2   HCO3    BE   HB    CO/MT   PO2   SO2   O2CT   %O2  AVO2  VO2   C.O.   A-a  Qs/Qt  PK/ PL/PP  MR/S
21 05:06 V   7.41    49.5   31.0   5.8  14.6   2/ 1    37    75   15.4    50                                    /   /15   25/
21 05:05 A   7.43    45.8   30.1   5.6  14.6   2/ 0    58    91   18.6    50   3.19  378  11.84  190    38      /   /15   25/
        SAMPLE # 131, TEMP 35.4, BREATHING STATUS : ASSIST/CONTROL
        MILD ACID-BASE DISORDER
        HYPOVENTILATION IMPROVED
        MILD HYPOXEMIA
21 00:00 V   7.39    50.9   30.4   4.8  14.5   2/ 1    34    73   14.9    50                                    /   /15   25/
20 23:59 A   7.41    48.1   30.2   5.1  14.6   2/ 0    46    87   17.8    50   2.75              200    51      /   /15   25/
       RATE   VT    VE     VC     MIF     COMP    VD/VT   VCO2   EXAM:                        X-RAY:

   ON   _____ _____ _____ ______ _______ ________ ________ ________ ¦                          ¦
   OFF  _____ _____ _____                                          ¦                          ¦
================================================================================================================
NEURO AND PSYCH: 1
   GLASGOW  9 (00:09) VERBAL ________   EYELIDS ________   MOTOR __________   PUPILS _______   SENSORY _______

   DTR ___________   BABIN. ________   ICP ___________   PSYCH __________
================================================================================================================
COAGULATION: 0
   PT:   11.1   (05:00) PTT:     30 (05:00) PLATELETS:  190 (05:00)   FIBRINOGEN:     (     ) EXAM: ______________________
   FSP-CON:     (     ) FSP-PT:     (     ) 3P:        (     )                                      ______________________
================================================================================================================
RENAL, FLUIDS, LYTES: 0
   IN   5217 CRYST    2950  COLLOID          BLOOD         NG/PO    2250 ¦ NA    133 (05:00) K     4.9 (05:00)  CL  100   (05:00)
   OUT  3907 URINE    2675  NGOUT      854   DRAINS        OTHER     378 ¦ CO2    29 (05:00) BUN  23   (05:00)  CRE   0.6 (05:00)
   NET  1310 WT             WT-CHG    0.00   S.G.    1.025               ¦ AGAP              UOSM               UNA        CRCL
================================================================================================================
METABOLIC --- NUTRITION: 0
   KCAL      2377  GLU  133   (05:00)   ALB          (     )  ¦  CA        (     )    FE       (     )   TIBC      (     )
   KCAL/N2   193   UUN        (     )   N-BAL                 ¦  PO4       (     )    MG       (     )   CHOL      (     )
================================================================================================================
GI, LIVER, AND PANCREAS: 0                                                                     EXAM:
   HCT     45.8 (05:00)  TOTAL BILI     (     )  SGOT     (     )  ALKPO4    (     )  GGT        (     ) ____________
   GUAIAC 1+    (18:00)  DIRECT BILI    (     )  SGPT     (     )  LDH       (     )  AMYLASE    (     ) ____________
================================================================================================================
INFECTION: 1
   WBC 12.6 (05:00) TEMP  37.1 (18:00) DIFF  41B, 52P,  7L,   M,   E (05:00) GRAM STAIN: SPUTUM ___________ OTHER __________
CULTURES:
   BLOOD _______  SPUTUM ________  URINE _________  CSF ________  CATH ________  WOUND _________  OTHER ______________
================================================================================================================
SKIN AND EXTREMITIES:
   PULSES ________  RASH ________  DECUBITI _____________
================================================================================================================
TUBES:
   VEN ________  ART ________  SG ________  NG ________  FOLEY ________  ET ________  TRACH ________ DRAIN______

   CHEST ______________ RECTAL ______ JEJUNAL ________  DIALYSIS ________  OTHER __________________________________
================================================================================================================
MEDICATIONS:

PENTOBARBITAL, INJ                       MGM   IV        800   AMPHOJEL, LIQUID                    ML     NG       120
TICARCILLIN (TICAR), INJ                 MGM   IV      18000   MYLANTA II, LIQUID                  ML     NG       170
GENTAMICIN, INJ                          MGM   IV      480.0   HEPARIN FLUSH                       UNITS  IV       500
PANCURONIUM (PAVULON), INJ               MGM   IV       75.0   OSMOLITE, LIQUID                    ML     NG D    1910
METAPROTERENOL (ALUPENT), SOLUTION       MGM   INHAL    90.0   POTASSIUM CHLORIDE, INJ             MEQ    IV      60.0
VERAPAMIL, INJ                           MGM   IV        5.0   POTASSIUM CHLORIDE, LIQUID          MEQ    NG        40
FUROSEMIDE, INJ                          MGM   IV         10   SODIUM BICARBONATE, INJ             MEQ    INHAL      2
```

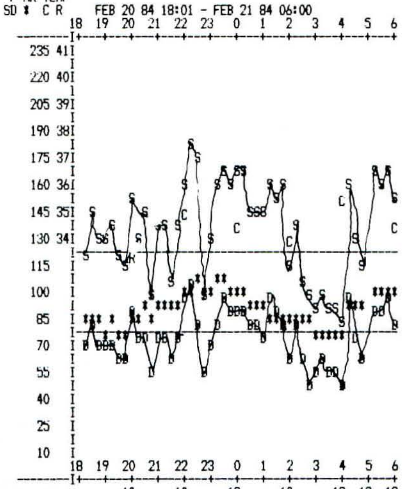
Figure 1. ***Rounds Report*** **for the example patient (Larry), showing data organized by organ system. Data is derived from many sources and stored in Larry's computer database. This report is available to physicians and nurses either on the bedside terminal or in the form of a "hard copy," as shown.**

Larry, a 30-year-old male, has a basal (resting) energy expenditure (or BEE) requirement of 1862 calories, and has a multi-organ failure (MOF) score of 6 (0 being normal). Results from the thermodilution pulmonary artery catheter indicate that his left ventricular status is within normal limits. Blood pressure and arterial lactate results give the Larry a cardiovascular organ failure score of 1. The respiratory score is 3, because Larry requires 50% oxygen and 15 cmH20 of PEEP yet still has a mild hypoxemia. A Glasgow Coma Score of 9 gives Larry a Neuro Psyc score of 1. Coagulation status, renal, fluid, and electrolyte status are adequate, as are the metabolic, GI, liver, and pancreas status. Larry has an elevated white blood count and, as a consequence, an infection score of 1. His currently scheduled medications are listed at the bottom of the rounds report.

Figure 2. A twelve-hour *shift report* for the example patient. Note the physiological data plotted at the top, with fluid balance information and summary laboratory data at the side. Physiological parameters, recorded intermittently, are shown below the plots. Cardiac output data with interpretations are shown next, followed by a list of all the drugs and IV fluids. The "electronic" signature of the nurse is printed. A detailed outline of all fluid intake and output is presented, and finally the blood-gas data for the twelve-hour period with its computer interpretation.

