COMPUTERIZED PATIENT MONITORING AT LDS HOSPITAL--AN EVALUATION

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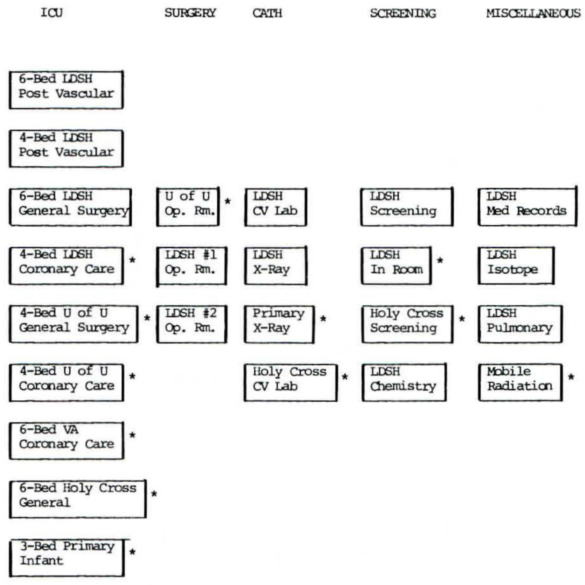
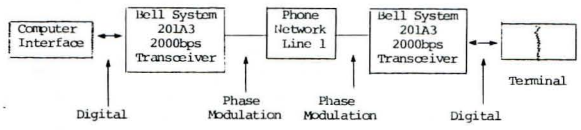
During the past four years a computerized intensive care monitoring system has been operational in five hospitals in the Salt Lake City area under the sponsorship of the Intermountain Regional Medical Program. Experience in these five hospitals with more than 3,000 patients has given us some insight into the value of computerized intensive care monitoring. The monitored patients have included post-vascular surgery patients, patients in the coronary care units following myocardial infarction, and patients in a general surgical unit following various types of surgery and trauma. This variety in class of patients is probably greater than that seen in any other computerized intensive care facility.

Figure 1 shows the 24 terminals connected to the clinical system. The system is capable of operating these terminals in a time-sharing, real-time mode. An expansion program will extend the number of allowable terminals to 64 within two months in an effort to satisfy demands and to more effectively use the system and make it more economical. The flexibility of this system has made it useful for multiple applications. Although there are 24 terminals presently connected to the system, only 11 are able to run simultaneously with present memory limitation. If more than 11 users want to run at the same time, the user who has been the least active will have his program swapped out on magnetic disc where it will remain until he requires service again, (in which case he will be swapped back into memory and another user will be swapped out of memory. System back-up is provided with a second computer which is also used to develop and process data from research applications,such as experimental animal laboratories and other experimental facilities (for example, those described by Dr. Clark and Richard Robb at this symposium).

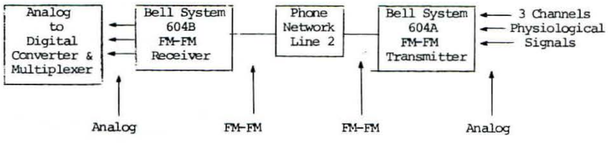


* Indicates Phone Line Communications

Fig. 1. Terminals Connected to Clinical System.



Digital Line



Analog Line

Fig. 2. Communication Hookup.

In order to implement the system in multiple hospitals, it has been necessary to develop a terminal and communications scheme as shown in Figure 2. As can be noted from Figure 1, approximately half the terminals are on a communications link, either through private line connections or using dial-up telephone lines. The dial-up network has added flexibility to our system since the computer can be run from anywhere that dial-up communications facilities are available. This has been amply demonstrated by a member of the Regional Medical Program staff who has demonstrated operation of a tumor registry program from New York, Los Angeles,

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and various other places in the United States. Limitation to three channels of analog information has made us very selective in the choice of signals to be processed and also in the method by which data is preprocessed at the terminals.

One of the outgrowths of the communication limitation is the concept of multiplexing within the intensive care unit, as indicated by Figure 3. Three signals from each bedside unit are brought to a central terminal within the ICU for display and retransmission to the central processing facility. The central facility is able to send control and switching information back to the bedside unit to control the multiplexing and service alarms. Experience with both four and six-bed multiplexing configurations indicates that the four-bed configuration is optimal where entry of a reasonable amount of comment information is expected. The multiplexing scheme will not permit continuous monitoring of all the patients, a practice we have tried but found to be very expensive in terms of computer and communications time. Therefore, 15-minute scheduled samples are taken for routine monitoring. Data can be taken at a 2-minute interval for a critical period. Manual intervention at any desired time is also allowed.

The signals measured at each bedside are as follows: 1) Central arterial pulse waveform from a transducer attached to the arm and a catheter fit, usually through the radial artery, into a central arterial location; 2) electrocardiogram using a Marriott modified chest lead system; 3) venous pressure, measured using a Statham P23V attached through a central venous line. The third line is also used intermittenly for dye dilution curves. (It is presently being used extensively for this purpose.)

