A MICRO-COMPUTER BASED SYSTEM FOR THE MANAGEMENT OF THE CRITICALLY ILL

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SUMMARY

A central station based system is described which employs a micro-computer for continuous monitoring of hemodynamic parameters for multiple patients. Monitored vital signs are displayed on a "WARD STATUS" video monitor and processed for long-term trend storage and retrieval. Alarm events and changes in module settings at the bedside are immediately reflected on the WARD STATUS display. Medication administration can be indicated and presented together with the graphical trends of any monitored parameter. Optional features of the system include on-line determination of Cardiac Output, Pulmonary Wedge Pressure Measurements, Arrhythmia and Respiratory Monitoring. An alphanumeric terminal connected to the micro-computer facilitates "background" programming in high level languages. This facility can be used to provide tailored patient data management capability to the medical staff or can be used as a tool for in-house development of special purpose application programs. The system is currently implemented on a Digital Equipment Corporation LSI-11 with 28K memory and dual floppy disks.

SYSTEM CONFIGURATION

The NC-848 is a central station based system which employs a Digital Equipment Corporation LSI-11 micro-computer for the continuous monitoring of hemodynamic parameters for multiple patients. Adding additional LSI-11 preprocessors facilitates expansion of the system to include full arrhythmia monitoring and respiratory monitoring capability.

SYSTEM DESIGN GOALS

The NC-848 is a central station based system which employs a Digital Equipment Corporation LSI-11 micro-computer for the continuous monitoring of hemodynamic parameters for multiple patients. Adding additional LSI-11 preprocessors facilitates expansion of the system to include full arrhythmia monitoring and respiratory monitoring capability.

INTRODUCTION

The role of managing the critically ill patient in a typical intensive care unit has become a more and more demanding one for the medical staff in recent years. Advances in technology has provided state-of-the-art instrumentation which offers more information on patient status than has ever been available before. Data derived from physiologic monitoring systems, clinical labs, as well as from direct observation of the patient must all be correlated in order to effectively manage the critically ill patient. The amount of data acquired can certainly be overwhelming and it is for this reason that computers have played an ever increasing role in critical care medicine.

In the late 60's, early 70's extensive research and development was performed in the area of computer application to on-line patient monitoring. 12,3 Most of this work, however, was performed in large research or university-affiliated hospitals. Within the last five years several commercial systems became available for the on-line monitoring of hemodynamic and/or arrhythmia related parameters. 4,5 These systems, employing mini-computers, were often too expensive for purchase by the smaller community hospitals.

With the advances in micro-computer and microprocessor technology in recent years, significant progress in design and development of low-cost computer-based monitoring systems has been made. In many instances, distributed micro-processors, each performing a specific task and communicating between one another, are replacing the more expensive single-processor mini-computer system of yesterday. Availability of sophisticated software for the micros has significantly enhanced the level of performance and application of such systems in the clinical environment.

It is the intent of this paper to present the Mennen Greatbatch NC-848 central station based system for the monitoring and management of the critically ill.

1. To develop a cost-effective, clinically viable system for monitoring a minimum of 8 beds from a central nurse station.
2. To provide industry standard serial communication from standard bedside monitors to the computer systems.
3. To assure reliability of all system components (hardware and software) as well as modularity in order to provide for future system expansion.
4. To assure simplicity of operation and ease of learning.
5. To assure simplicity of installation and maintenance.

REFERENCES

They are:

1. Patient bedside monitor with serial ASCII interface.
2. Central nurse station with non-fade displays, video monitors and chart recorders.
3. LSI-11 micro-computers.

Each standard patient bedside monitor can be equipped with a serial ASCII interface option. This option facilitates transmission of all monitored and calculated physiological parameters to a remote central station or host computer. The serial transmission of the data follows a simple message block format whereby each message consists of a START OF MESSAGE (SOM) block, a DATA block and an END OF MESSAGE block. The SOM block is formatted to include alarm status information and bedside configuration information. The DATA block is assembled to include numeric values, module status information (standby, lead fault, etc.) as well as identification of the module type. Lastly, a standard EOM block (using ETX and EOT characters) is generated.

Transmission of this asynchronous serial ASCII sequence (2400, 4800 or 9600 baud) of the SOM, DATA and EOM blocks is initiated by the nurse station processor transmitting an ASCII character command "ENQ". With the bedside monitor responding by transmitting the complete data stream, the computer data acquisition rate is thus established under software control.