```
                          #          4S30

AGE:  30   WT:  81.00 KG   HT: 178 CM   BSA  1.99 SQM   DR: PRICE, RICHARD R.            SEQUENCE #    58
            P HR TEMP
            SD #  C R      FEB 20 84 18:01 - FEB 21 84 06:00
```



```
                                                   YESTERDAY'S WEIGHT:
                                                   TODAY'S WEIGHT:
                                                 #                                #
                                                 ########## 06:00 TO 06:00 ########
                                                 #                                #
                                                   MAXIMUM TEMP: 36.5

                                                  INPUT
                                                    IV:          2470
                                                    BLOOD:        500
                                                    COLLOID:
                                                    TOTAL:       5143    NET:    651

                                                  OUTPUT
                                                    URINE:       3310
                                                    DRAIN:        974
                                                    TOTAL:       4492
                                                 #                                #
                                                 ########## LAB RESULTS ##########
                                                 #                                #
                                                  WBC      12.5    FEB 21 84 05:00
                                                  HCT      45.8    FEB 21 84 05:00
                                                  HGB      15.3    FEB 21 84 05:00

                                                  NA      133      FEB 21 84 05:00
                                                  K         4.9    FEB 21 84 05:00
                                                  CL      100      FEB 21 84 05:00
                                                  CO2      29      FEB 21 84 05:00
                                                  BUN      23      FEB 21 84 05:00
                                                  GLUC    133      FEB 21 84 05:00
                                                  CREAT     0.5    FEB 21 84 05:00

                          18  19  20  21  22  23   0   1   2   3   4   5   6
                  --------I+---+---+---+---+---+---+---+---+---+---+---+---+
RAP (MMHG)                        10      10      12      10      12  12  12
PA SP (MMHG)                      40      42      44      42      40  40  46
PA DP (MMHG)                      20      22      24      20      22  22  24
PA MEAN (MMHG)                    34      36      35      34      33  33  36
PA WEDGE (MMHG)                   11      12      14      11      13  13  14
CO (L/MIN)                                                          11.84
RESP RATE                         25      27      25      25      25      25
URINE OUTPUT (ML)                220     650     210     220     200     225
URINE SP G                                                            1.025
URINE GLUCOSE                                                           NEG
URINE ACETONE                                                           NEG
STOOL NO.                          1
NG PH                            4.0             4.0             5.0

TIME             CO     CI    HR  SV  SI   VP  MSP  MP SVR LWI  PW  PA  PVR   RWI
NORMAL HI      7.30   3.50    89 101  48    5  123 105  18  85  12  19  1.0  11.0
NORMAL LOW     2.90   2.80    49  47  38    1   80  70  12  48   4   9  0.5   8.0

FEB 21 04:53  11.84   5.95    95 125  63 12.0M  97  83   6  72  13  33  1.7  18.0
          LV PARAMETERS ARE WITHIN NORMAL LIMITS
```

```
                                                                   FEB 20 84 18:01 - FEB 21 84 06:00
                                                                18  19  20  21  22  23   0   1   2   3   4   5   6
                                                   -------------I+---+---+---+---+---+---+---+---+---+---+---+---+
PENTOBARBITAL, INJ                            200 MGM   IV                      1                       1
GENTAMICIN, INJ                             120.0 MGM   IV                      1                                   1
TICARCILLIN (TICAR), INJ                     3000 MGM   IV            1                   1                   1
PANCURONIUM (PAVULON), INJ                    5.0 MGM   IV                1           1       1           1       1   1
METAPROTERENOL (ALUPENT), SOLUTION           15.0 MGM   INHAL    1                    1                   1
FUROSEMIDE, INJ                                10 MGM   IV                    1
ACETYLCYSTEINE (MUCOMYST) 20%, SOLUTION         2 ML    INHAL    1                    1                   1
MYLANTA II, LIQUID                             30 ML    NG                1                                   1
AMPHOJEL, LIQUID                               30 ML    NG                                1
HEPARIN FLUSH                                 100 UNITS IV                               1
DURA-TEARS, OINT                                1 APPLICOPTHN             1       1       1       1       1       1
NORMAL SALINE, INJ                              3 ML    INHAL    1                    1                   1
POTASSIUM CHLORIDE, LIQUID                     40 MEQ   NG                        1
OSMOLITE, LIQUID                              270 ML    NG D   ############
D5 IN 0.45 NACL, INJ                          350 ML    IV     ##########################################
  POTASSIUM CHLORIDE, INJ                    10.5 MEQ
NORMAL SALINE, INJ                             20 ML    IV     ####################
PACKED RBC                                    250 ML    IV     ##############
  NO.                                     9011764
  O  NEGATIVE
D5 IN 0.45 NACL, INJ                          200 ML    IV     ###############################################
  POTASSIUM CHLORIDE, INJ                     6.0 MEQ
OSMOLITE, LIQUID                              240 ML    NG D               ############
PACKED RBC                                    250 ML    IV                   #######
  NO.                                     9011374
  O  NEGATIVE
OSMOLITE, LIQUID                              450 ML    NG D                                 ########################
NORMAL SALINE, INJ                             50 ML    IV                                                    ##
D5 IN 0.45 NACL, INJ                          100 ML    IV                                                        #####
  POTASSIUM CHLORIDE, INJ                     4.0 MEQ
D5 IN 0.45 NACL, INJ                            0 ML    IV                                                            #
  POTASSIUM CHLORIDE, INJ                     0.0 MEQ
                                                                18  19  20  21  22  23   0   1   2   3   4   5   6
                                                   -------------I+---+---+---+---+---+---+---+---+---+---+---+---+
  FEB 20 84 18:01 TO FEB 21 84 06:00   KLINGLE, CONNIE J, RN   ##############################################

INTAKE (ML):  BLOOD             500   OUTPUT (ML):  INSENSIBLE LOSS      73
              NON-BLOOD IV      720                 URINE OUTPUT       1725
              ENTERAL FEEDING   960                 NG TUBE DRG.        420
              NG DRUG            90
              OTHER DRUG         15
                TOTAL          2285                   TOTAL            2218    NET BALANCE        67

FEB 20 84      pH    PCO2    HCO3    BE    HB   CO/MT   PO2   SO2   O2CT   %O2  AVO2  VO2   C.O.  A-a  Qs/Qt  PK/ PL/PP  MR/SR
               --    ----                                ---
NORMAL HI     7.45   40.0    25.0   2.5  19.0   2/ 1    85    95   25.4         5.5  300   7.30         5
NORMAL LOW    7.35   34.0    19.0  -2.5  15.0   0/ 1    68    93   19.6         3.0  200   2.90         0

21 05:06 V    7.41   49.5    31.0   5.8  14.6   2/ 1    37    75   15.4    50                                  /    /15   25/
21 05:05 A    7.43   45.8    30.1   5.6  14.6   2/ 0    58    91   18.6    50   3.19 378  11.84  190    38     /    /15   25/
          SAMPLE # 131, TEMP 35.4, BREATHING STATUS : ASSIST/CONTROL
          MILD ACID-BASE DISORDER
          HYPOVENTILATION IMPROVED
          MILD HYPOXEMIA

21 00:00 V    7.39   50.9    30.4   4.8  14.5   2/ 1    34    73   14.9    50                                  /    /15   25/
20 23:59 A    7.41   48.1    30.2   5.1  14.6   2/ 0    46    87   17.8    50   2.75              200    51     /    /15   25/
          SAMPLE # 130, TEMP 34.5, BREATHING STATUS : ASSIST/CONTROL
          MODERATE CHRONIC RESPIRATORY ACIDOSIS
          HYPOVENTILATION (PREVIOUSLY NORMAL)
          SEVERE HYPOXEMIA BREATHING OXYGEN **CONTACT MD OR RN!!!!

                          #          4S30

                          COMPUTER TECH ------------------------------
   TIME OUT: FEB 21 84 08:20        PROCESS TIME: 00:41                        SEQUENCE #    58
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ence the therapy. Larry's physician and nurse use the computer to collect, organize, and interpret his data, including clinical notes and observations. Thus, they never have to write on the chart. A microcomputer-based bedside monitor collects, transmits, and records Larry's physiological data. Other devices record the ventilator status, intravenous fluid infusion rates and volumes, and fluid output (urine and drainages). This information is automatically logged into the computer via a medical information bus (MIB) local area network. A computer-activated nursing plan guides Larry's care.

At morning rounds, Larry's progress and planned therapy are independently assessed by various members of the medical staff, assisted by their own copies of the computer-generated rounds report (Figure 1), which is organized by organ system. Discussions at rounds are lively, since all members of the care team can have an equally complete picture of the patient's state.