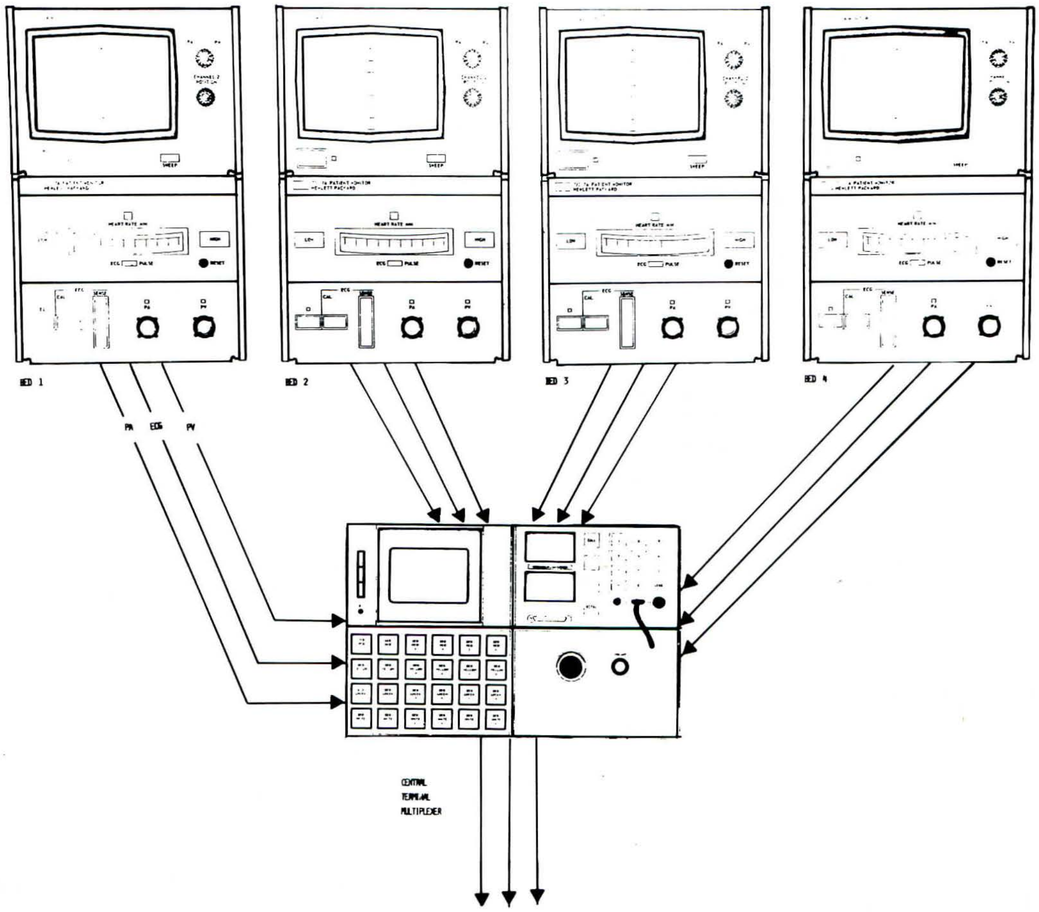
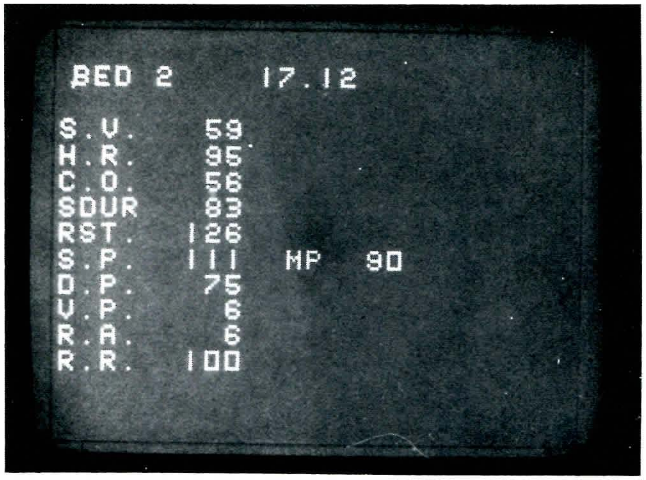


Fig. 3. Central Multiplexer Block Diagram.



```
BED 2      17.12
S.V.    59
H.R.    95
C.O.    56
SDUR    83
RST.   126
S.P.   111    MP   90
D.P.    75
V.P.     6
R.A.     6
R.R.   100
```

Fig. 4. Results of a "Measure Once".