This type of digital transmission of data from the bedside has offered much greater flexibility of system design and implementation over standard analog interfacing methods. Many different kinds, and certainly greater amounts of data are transmitted over a single twisted pair of wires. In addition, by adopting an industry standard code for data transmission, communication to any manufacturer's computer system can be effected with the same ease as an alphanumeric terminal. Such a capability has been proven quite valuable in hospitals where in-house research and application program development is pursued.

a) START OF MESSAGE BLOCK

"SOH" STATUS STATUS STATUS SPARE "STX"

b) DATA BLOCK

"DLE" STATUS STATUS DIGIT DIGIT DIGIT

c) END OF MESSAGE BLOCK

"ETX" SPARE SPARE SPARE SPARE "EOT"

Fig. 1 a) START OF MESSAGE BLOCK identifies type of bedside, assigned ID number, gross alarm activity and bedside status indicators. b) DATA BLOCK is transmitted for each parameter in bedside identifying parameter type, alarm and module status as well as 3 digit current value. c) END OF MESSAGE BLOCK terminates the transmission.

A central nurse station for monitoring 8 patients would typically include: Eight channels of non-fading display for presentation of each patient's ECG waveform, a single-channel chart recorder with full alphanumeric printing capability for documenting alarm events, a general WARD STATUS video display for presentation of all patients current vital signs, an interactive video display for entering and recalling data, and a system keyboard. Within the nurse station resides all the interface equipment required to communicate to the bedside monitors as well as the LSI-11 processors. The processors themselves may or may not be built into the nurse station depending upon space limitations and specific configuration. (Fig. 2)

Fig. 2 A typical central nurse station with 8 channel non-fade display, chart recorders and controllers, WARD STATUS and interactive displays plus system keyboard.

NC-848 SYSTEM BLOCK DIAGRAM

Fig. 3 Block diagram of NC-848 system.
The nurse station processor consists of an LSI-11 with 28K words of random access memory and a multiple channel serial interface device. Peripherals attached to the processor include a disk storage device (typically floppy disks) and an alphanumeric terminal for data management purposes. A real-time operating system RT-11, is used which supports foreground/background programming. (Fig. 3)

SYSTEM FUNCTIONS

The host processor in the central nurse station is responsible for the acquisition, processing, display and control of all information brought to the central station. Specifically, its task includes:

1. Acquisition of each patient's current status by periodically polling each bedside monitor in order to initiate data transmission.
2. Display of current vital signs and alarm status onto the general WARD STATUS display.
3. Long-term storage of all monitored parameters and special events for recall by the user for presentation on the interactive display.
4. Control of the system keyboard and optional data management terminal.
5. Control of the nurse station chart recorder for documenting detected alarm events.

The user at the nurse station requests various system functions by interacting with a special system keyboard. The system keyboard is designed to make user interaction simple, with keys clearly labeled, grouped according to function and distinguished by color and shape.

A description of SYSTEM FUNCTIONS follows:

 Ward Status

The dedicated WARD STATUS display presents an up-to-the-second overview of all patients connected to the system. Data, as derived at and transmitted from each bedside monitor, is processed by the host processor, formatted, and continuously updated on the video display. The displayed parameters include Heart Rate, Arterial Pressure (SYS/DIA), Central Venous Pressure (MEAN), Respiration Rate and Temperature. Alarm conditions detected by the system are brought to the immediate attention of the medical staff by high-lighted boxes enclosing the data. In addition, various conditions such as "module in standby" or "electrode lead fault" are also indicated on the WARD STATUS display. (Fig. 4)

 Vital Signs Display

Data presented on the upper portion of the interactive display refers only to that patient selected by the user via the system keyboard. Patient bed number, identification number, date and time, as well as continuous display of vital signs and alarm information are always presented on the display. (Fig. 5)

Vital Signs Trending

NC-848 provides a unique facility for long-term high resolution trending of each patient's monitored parameters. All data acquired by the host processor is stored in memory and on disk for a total of 72 continuous hours. As a result, the user, via simple keyboard commands, may select any one or combination of two continuously monitored parameters for presentation in graphical form. With 72 hours of data stored, any segment of this period in multiples of 1 hour from 1 to 24 hours may be selected for presentation on the lower two-thirds of the interactive display. Pressure trends are always shown with plots of systolic, diastolic, and mean pressure plotted on the same grid. The amplitude scales of each plot are dynamically adjusted to assure plotting of each data point within the time period specified. Being able to flexibly recall a trend of heart rate and arterial pressure, over any period of time within the last 72 hours, for example, enables the medical staff to observe correlations between changes in heart rate versus pressure changes and the effects of drug therapy. (Fig. 6)

Logging Special Events

The MARK function enables the user to record the administration of drugs or treatment to a specific patient. By a simple keyboard dialog, the user specifies which out of a list of 8 drugs and/or treatments were given and the time of administration. This information is logged together with trend data in the patient's file residing on disk and may be viewed in graphical form with the trends of any parameter, or by itself. If both MARK and a trend plot are requested, a comparison of treatment with the parameter trends provides an easy method for evaluating treatments at a glance. (Fig. 7)