The computer also generates a compact summary of the preceding week every morning, and a shift report every twelve hours to serve as a legal and historical medical record (Figure 2). The twelve-hour report graphs the physiological data; summarizes critical laboratory data; presents hemodynamic and observational data; reports the drug, IV, and blood status; summarizes Larry's fluid balance; gives blood gas results with interpretations, and shows the night nurse's electronic sign-off. All of these computerized assists help the physicians and nurses caring for Larry, while simultaneously logging all the

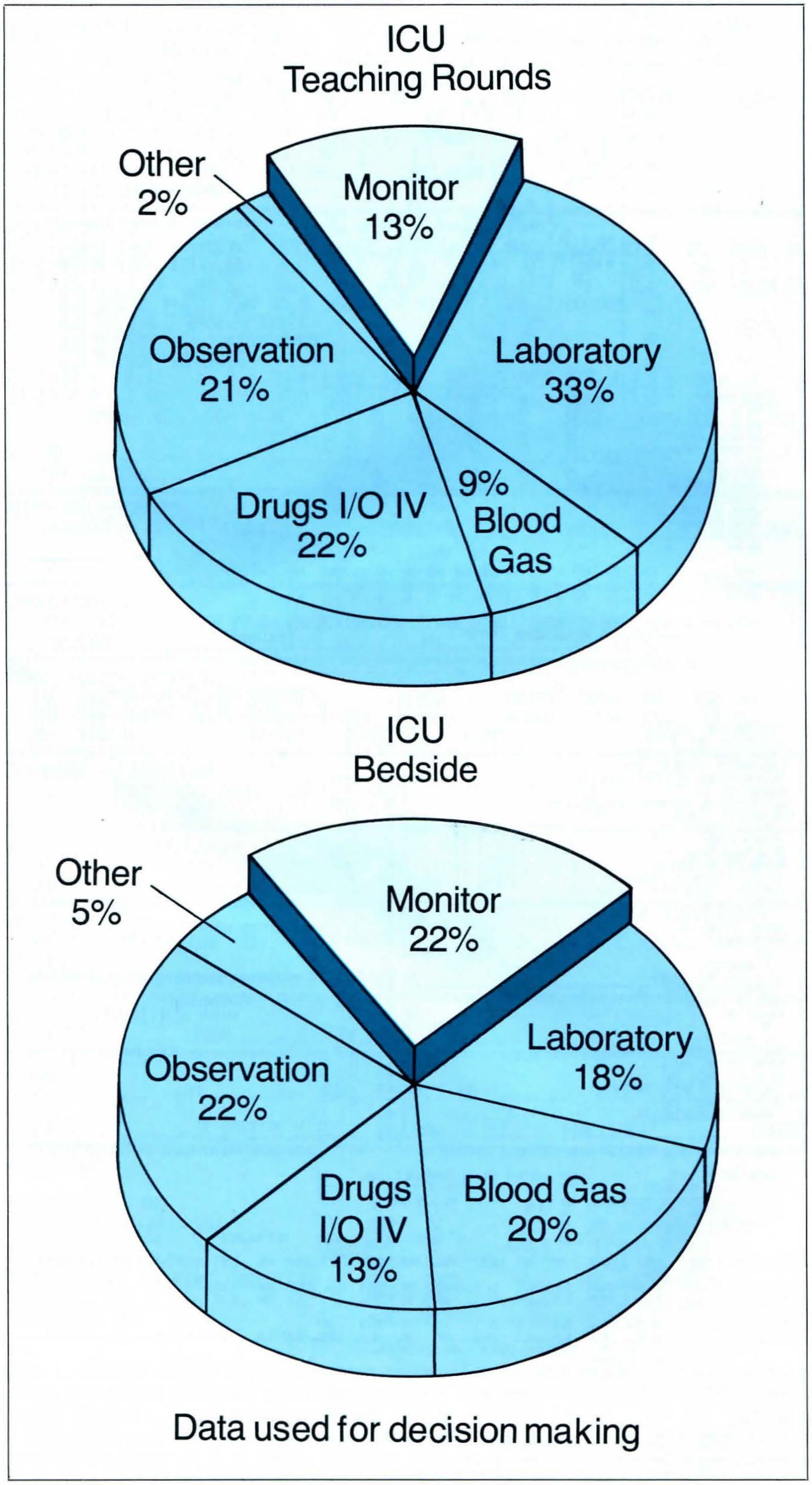


Figure 3. Pie charts of ICU patient data used for decision making at teaching rounds and at the bedside. (Adapted from the *International Journal of Clinical Monitoring and Computing*, by permission [4].)

data for administrative (billing) and medical-legal purposes.

Does this computer-based scenario seem far-fetched? It isn't. Each of the elements discussed is currently operational or under development in at least one ICU.

THE PROBLEMS

To sort out the present benefits of commercially available ICU monitoring systems and the potential impact of developmental systems, it is helpful to review the information needs of the health care team. As illustrated by the above example, the care of critically ill patients requires considerable skill and prompt, accurate treatment decisions. Physicians and nurses collect a great deal of data through frequent observation, regular testing, and continuous monitoring of critically ill patients. Physicians generally prescribe complicated therapy regimens for such patients. As a result, the physicians can miss important events and trends unless the mass of accumulated data is presented in a compact, well-organized form. Economic pressures to reduce the use of therapeutic and diagnostic resources compound the physician's difficulties.

The medical record is the principal instrument for ensuring some continuity of care for patients [1]. Continuity is especially important for critically ill patients, who generally are served by a team of physicians, nurses, and therapists, and whose data is often transferred from one individual to another; for instance, the lab tech calls the nurse on the ward, and the nurse reports the information to the decision-making physician. Each step in this transmission process is subject to error.

As an unifier of the care process, the traditional medical record has several limitations. First, it might be unavailable; or if it is available, it can only be used by one individual at one location. Moreover, it is often poorly organized and illegible; thus, retrieval of information is slow and prone to error. Fries has shown that in complicated cases, the conventional medical record is less helpful than a structured flowchart-type

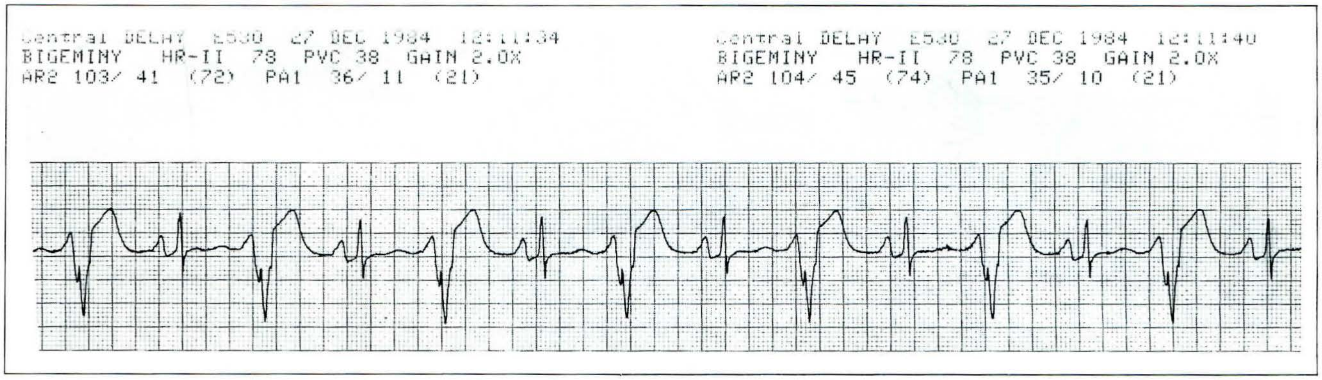


Figure 4. Strip recording of a bigeminy detected by a computerized arrhythmia monitoring system.

record [2]; Whiting-O'Keefe and colleagues have also shown that structured records are easier and quicker to review [3].