A major problem with this or any computerized system is to assure signal quality at the transducer or patient attachment. In order to assure this quality, the following steps have been taken: 1) The information is displayed at the bedside unit for a quality check at the time catheters and transducers are applied to the patient. 2) A continuous flush system has been developed for flushing the central arterial line and determining signal quality at the bedside. 3) High quality stable pressure amplifiers in the bedside units are used to minimize electrical artefacts, such as drift and electrical noise. 4) A switching scheme has been developed for monitoring central venous pressure which allows one central venous line to be used for both IV infusion and measurement of central venous pressure.

COMPUTER PROCESSING

The central computer provides the following signal processing and data processing functions.

A. The pressure pulse method developed by Warner and others is used to measure stroke volume from central arterial pulse contour. It allows the measurement, from computer pattern recognition and computation, of the following average variables for 16 heart beats: 1) Stroke volume; 2) heart rate; 3) cardiac output; 4) duration of systole as a percentage of the normal duration for that heart rate; 5) peripheral vascular resistance; 6) systolic pressure in mmHg; 7) diastolic pressure mmHg; 8) mean systemic pressure mmHg. Other programs are being developed to obtain other parameters relating to the wave shape.

B. Venous Pressure: The venous pressure signal is sampled by the computer at the same time arterial pressure is taken. Cardiac variations in the venous pressure are eliminated using timing information from the arterial pulse wave. The following three parameters are then derived from the venous pressure: 1) Mean central venous pressure in cm of water; 2) respiratory rate in breaths/min. (Since data is collected over 16 heartbeats, this is usually a measurement based on two to three respiratory cycles); 3) respiratory amplitude in mmHg, which is a measure of change of intrathoracic pressure with each breath. Figure 4 shows a scope display of data derivable from the arterial and venous pressure signals.

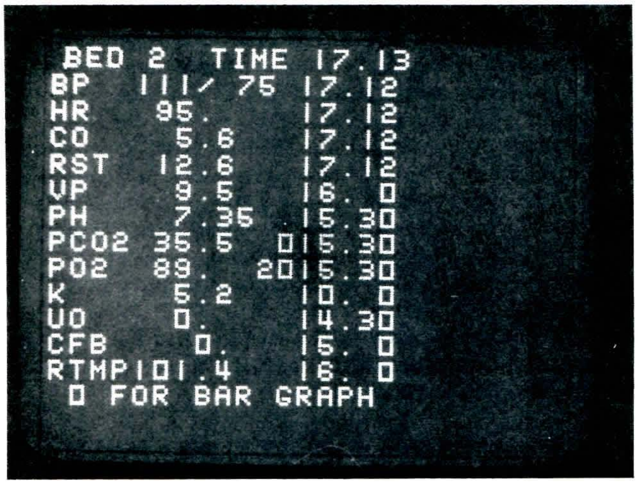
C. ECG Signal: ECG signals have been used for a variety of things in development of the program. Our most recent utilization has been in determining changes in rhythm between ordinary 15-second sampling intervals. The signal is also used to drive a bedside rate alarm as a continuous alarm system.

D. Dye dilution curves are easily run utilizing the system by using the capabilities of the catheterization laboratory dye dilution programs from any of the intensive care beds.

E. Blood gas information is entered either semiautomatically or manually from a terminal in the pulmonary function laboratory and is automatically entered into the unified patient file by patient number. If alarm conditions exist, a warning light will indicate in the appropriate ICU bed.

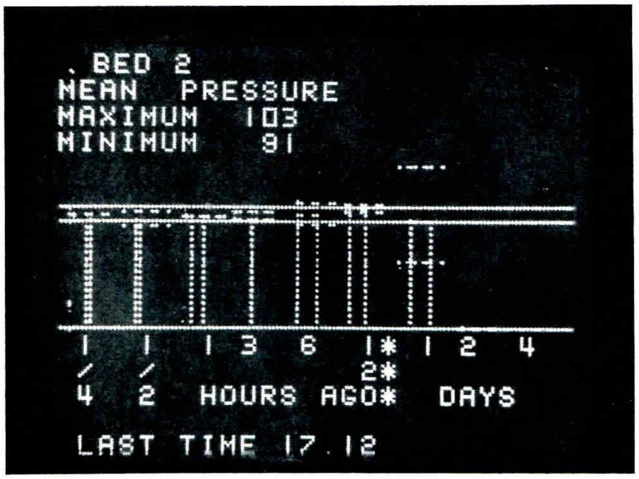
F. Comment Entry: Entry of a variety of comments for keeping a nearly complete medical record on the patient is available through entry of a four-digit comment code at the central console. Primary entries are entry of IV fluid intake and outputs as well as drugs and laboratory information, temperatures, and other parameters which are not automatically entered into the system. A variety of displays and information are available. The most frequently utilized ones are the "measure once" option shown in Figure 4; the "last measurement" option as shown in Figure 5; the bar graph display which shows long-term signal trends as shown in Figure 6. Multiple other review options are also available; e.g., Figure 7 shows a display of the last nine heart rate readings along with their time-of-measurement.