While these criticisms apply to all patients' medical records, they are especially important for critical-care medical records because of the large amounts of data collected and the time pressures on decisions. The importance of having a unified patient database was recently demonstrated by a study conducted at LDS Hospital [4]. We kept detailed records of the kinds of data used by physicians to make treatment decisions during teaching rounds at the bedside in a computerized shock-trauma ICU [5] (see Figure 3). We were surprised to find that laboratory data was the information most frequently used to make decisions. Clinicians' observational data was a close second. The information provided by the bedside physiologic monitor accounted for a much smaller percentage (between 13 and 22 percent of the data used to make therapeutic decisions). These findings clearly imply that data from several sources—not just traditional physiological monitoring devices—must be integrated to make effective treatment decisions in the ICU.

THE ROLE OF THE ICU MONITOR

Computers installed in ICUs provide two kinds of capabilities that help improve patient care:

1. *Physiological monitoring.* Computers can acquire, process, store, and display data, and can sound alarms when continuously

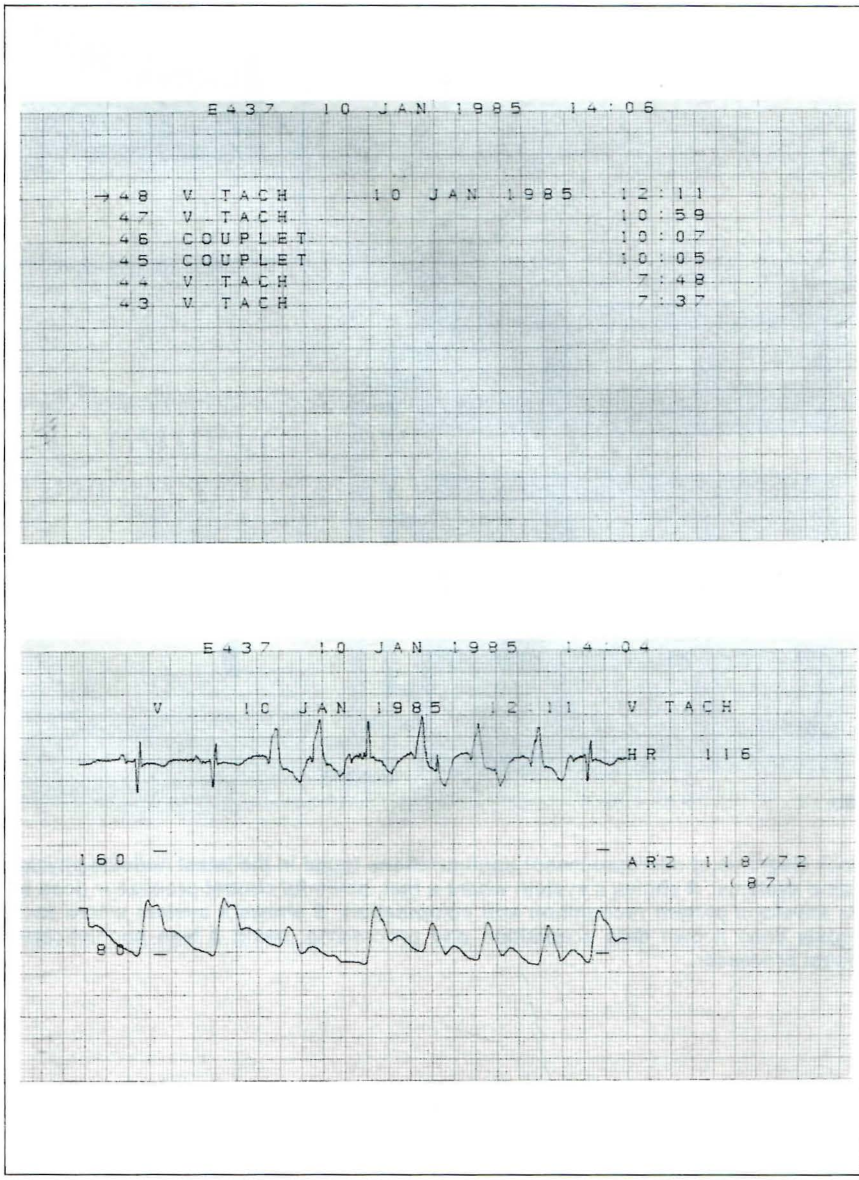
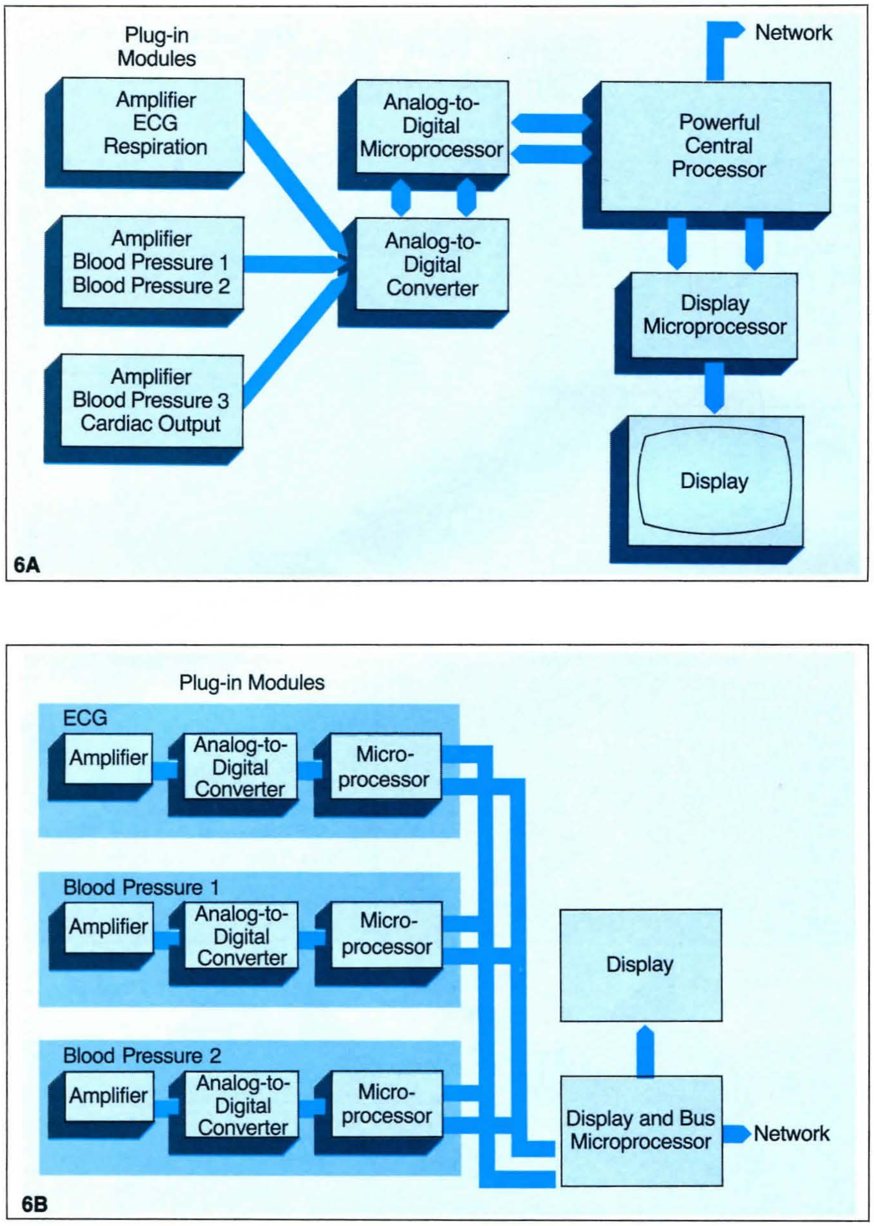


Figure 5. (*A*) Bedside history of a patient's arrhythmias for 10 January 1985. (*B*) Printout of the ECG and arterial pressure waveform for the ventricular tachycardia indicated at 12:11 in *A*.