G. To summarize information for eight-hour shifts, a shift report as shown in Figure 8, is generated.



```
BED 2  TIME 17.13
BP   111/ 75 17.12
HR    95.    17.12
CO     5.6   17.12
RST   12.6   17.12
VP     9.5   16. 0
PH     7.35 .15.30
PCO2 35.5   015.30
PO2  89.   2015.30
K      5.2   10. 0
UO     0.    14.30
CFB     0.   15. 0
RTMP101.4    16. 0
 0 FOR BAR GRAPH
```

Fig. 5. Review of Latest Information.



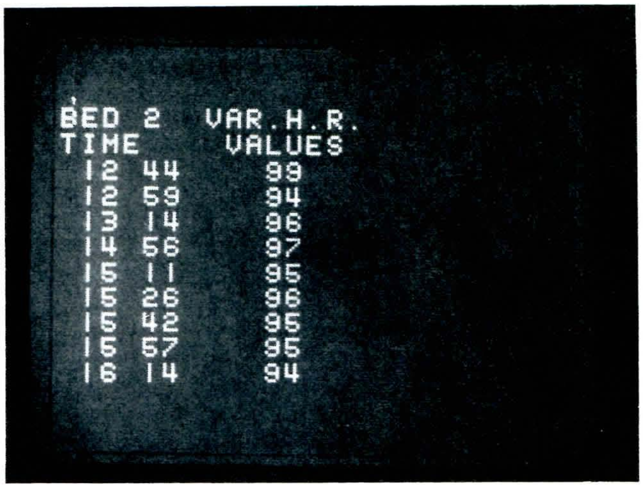
```
. BED 2
MEAN  PRESSURE
MAXIMUM  103
MINIMUM   91
```

```
 LAST TIME 17.12
```

Fig. 6. Bar Graph Display of Mean Arterial Pressure.

SYSTEM UTILIZATION

Figure 1 shows the hospital and type of ICU in which each of the 43 intensive care beds are located. The utilization of the patient monitoring system is rather diversified among the post vascular surgery, coronary care general surgery, and infant monitoring. However, basically the same measurements are made on all patients since they are all in critical condition,and cardiovascular monitoring is very important in any of these classes of patients. The system is oriented around a physician-technician-nurse team to provide therapy and care for these critically ill patients.



```
BED 2   VAR.H.R.
TIME     VALUES
 12 44     99
 12 59     94
 13 14     96
 14 56     97
 15 11     95
 15 26     96
 15 42     95
 15 57     95
 16 14     94
```

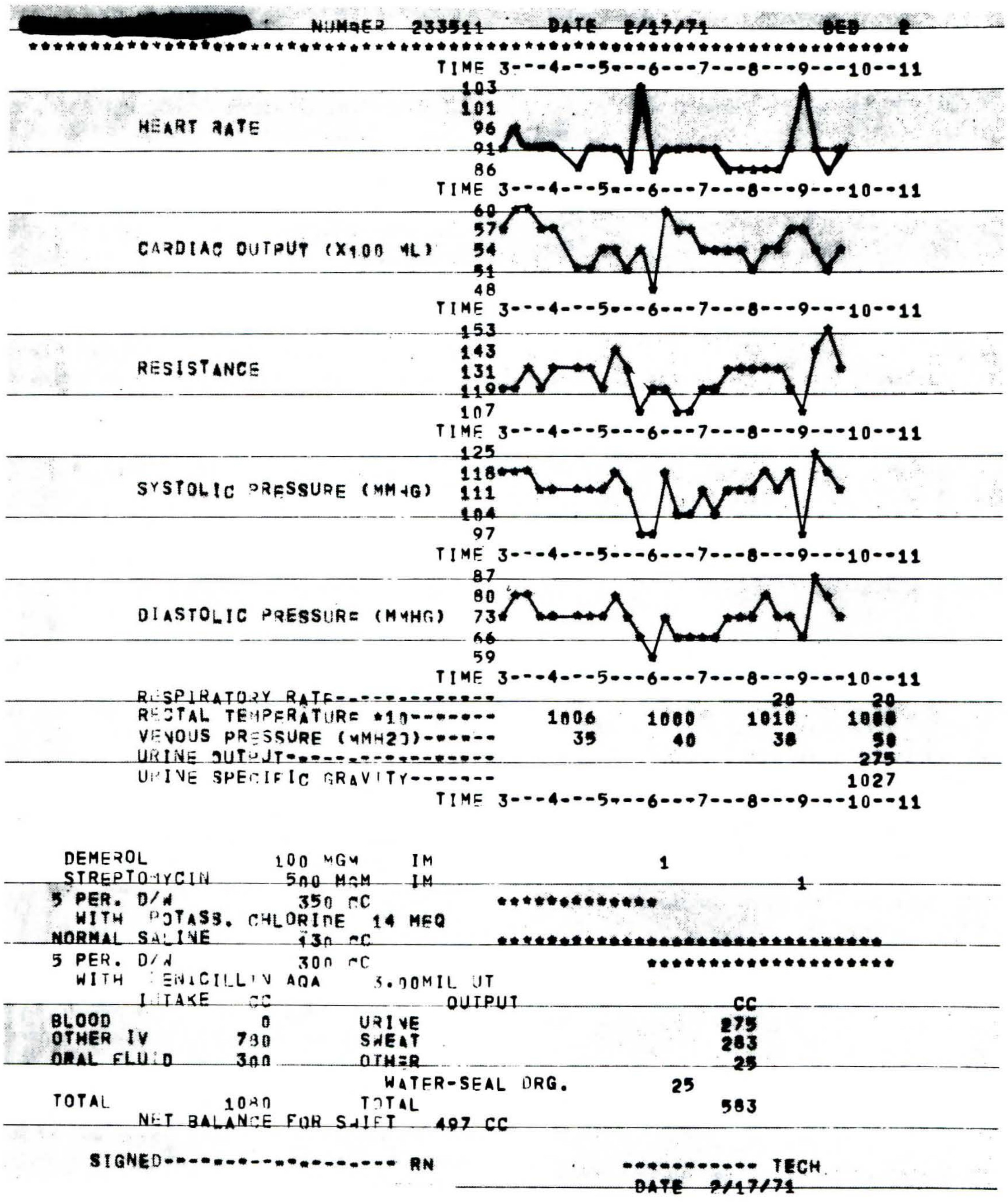
Fig. 7. Review Option Showing Last 9 Heart Readings.

In order to implement the system on a 24-hour-a-day basis, it has been necessary to employ technicians to interface between computer operation and the nurse and staff operation in the units. These technicians perform a variety of functions, such as assuring signal quality, watching for arrythmias, generation of reports, entry of nonautomatic physiologic data,as well as helping the nurse in a variety of situations, such as moving or weighing patients. These technicians, who are typically college students with an interest in medicine, have proved to be a valuable part of the operating system and are well accepted by both the nurses and physicians.

Nurses provide the care in most of these units since physicians are in the units for such a short time during the day. Therefore, nurses must make clinical decisions and get approval from the physician in order to implement various types of therapy.

The system has evolved from a research oriented operation to a clinically oriented operation, as evidenced by the LDS Hospital utilization over the past five months shown in Table 1. There are several research projects still going on, and as new and better instrumentation and physiologic measures become available, they will be incorporated.

A unique feature of the system is that it is capable of monitoring patients in surgery and providing continuity of data after the transfer of the patient from surgery to the ICU. Presently,the system is in operation in three surgical suites, as shown in Figure 1.



```
[redacted]  NUMBER  233511      DATE  2/17/71                  BED   2
*********************************************************************
                                 TIME 3---4---5---6---7---8---9---10--11
                                  103
                                  101
            HEART RATE             96
                                   91
                                   86
                                 TIME 3---4---5---6---7---8---9---10--11
                                   60
                                   57
            CARDIAC OUTPUT (X100 ML)  54
                                   51
                                   48
                                 TIME 3---4---5---6---7---8---9---10--11
                                  153
                                  143
            RESISTANCE            131
                                  119
                                  107
                                 TIME 3---4---5---6---7---8---9---10--11
                                  125
                                  118
            SYSTOLIC PRESSURE (MMHG)  111
                                  104
                                   97
                                 TIME 3---4---5---6---7---8---9---10--11
                                   87
                                   80
            DIASTOLIC PRESSURE (MMHG)  73
                                   66
                                   59
                                 TIME 3---4---5---6---7---8---9---10--11
            RESPIRATORY RATE-------------                    20      20
            RECTAL TEMPERATURE *10--------   1006    1000    1010    1000
            VENOUS PRESSURE (MMH2O)-------     35      40      38      50
            URINE OUTPUT-----------------                            275
            URINE SPECIFIC GRAVITY--------                          1027
                                 TIME 3---4---5---6---7---8---9---10--11

      DEMEROL            100 MGM     IM                 1
      STREPTOMYCIN       500 MGM     IM                              1
     5 PER. D/W           350 CC          **************
       WITH  POTASS. CHLORIDE  14 MEQ
     NORMAL SALINE        130 CC          *********************************
     5 PER. D/W           300 CC                   *********************
       WITH  PENICILLIN AQA    3.00MIL UT
            INTAKE      CC                OUTPUT                  CC
     BLOOD               0       URINE                           275
     OTHER IV          780       SWEAT                           283
     ORAL FLUID        300       OTHER                            25
                                   WATER-SEAL DRG.       25
     TOTAL            1080       TOTAL                           583
            NET BALANCE FOR SHIFT   497 CC

        SIGNED------------------- RN                ----------- TECH
                                                    DATE  2/17/71