Block diagrams of microprocessor configurations found in the latest bedside physiological systems: *A* shows a system where a fast, powerful central processor does all the waveform pattern recognition and computation. *B* shows a system where each module does it own data acquisition and processing, using a less sophisticated central processor.

monitored physiologic variables become abnormal (as in an onset of hypotension or ventricular tachycardia).

2. *Integrated patient management.* Because all data are available, the most advanced systems issue alerts and suggestions based on the total clinical database, just as monitoring systems give alerts on ECGs or blood pressure.

Let's take a closer look at each of these aspects.

Monitoring Physiological Variables

BACKGROUND OF BEDSIDE PHYSIOLOGICAL MONITORING

The bedside physiological monitor is the cornerstone of the modern ICU. All of the estimated 75,000 adult, pediatric, and neonatal intensive-care beds operating in the United States are equipped with some type of physiological monitor. The simplest units display the ECG and heart rate, and have simple high/low-rate alarms. The most sophisticated monitors can also: analyze ECG arrhythmias, monitor intravascular pressures and respiratory status, and measure arterial and mixed venous oxygen saturation. Arterial catheters and pulmonary artery balloon-tipped catheters are frequently used to measure physiological pressures and blood gases. Some monitors even compute cardiac output from thermal dilution curves, a process which formerly required special procedures performed in the cardiac catheterization laboratory.

STRENGTHS OF CURRENT MICROCOMPUTER SYSTEMS

The use of microcomputers in bedside monitors has revolutionized the acquisition, display, and processing of physiological signals. Today, the newest commercial bedside monitors contain multiple microprocessors. They have more computer power than earlier computer systems that would have filled a room, and they require less space than their predecessors' cooling fans. A discussion of how these signals are acquired and processed may be found in Gio Wiederhold's article, "Processing Biological Data in Real Time" (*M.D.*

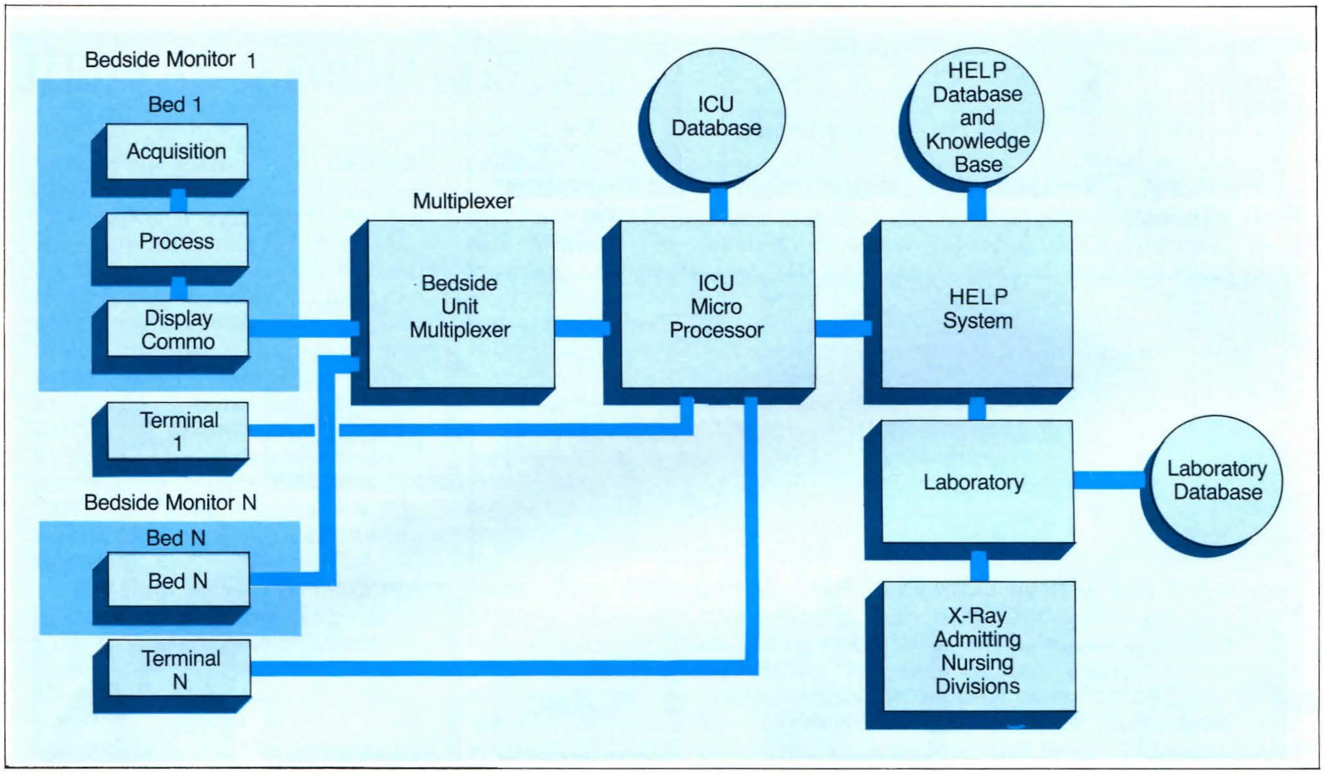


Figure 7. Block diagram of the HELP system.

COMPUTING 2(6):16–25).

Monitoring instruments with built-in microcomputers have many additional advantages over their analog predecessors:

- Systems can easily be upgraded by changing software programs in read-only memory. (Upgrading older systems necessitated replacing the hardware, because the logic was "wired in.")
- The digital computer's ability to store patient waveform information (such as the ECG) permits sophisticated pattern recognition. Older systems built with analog computer technology did their work "on the fly," with only a small "peek" at the patient waveform.
- Signal quality can be monitored and maintained. For example, the computer can "watch" for degradation of ECG skin/electrode contact. If the contact is not good, the monitor can alert the nurse to change a specific electrode, thus assuring good signal transmission from skin to sensor.
- Physiological signals can be acquired more efficiently by converting them to digital form early in

COMMERCIAL COMPUTERIZED PATIENT DATA MANAGEMENT SYSTEMS

Manufacturer	Number of Systems Delivered	Number in Routine Use	Cost of Each System (16 beds)
Hewlett-Packard	200	14–20	$100,000
Mennen Medical	15	3	$100,000
Siemens	new	new	$75,000

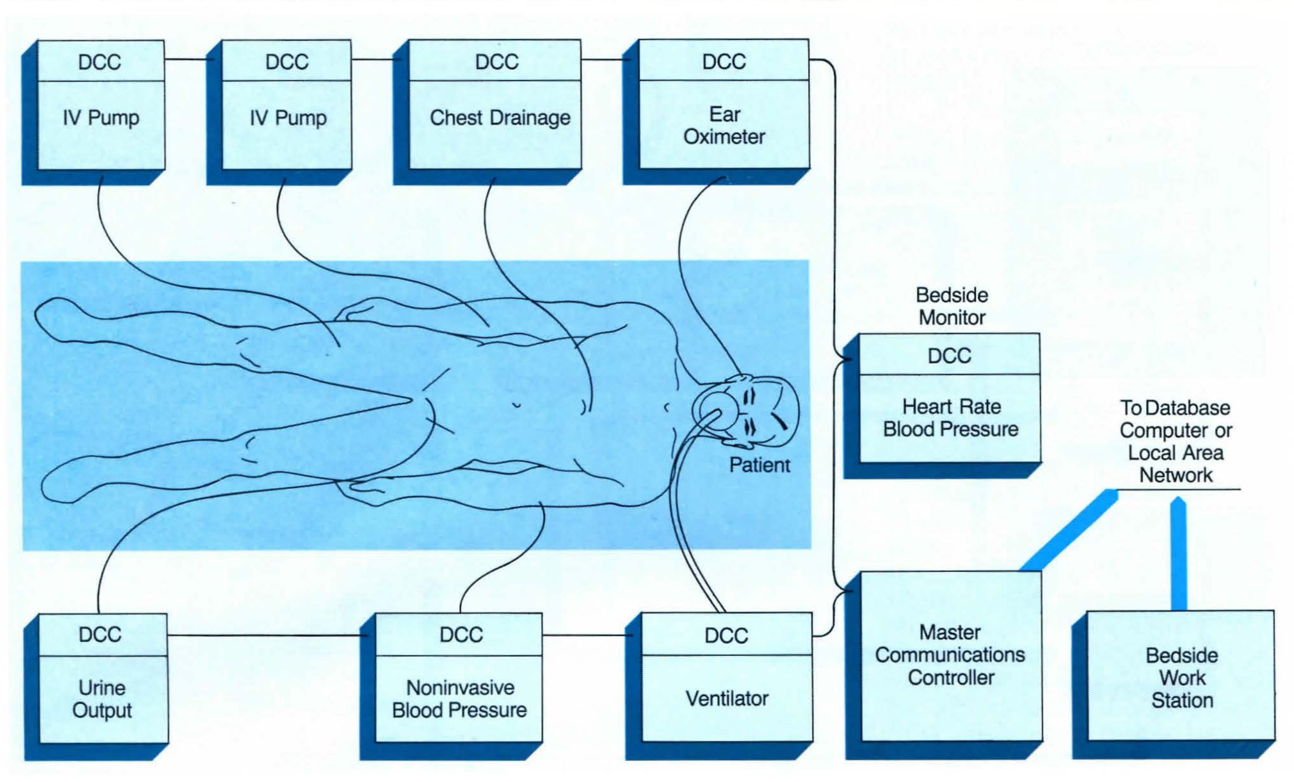


Figure 8. ***Medical information bus*** **(MIB). This is a local area network that allows collection of patient data from a variety of bedside instruments, such as ventilators, IV pumps, urine output measuring devices, and others.**

INSTITUTIONS USING COMPUTERIZED DATA MANAGEMENT SYSTEMS

Phoenix Baptist Hospital
Phoenix, AZ

University of Alabama
Birmingham, AL

Pacific Medical Center
San Francisco, CA

Michael Reese Hospital
Chicago, IL

Cedar-Sinai Hospital
Los Angeles, CA

Crawford Long Hospital
Atlanta, GA

New York Hospital—Cornell Medical Center
New York, NY

LDS Hospital/University of Utah
Salt Lake City, UT

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Baltimore, MD

the processing cycle, and handling "waveform processing" functions (such as calibration and filtering) in the microcomputer. Local computer power also simplifies the nurse's task of operating the bedside monitor.

- Pattern recognition and waveform feature extraction can also be done in microcomputer-based monitors. The computer can use waveform "templates" to identify abnormal waveform patterns and to classify ECG arrhythmias.
- Selected data can easily be retained. For example, "strips" of interesting physiological sequences—such as periods of arrhythmias or marked changes in heart rate—can now easily be stored in the bedside monitor for later review. Measured variables, such as heart rate and blood pressure, can be graphed for detection of life-threatening time-oriented trends.

MEDICAL INFORMATION BUS

Care of the critically ill patient requires data from a wide variety of devices and instruments. It is not unusual, for example, for the patient to be connected to a bedside monitor, a noninvasive blood pressure monitor, infusion pumps, a ventilator, a urine output system, chest tube drainage measuring system, and an ear oximeter (see Figure 8). Each of these devices may be made by a different manufacturer, and each may have a different data communications interface.

To help solve the dilemma of manually acquiring data from this multitude of electronic sources, a *medical information bus* (MIB) has been proposed to provide a local area network around the patient to acquire data from all bedside devices. As noted in Figure 3, a large amount of device-generated data can be automatically entered into the database via the MIB. Such a bus system is currently being developed at Phoenix Baptist and LDS Hospitals.

The MIB uses a master/slave communications protocol approach (Figure 8). The MIB has a multi-drop (daisy-chain) structure, and will use a single shielded pair of twisted wires as the physical communications medium (much like a telephone cord). The system will run at a fast rate (375 Kbits/sec), and is self-clocking. The *master communications controller* (MCC) oversees all bus communications. It accepts, processes, and relays information between the host and the MIB. It is responsible for polling all on-line medical devices and reporting significant events to the host. The *device communications controller* (DCC) is the slave which interfaces between the MIB and the particular medical instrument. The DCC accepts MIB protocol messages, and processes and converts them to instrument-specific codes. The DCC also converts the instrument-specific outputs into the MIB protocol and returns a response to the MCC.

The MIB uses a subset of the highly reliable *synchronous data link control (*SDLC) protocol. SDLC uses a frame check sequence to assure the accuracy of the data sent in each SDLC frame. This error checking assures nearly "bullet-proof" or error-free data transmission, a requirement for medical applications: less than one error for each billion bits transmitted!

The bus can have up to 255 devices attached; and each device will have an identification (ID) code. The current design concepts will allow up to 10,000 device ID codes. Common descriptors will be specified for each class of machine (*fluid delivery devices* such as IV pumps, *fluid collection devices* such as urine output measurement devices, *respiratory life-support instruments* such as mechanical ventilators, and *noninvasive measurement devices* such as automatic cuff blood-pressure instruments). Thus, for example, a patient might be connected to two IV pumps, one manufactured by IVAC and the other by IMED. Under host control, the MCC could make a request to each device, querying for the fluid flow rate. The DCC on each IV pump would interrogate the device and send the requested information.

The final details of the MIB and its protocol are still under development, and will probably take another two or three years to complete. Industry-wide standards are essential to make the scheme work.

Those interested in participating in the development of the standard should contact Ron Norden-Paul, Chairperson, Medical Information Bus Committee (IEEE P1073), Emtek Health Care Systems, 1702 West Harmont, Phoenix, AZ 85201.

■ Signal transmission is simpler and more reliable. Consequently, it is possible for a bedside monitor to transmit its signal to a central display for review by nurses or physicians.

■ Alarms from the bedside monitor are now much "smarter," and therefore less often false. In the past, alarm systems used only high/low-threshold limits, and thus were susceptible to signal artifacts. Now, the computers and bedside monitors can distinguish between artifacts and disasters, and can "confidently" alert physicians and nurses about problems. The bedside monitor may process many different signals, and can use information from one signal to verify another—for example, by comparing the heart rate derived from the ECG tracing with that derived from the arterial pressure. Thus, the system is more like a human observer, who always cross-compares many kinds of redundant information.

ARRHYTHMIA MONITORING

Arrhythmia monitoring of the ECG is the most sophisticated of the bedside monitor's tasks. Romhilt reports that "people-based" arrhythmia monitoring is expensive and unreliable, and that those who do it find it tedious and stressful [6]. One way around the limits of human monitor-watchers is to buy a large central computer-based system to do the rhythm monitoring. In the past, such minicomputer-based systems cost $50,000 or more, and could only monitor 8 to 16 beds. The newest bedside monitors have the rhythm-monitoring computer built in. These 16-bit computers use "waveform templates" and real-time cross-correlation techniques to classify rhythm abnormalities.

Figure 4 shows the output of a bedside monitor that detected "bigeminy," and then provided a strip recording of a patient's ECG annotated with the arterial and pulmonary artery pressure. The system also retains "copies" of these and other problem strips for later review. Figure 5A shows a historical listing of important rhythms for a patient. A *V Tach* (ventricular tachycardia) condition was noted at 12:11. The nurse or physician can review the data as represented in Figure 5B, which shows a "history strip" of the identified V Tach, along with the simultaneously logged arterial-pressure waveform which occurred at 12:11. Note that the strip was printed out at 14:04.