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Fig. 8. Shift Report for 8-hour Shift.

TABLE 1. Summary of Occupancy and Utilization of Computerized ICUs at LDS Hospital.

	GENERAL SURGERY				CORONARY CARE				POST VASCULAR SURGERY			
	6 Beds				4 Beds				10 Beds			
	Pts. with Catheters				Pts. with Catheters				Pts. with Catheters			
	Pts.	Pt. Days	Ave. Stay	Total Pt. Days	Pts.	Pt. Days	Ave. Stay	Total Pt. Days	Pts.	Pt. Days	Ave. Stay	Total Pt. Days
Sept.	19	127	6.6	117	13	36	2.7	98	32	96	3	141
Oct.	25	84	3.3	128	10	30	3	73	33	116	3.5	199
Nov.	8	46	5.7	104	17	43	2.5	90	19	81	4.2	171
Dec.	8	37	4.6	155	16	64	4	101	26	99	3.8	176
Jan.	10	72	7.2	132	9	36	4	104	23	77	3.3	195
TOTAL	70	366	5.2	636	65	209	3.3	466	133	479	3.6	882

	GENERAL SURGERY	CORONARY CARE	POST VASCULAR SURGERY	
Unit Occupancy %	71%	78%	59%	
Average Pts/Day	4.2	3.1	5.9	Average Total 7.1
Average Pts/Day with Catheters	2.5	1.4	3.2	
% Catheters in Unit	58%	45%	54%	

System complications have been few, but they are very annoying. The problems have been involved with the following: 1) System downtime as a result of disc memory problems; 2) computer downtime as a result of central processor breakdown; 3) system downtime as a result of air conditioning failure. Although each of these has been very small in relationship to total operating time, a system downtime at an inappropriate time makes data unavailable for the physician and nurse and is a very distressing condition. System reliability is relatively good, yet not perfect. In the past six months the system has been out of operation for about 70 hours for all causes; i.e., failures, preventive maintenance, equipment cleaning, etc.

Complications due to ECG lead placement, catheter placement and bedside equipment failure have been minimal but are nonetheless important to consider. Electrode placement is still a problem in all intensive care units as ECG electrodes are replaced at least every 24 hours on all patients and more frequently on other patients. Catheter placement problems have been minimal. More than 3,000 central arterial catheters have been placed in the last four years, and only minor complications have resulted. As a result of break in sterile technique, the insertion site has become infected in about 10 patients. One thrombectomy has had to be performed on a patient's arm following catheter insertion. However, indications in a follow-up autopsy of the patient showed that the clotting was not caused by the catheter but was caused by the surgical intervention, as indicated by general arterial and left ventricular clots. It was interesting to note in this case that the surgeon immediately had a catheter inserted in the other arm in order to follow his patient with the computerized monitoring scheme. Minor problems with catheter clotting, waveform damping, and other catheter problems have been kept to a minimum by using a continuous flush system. One problem which continues to plague us is bending of the arm at the elbow by about 10% of the patients, causing the arterial catheter to kink and the waveform to be damped. A simple arm restraint is the best current solution to this problem, and has worked out well in most cases. Until recently, central venous pressure measurement has been impractical since only one IV line is available. Implementing the following scheme has made it more practical. A computer controlled switch turns off the IV drip for a period of not more than 20 seconds (local hardware controlled). This switching eliminates pressure errors due to IV flow. By placing the transducer (Statham P23V) on the chest the usual error caused by change of patient position is minimized.

NURSE-PHYSICIAN-TECHNICIAN EVALUATION

Over the past few months a concerted effort has been made to evaluate nurses', technicians' and physicians' response to the system. This system is unique in that we are involved with multiple intensive care units with multiple types of critically ill patients, yet all are monitored by the same measurement techniques. At the Latter-day Saints Hospital there are 40 physicians who, in the past five months, have admitted patients to these units, with ten physicians accounting for about 75% of the patients. There are 60 intensive care nurses and 15 computer technicians who work with the patient monitoring system. The problem of training and alerting all concerned has been a major task. Recent training sessions with the nurses and technicians have proved to be most valuable as evidenced by an increased utilization of available information.

Training and utilization of the system by the outlying hospitals has been a continuing process. We are still deeply involved as new physicians and nursing personnel are employed at these hospitals. The training of and utilization by personnel who are not actively and regularly involved in computer monitored units has been a major problem and will continue to be a challenge. Despite the capabilities of this system, if the people who are using it do not understand its capability and don't know how to use the information which it makes available, the system will be useless. Therefore, major emphasis, at present, is to train physicians, nurses and technicians in these facilities to better utilize the information that the system can presently make available to them.

A recent survey of the 40 physicians and a patient by patient survey of the technicians and nurses in the intensive care units has shown the following: 1) For all those patients monitored with catheters and ECG leads, the system is used, without exception, as a measure of vital signs. Occasionally a cuff pressure will be taken just to assure the nurses there are no mechanical problems, but the system reliability is such that the nurses use the system almost entirely for measurement of rate, blood pressures, and other vital signs. 2) The system and its alarming capabilities are utilized in almost every patient to indicate changes in therapy or to warn of an impending crisis. Utilization of computer alarms to effect therapy is one of the most significant outgrowths of the system. The alarms have been derived from a variety of parameters and have resulted in therapy, such as cardioversion, drug administration, fluid infusion, blood transfusion, and surgical intervention. For the 47 patients studied, an average of two life-threatening alarms were generated; that is, alarms that were judged by the nurses and computer technicians to have been lifesaving. This average of two per patient considers only that during an 8-hour shift one or more such alarms occurred. There are cases during some of the shifts when multiple alarms occurred but are documented as only one alarm. Therefore, actual alarms per patient stay may have averaged as many as four. Criteria for alarms are as follows:

A. Stroke volume, heart rate and mean arterial pressure are used for hemodynamic alarms.

B. The bar graph routine shown in Figure 5 is used for two types of alarms, one showing a drastic change and the other showing a trend. The criterion for the drastic change alarm is a percentage change of greater than 20% in the last measurement as compared to the average value over the last hour. For the trend change, if a 10% change has occurred within the last half hour, and this change is in the same direction as the change within the last hour, then a trend alarm is indicated.

C. Alarms are also used for blood gases if the pH is out of the range 7.35 to 7.45, or if the pCO_2 is out of the range of 30 to 50 mmHg. The pO_2 is a more complex scheme indicating hypoxia and oxygen poisoning with various time factors.

There are documented cases where the computerized alarm system, without doubt, alerted personnel to difficulties that would not have been detected by currently used nursing and physician observation, and have, in these cases, saved lives. Another outstanding use of the system has been in the titration of various drugs to control blood pressure, heart rate, cardiac output, and arrythmias, as a result of changes noted from the computerized system. Control of these patients has been simplified by observing the hemodynamic effects of drug injections and blood and IV solution infusions.

MONITORING COST AND COST JUSTIFICATION