The improvements in computerized arrhythmia monitoring just within the past two years have been dramatic. In fact, in three short years since the review of computerized arrhythmia-monitoring systems by Sanders and Harrison [7], the industry has shifted away from central shared systems in favor of local microcomputers within each monitor for arrhythmia detection. Thus, many of the specific recommendations given by Harrison and Sanders no longer apply. However, their general advice is still valid.

Be sure to choose a vendor who will be in business after you have purchased the system. Worry about the availability of maintenance service before you buy. In addition, review the training opportunities given by the vendors. Ideally, this should include on-site training, illustrated instruction manuals, and other aids. My advice is to be sure to investigate the capabilities of at least three manufacturers; and when possible, field-test their monitors in your hospital before committing yourself to a purchase.

More than 25 manufacturers supply bedside monitors. They include such features as non-fade traces, color video displays, trend storage, multi-lead ECG systems, touch screens, inter-bed communication, built-in calculator functions, on-screen alarm messages, and telemetry. The cost of current bedside monitors ranges from about $5,000 for a simple stand-alone bedside unit to about $19,000 per bedside for a monitor with a central station (see table at right).

Microcomputer bedside monitors are based on a variety of de-

BEDSIDE MONITOR MANUFACTURERS (MICROPROCESSOR-BASED MONITORS)

Note: Systems noted are generally for a typical bedside unit (no central display communications or display system) with ECG, respiration, two pressure channels, and a cardiac output module. Manufacturers' list prices are given as of March 1985.

Company	Data Scope Corp
Location	Paramus, NJ
Phone	201/265-8800
Contact	Ted VanderWiede
Model	2000
Type Display	moving window
Traces	3
Modular	no
Parameters	ECG, 2 pressures; no cardiac output
ECG Lead Fault	yes
Arrhythmia	no
Location	—
Method	—
Alarms	yes
Trending	yes
Limit (hrs.)	4
No. of Microcomputers	1
List Price	$7,500 without cardiac output, without arrhythmia
Special Features	expandable, modular system; annotated recorder

Company	Hewlett-Packard
Location	Waltham, MA
Phone	617/890-6300
Contact	Rich Grant
Model	78353B
Type Display	erase bar
Traces	3
Modular	no, but configurable
Parameters	ECG, resp, 2 pressures; no cardiac output
ECG Lead Fault	yes
Arrhythmia	yes
Location	central
Method	feature extraction & template matching
Alarms	yes
Trending	yes
Limit (hrs.)	24
No. of Microcomputers	5

signs. Two of the more common designs are shown in Figure 6. Both make use of the latest physiological waveform-pattern-recognition and communications technology. Although bedside monitors represent a major share of ICU equipment cost, they provide assistance in only a limited number of ICU medical decisions.

Integrated Data Management Systems

To assist in the majority of critical-care management decisions, the computer must deal with a large and varied flow of data into a patient's computerized record. Relevant patient data comes from such diverse locations as the admissions desk, bedside physiological monitors, clinical laboratories, radiology, and the pharmacy. Vendors and developers now propose an integrated computerized ICU record to assist routine medical management.

Unfortunately, most commercially available integrated data management systems for ICUs have not been widely successful, from the point of view of either users or vendors. The vendors have tended to underestimate the complexity of the medical practice and the diversity of situations found in intensive-care medicine. Differences among hospitals have required expensive customization at each new location. Products have tended to focus on the acquisition and processing of physiologic data without taking into account the need for a linkage to other sources of data within the hospital (see Figure 3). The systems generally have not included "user-programmable" functionality so that each user could tailor the system to serve one's particular needs.

Rarely have any of the systems been integrated with administrative or clinical data procedures. Thus, in most operational systems, duplicate charting is required. Most of the systems have not resolved the difficulties of manual data entry into a computer; if this is to compete with a ballpoint pen and piece of paper, it must be simple, fast, and reliable. Finally, most of the systems have not provided integrated databases

BEDSIDE MONITORS CONTINUED

List Price	$7,090 without cardiac output, without arrhythmia
Special Features	bed-to-bed commo network; softkeys; functionally modular
Company	Hewlett-Packard
Location	Waltham, MA
Phone	619/890-6300
Contact	Rich Grant
Model	78534B
Type Display	space bar
Traces	4
Modular	yes
Parameters	ECG, resp, 2 pressures; cardiac output
ECG Lead Fault	yes
Arrhythmia	yes
Location	central
Method	feature extraction & template
Alarms	yes
Trending	yes
Limit (hrs.)	24
No. of Microcomputers	6
List Price	$17,847 without arrhythmia
Special Features	24-hour database with trend or tabular, plug-in database module
Company	Honeywell Medical Electronics
Location	Pleasantville, NY
Phone	914/769-6700
Contact	Steve Pontzer
Model	RM 300
Type Display	moving window & erase bar
Traces	3
Modular	yes
Parameters	ECG, 2 pressures
ECG Lead Fault	yes
Arrhythmia	to be announced
Location	bedside
Method	?
Alarms	yes
Trending	yes
Limit (hrs.)	2 to 24
No. of Microcomputers	1
List Price	$6,400 without cardiac output, without arrhythmia
Special Features	modular concept; long-term power; fail protect; hard & soft keys; powerful but small
Company	Kone Instruments
Location	Bensonville, IL

or decision-making capabilities.

In a few institutions, the systems have been deemed successful [8]. The common denominators of these "successful" systems were:

- The medical staff generally recognized the need for computers and were committed to making them work.
- A powerful physician/advocate of the computer system served as its manager.
- The system not only met the needs identified before the installation, but accommodated additional changes.
- The hospital staff were properly oriented and trained in the system.
- The systems were extremely reliable.

But despite large investments by many capable and reputable companies, patient data management systems have not achieved significant market penetration, as shown in the list on page 43. Therefore, several manufacturers are now stepping back to take a broader look at the needs of the entire hospital before investing further in ICU patient management systems. From our successful experiences in applying computers to ICU patient management [5, 8], it is clear that a certain "critical mass" of data is required before this kind of system can be successful.

AN EXAMPLE OF A SUCCESSFUL SYSTEM

LDS Hospital in Salt Lake City provides an example of an advanced application of an integrated ICU patient data management system. This system was not an overnight accomplishment, but rather the result of a lengthy process (the initial computer monitoring having been begun in the late 1960s). Here, we use a large integrated database system called HELP [9]. Our 64 intensive-care beds have computerized bedside monitors—forming a local database—and are connected to the HELP decision-making system (see Figure 7 and page 37). A network of computers acquire and distribute more patient information.

Physicians use the rounds report (Figure 1) extensively in daily teaching rounds, and at other

BEDSIDE MONITORS CONTINUED

Phone	1-800-323-4306
Contact	Jeff Mosdale
Model	565
Type Display	moving window & erase bar
Traces	up to 6
Modular	yes
Parameters	ECG, resp, 2 pressures; cardiac output
ECG Lead Fault	yes
Arrhythmia	yes (future)
Location	central
Method	correlation, template
Alarms	yes
Trending	yes
Limit (hrs.)	3, 9, 27
No. of Microcomputers	1
List Price	$15,420 without arrhythmia
Special Features	multicolor display; configurable, patient data management

Company	Kontron Medical
Location	Everett, MA
Phone	617/389-6400
Contact	Larry Liebman
Model	Supermon 721000
Type Display	moving window
Traces	5
Modular	yes
Parameters	ECG, resp, temp, pressures
ECG Lead Fault	yes
Arrhythmia	to be announced
Location	bedside
Method	variant
Alarms	yes
Trending	yes
Limit (hrs.)	2 or 8
No. of Microcomputers	4
List Price	$10,000 without cardiac output, without arrhythmia
Special Features	modular; up to 15 parameters; variant alarm identification; snapshot of all parameters on alarm; clinical status display

Company	Litton-Datamedix
Location	Sharon, MA
Phone	617/389-6400
Contact	Paul Hughes
Model	SMC 108
Type Display	moving window
Traces	4

times when data must be quickly reviewed and therapeutic decisions made. With a few keystrokes, physicians in our ICU can obtain a patient's summary in less than a minute. Because of the convenience of the CRT review, physicians routinely review the patient's course through the computer rather than a chart. The computer also produces suggestions about contraindicated drugs at the time they are being ordered, calculates cardiac function and interprets blood gas measurements using medical knowledge contained in the system, and suggests the best and most effective antibiotics when positive microbiologic culture results are reported.