A good way to evaluate any clinical system is to look at its cost effectiveness. The cost part of this evaluation is rather easy but the effectiveness is considerably harder to quantify. For the present, for our system, physician acceptance is assumed to be directly related to effectiveness. A recent cost study of our system has shown that computerized intensive care costs are very large, as indicated by the plot of Figure 9. Information in this figure was taken more than a year ago. As a result of the data shown, sampling intervals were extended from every two minutes to every 15 minutes, and system software changes made to improve the efficiency of computer processing. The cost data shown in Figure 9 is based on central processor utilization, and since the intensive care unit is one of the largest total users of computer time, this is one of the most expensive. For example, an average of 1800 seconds of central processor time are used for each patient day in the intensive care unit, whereas only 34 seconds are used for a complete multiphasic screening which includes automated electrocardiogram, pulmonary function, patient history, and blood chemistry. Note from Figure 9 that the costs of intensive care monitoring are most dramatically affected by central processor utilization. During the past year central processor utilization ran at an average of about 16 or 17%. Based on this utilization and an 8 year amortization of computer and peripheral equipment, it is estimated that it costs $74 per patient day for computerized monitoring. Based on these calculations, beginning April 1 of this year a charge of $18 per patient day will be made for computerized monitoring. This $18 a day represents 25% of the total possible cost based on last year's utilization. The expansion of the system is being made to increase utilization, and this increased utilization will have a dramatic effect on costs. Already the computerized capability has been evaluated by most of the participating hospitals and they are willing to pay the charge for computerized service. Future evaluation after the charges have been implemented will provide excellent indications of the value of computerized monitoring. Indexes such as mortality and morbidity, length of stay, and others, are good indicators of the value of the system but are also influenced by so many other factors that it would be impossible to verify which factor was the most important. Therefore, we feel the medical-clinical judgment of physicians in establishing charges for services is the best index of effectiveness.

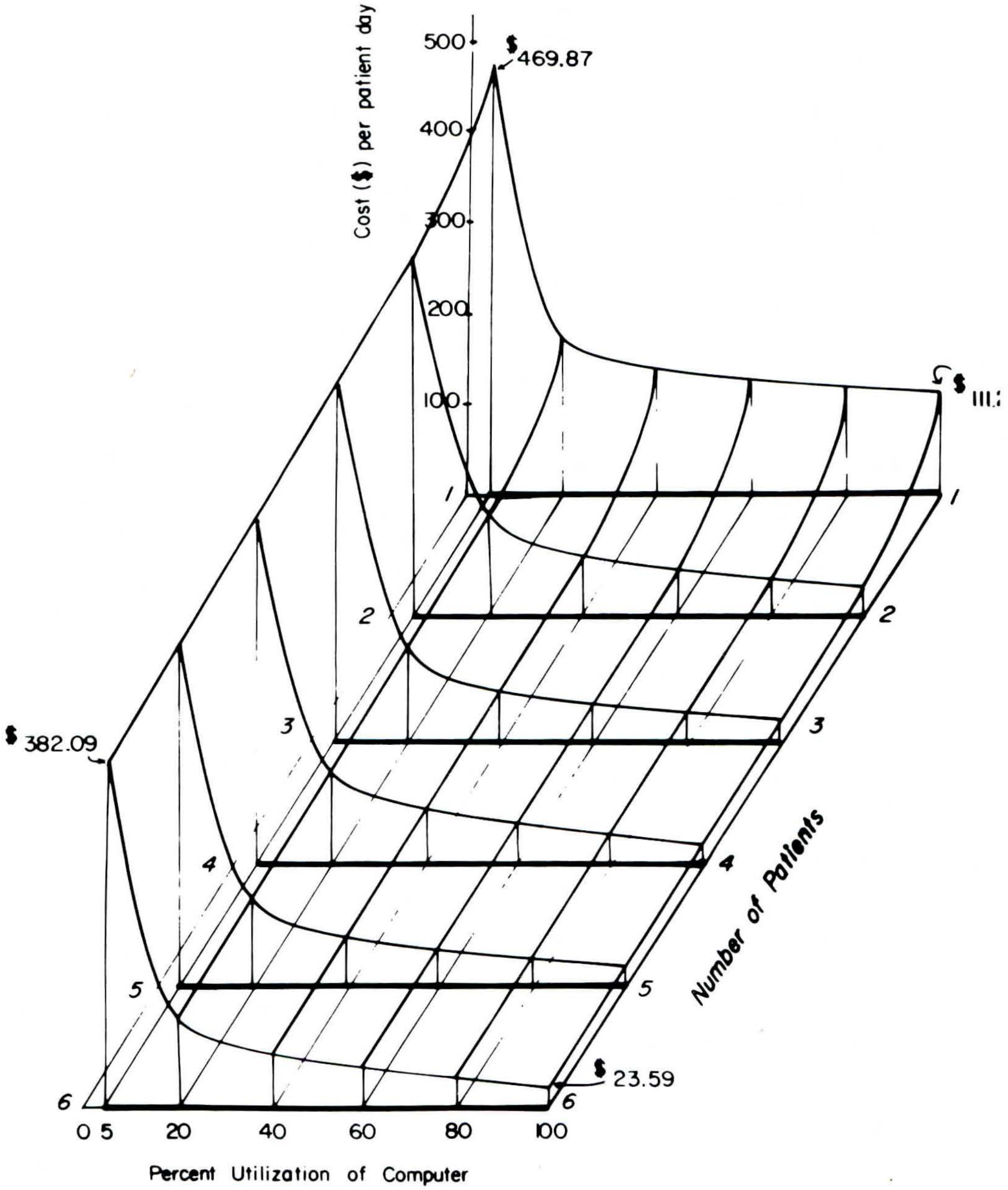

Fig. 9. Cost Data for ICU Showing Effect of Computer Utilization and Unit Utilization.

NEW AREAS OF RESEARCH

A. Computer automated blood analysis system (CABAS) described by Dr. Clark in an earlier paper, is one that is very exciting, especially in the case of the post vascular surgery patient and the newborn infant, as described by Dr. Clark. It is our hope that we will be able to implement this scheme in several of our intensive care environments.

B. Medical Mass Spectrometer: For the past four months we have been using a medical mass spectrometer developed by the Perkin-Elmer Company for breath-by-breath analysis of respiratory gases, CO_2, O_2, N_2 and water, and have found some very interesting information and will further utilize this instrument to monitor patients, especially those on respirators.

C. Statham Spirotach, as described by Jackovich and Eberhart in another paper presented at this symposium, will be used in conjunction with the medical mass spectrometer to further evaluate the respiratory status of critically ill patients. The mass spectrometer and spirotach will be set up to monitor respiratory physiology in much the same manner as the group has done at Pacific Medical Center in San Francisco.

D. Feedback schemes will be further explored to enable us to control blood, fluid, and drug infusions in a variety of patients. Expansion to other measurement techniques for measuring urine output and other physiologic parameters will greatly assist in management of these critically ill patients.

E. More sophisticated alarms based on multiple parameters derived from automated measurements and manually entered clinical findings will be used. Drs. Warner and Rutherford are presently working on this scheme for a coronary care unit and preliminary results are encouraging.

CONCLUSION

Experience with over 3,000 patients in a variety of intensive care units has shown us the value of computerized monitoring. Further cost benefit studies and evaluations will be made to assure high quality cost effective care in these units. Present evaluation evidence shows that the units are detecting and correcting several life-threatening conditions in a way that would be difficult, if not impossible, without the computerized system.

The computer system is presently an integral part of the patient care system at the Latter-day Saints Hospital and will play an ever larger role in the care of critically ill patients.

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