RECOMMENDATIONS FOR INTENSIVE CARE—CAN THE COMPUTER HELP?

Based upon the monitoring, integration, and decision-making functions provided by the computer, we have asked ourselves, "Has the computer system really affected patient care?" A secondary but more profound question is "How do you show that the ICU itself is effective?"

A recent consensus conference on Critical Care Medicine, sponsored by the National Institute of Health, provided insight into the application of technology to the problems of the critically ill [10]. The conferees found evidence that ICU care can be life-saving to patients with acute reversible diseases (such as respiratory failure from drug overdose, or cardiac conduction disturbances amenable to pacemaker therapy), as well as patients with septic or cardiogenic shock, and patients who have just recovered from major surgery or who suffer from acute myocardial infarction.

The same technology-assessment conference pointed out that technical difficulties, errors in data interpretation, and increasing interventions induced by continuous monitoring are potential iatrogenic hazards for ICU patients.

THE FUTURE

Both the cost and size of computer hardware have decreased dramatically in the past several years, a

BEDSIDE MONITORS CONTINUED

Modular	yes
Parameters	ECG, resp, temp, pressures; cardiac output
ECG Lead Fault	yes
Arrhythmia	to be announced
Location	bedside
Method	template matching
Alarms	yes
Trending	yes
Limit (hrs.)	2, 8, 24
No. of Microcomputers	6
List Price	$12,800 without arrhythmia
Special Features	advanced data processing; trend & tabular reports

Company	Marquette Electronics
Location	Milwaukee, WI
Phone	414/355-5000
Contact	Phil Weinfurt
Model	7000
Type Display	moving window
Traces	4
Modular	yes
Parameters	ECG, resp, pressure; cardiac output
ECG Lead Fault	yes
Arrhythmia	yes
Location	bedside
Method	cross-correlation & feature extraction
Alarms	yes
Trending	yes
Limit (hrs.)	24
No. of Microcomputers	3
List Price	$13,500
Special Features	multi-lead ECG; bedside arrhythmia; soft keys

Company	Mennen Medical
Location	Clarence, NY
Phone	716/759-6921
Contact	Dan Schelk
Model	Horizon 2000
Type Display	erase bar
Traces	4
Modular	no
Parameters	ECG, resp, temp, 2 pressures; cardiac output
ECG Lead Fault	yes
Arrhythmia	yes
Location	central
Method	feature extraction

trend expected to continue in the future. Thus the proliferation of personal computers into the ICU is inevitable. With the recent introduction of cost-effective local area networks (LANs) for personal computers, new communication links will be established, encouraging a further integration of ICU patient recordkeeping. Closed-loop therapeutic devices, which use a computer to sense a physiological variable and control it by altering therapy, are now being applied in the ICU. These systems work well under a wide range of clinical situations, and provide better patient control while saving nursing time. Several investigators are working to apply closed-loop control to a variety of ICU problems.

COMPUTERIZED DECISION-MAKING

The ultimate goal of a medical computer system is, after all, to assist physicians in making medical decisions. Computers can be set up to apply rule-based logic to patient care. Early work in this field has led to some simple but helpful data interpretation and alarm protocols [11]. In a sense, we are now at the same stage of generating alerts from the integrated data as we were twenty years ago with physiological data. Just as the computer filled that need, it seems probable that automated decision-making will gain acceptance to the point that it becomes indispensable.

Computer software tools and strategies are emerging for use with decision-making or "intelligent" systems. Many medical mistakes appear to be due to errors associated with simple clinical events, which could be avoided with computer-aided decision making. Data indicate that application of clinically relevant medical knowledge is frequently lacking because of ignorance or the inability to process all the patient's data [12]. The computer should be able to assist physicians in making their actions consistent with their medical knowledge. The challenge, of course, is to develop good medical logic that can be applied in something beyond trivial demonstration situations. This requirement again parallels the improved "robustness" that has developed

BEDSIDE MONITORS CONTINUED

Alarms	yes
Trending	yes
Limit (hrs.)	1, 8, 24
No. of Microcomputers	1
List Price	$8,500 without arrhythmia
Special Features	color display; multi-lead ECG; hemodynamics calc; advanced BP algorithm

Company	Nihon Khoden (America) Inc.
Location	Irvine, CA
Phone	1-800-325-0283
Contact	Dennis Javens
Model	OMP 7201C
Type Display	moving window
Traces	4
Parameters	ECG, resp, 2 pressures, arrhythmia
ECG Lead Fault	yes
Arrhythmia	yes
Location	bedside
Method	correlation, feature extraction, & template
Alarms	yes
Trending	yes
Limit (hrs.)	2, 4, 8
No. of Microcomputers	1
List Price	$9,600 without cardiac output
Special Features	multiple-channel telemetry transmission from patient to monitor; arrhythmia detection

Company	Siemens Medical Systems
Location	Iselin, NJ
Phone	201/321-4500
Contact	Andy Levy
Model	Sirecust 404-1
Type Display	moving window, space bar
Traces	4
Modular	yes
Parameters	dual ECG, pressures; cardiac output
ECG Lead Fault	yes
Arrhythmia	yes
Location	bedside
Method	feature extraction & template
Alarms	yes
Trending	yes
Limit (hrs.)	2 to 24
No. of Microcomputers	4

in the arena of physiological monitoring.

CONCLUSION

Recently Dr. John J. Osborn compared the practice of medicine to driving an antique car [13]. "My grandfather had such a car," he said, "a 1908 curved-dash Oldsmobile. Since it took all his skill just to start and drive it, he hired a chauffeur, but not even the chauffeur was able to keep it running all of the time." Osborn's grandfather then faced the dilemma of whether to upgrade the chauffeur's training or hire a better-trained man. The question, however, soon became moot, as automobiles were developed whose parts and functions were so integrated they took over most of the small, finicky functions that the chauffeur used to cope with: advancing the spark, adjusting the jet, closing the choke, and so on. The new automobiles let the driver concentrate on the driving.

Today, we find ourselves in much the same position as the owner of the 1908 Oldsmobile. (Will newer computers themselves take over the small, finicky functions we chauffeurs—I mean *physicians*—must now cope with?) We do need to harness computers to help us manage the mass of detail required to operate a modern ICU. Computers, like Oldsmobiles, are only vehicles for getting us where we want to go. We must find a way to use the computer effectively as a tool—a tool that will assist us in integrating, evaluating, and simplifying the necessary data while we use our human skills to make our care more personal. □

BEDSIDE MONITORS CONCLUDED

List Price	$15,685
Special Features	software-driven; distributed processing; electrically isolated modules; built-in arrhythmia
Company	Spacelabs
Location	Bellview, WA
Phone	1-800-423-5037
Contact	Bill Sundheimer
Model	Alpha PC
Type Display	moving window
Traces	5
Modular	yes
Parameters	ECG, resp, pressure
ECG Lead Fault	yes
Arrhythmia	to be announced
Location	central
Method	cross-correlation & feature extraction
Alarms	yes
Trending	yes
Limit (hrs.)	1, 2, 6, 12, 24
No. of Microcomputers	7
List Price	$16,500 without cardiac output, without arrhythmia
Special Features	IBM-PC programmability; software-driven; touchscreen; anticipatory programming; communications network

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