On-Line Cardiac Output Measurements

As part of the Special Procedures Option, Cardiac Output Measurements can be performed with the NC-848 system. The Thermodilution method may be used with the Mennen Greatbatch Cardiac Output module. Catheter characteristics, temperature and volume of injectate as well as the patient's temperature and heart rate are entered manually via the keyboard. A calibration step followed by the actual thermodilution curve is presented on the video screen. Calculated values of Cardiac Output (CO), Cardiac Index (CI), Stroke Volume (SV) and Stroke Index (SI) are displayed. The system accommodates repeated trials for cardiac output determination based upon user acceptance of the results. The last determined Cardiac Output value is presented in the vital signs display together with the time of measurement. The system also supports Cardiac Output measurement using the FICK method or by direct entry. (Fig. 8)

On-Line Pulmonary Wedge Pressure Measurement

Also part of the Special Procedures Option to the NC-848 system is a function for measuring Pulmonary
Fig. 4 NC-848 WARD STATUS display showing current values of all monitored parameters and active alarms.

Fig. 5 The vital signs portion of the interactive display presents current vital signs and alarm activity for the selected bed.

Fig. 6 Long-term high resolution trends for up to two monitored parameters may be presented on the lower portion of the interactive display.

Fig. 7 Display of drug administration together with trends of a selected parameter provides an easy method for evaluating treatments at a glance.

Wedge Pressures. The system displays various messages to assist the clinician through the catheter placement, measurement and catheter repositioning steps required in a Wedge Pressure determination. The actual wedge pressure waveform is presented on the video display for viewing throughout measurement stages. Results of the measurement are accepted or rejected by the clinician via the keyboard. The last accepted Wedge Pressure value is presented in the Vital Signs display together with the time of measurement. (Fig. 9)

Alarm Event Documentation

The host processor examines each transmission from every bedside to determine if any alarm conditions exist. If it finds an alarm active, it activates the nurse station chart recorder and records that patient's ECG waveform. Using the alphanumeric printing capability of the chart recorder, the processor documents each strip with patient bed and ID numbers, date, time, and current monitored vital signs. In addition, the data field of the
Fig. 8 Measuring Cardiac output on-line by the Thermodilution method. Cardiac Index (CI), Stroke Volume (SV) and Stroke Index (SI) are derived.

Background Data Management

The LSI-11 host processor runs under DEC’s RT-11 real-time foreground/background operating system. Time critical tasks such as data acquisition, display updating, alarm detection, etc. are run as “foreground” tasks and have first priority to get the processor's resources. When the processor is not busy, the "background" requests are acknowledged. In the case of NC-848, the background can be either clinical packages written in high-level languages such as BASIC or FORTRAN or may be special user-written application programs.

The background of NC-848 provides approximately 12K words for data management programs. A library of programs are available with the system which facilitates such functions as laboratory data logging and retrieval, fluid intake and output management, cardiovascular calculatory packages, etc. In some instances, the background capability is used for purposes totally unrelated to the management of patients in the unit. An example is an installation at which a resident bio-engineer programmed the system to maintain inventory control of their extensive module library and keep track of maintenance calls on the bedside equipment. In this case, the alphanumeric terminal was remotely located in his lab and not at the central nurse station. If the hospital has staff capable of programming in a simple language like BASIC, the possibilities for using the background facility are endless.

However, a typical example of the clinical use of such a facility is the LAB DATA LOGGING package used at Naval Regional Hospital, Portsmouth, Virginia. By way of interaction with an alphanumeric video terminal located at the nurse station, the staff may register patients, discharge patients, display a patient directory, enter lab data and review lab data. Lab data in the categories Hematology/Coagulants, SMA-6/Urines, SMA-12 and Respiratory are entered into the system several times a day by a ward clerk. At the end of the day, a report is generated for all patients and put in the patient's file with the other records for review by the medical staff during rounds. Such a package, written in BASIC, is structured in a modular, table-drive fashion to accommodate tailoring to the specific needs of each user. (Figs. 10, 11)

Arrhythmia Monitoring Option

A hardware/software option to the NC-848 system is the addition of in-depth arrhythmia monitoring for all patients. Taking advantage of almost 10 years experience in the development and enhancement of the ARGUS computer-supported arrhythmia monitoring system for Coronary Care, the ECG analysis algorithms portion of that system was extracted and implemented on an LSI-11 processor, with 28K words of memory, a 64 channel analog-to-digital converter and a serial interface. 67,8

This Arrhythmia Preprocessor (AP) examines each patient's electrocardiogram continuously, classifying every beat as to type and detects the presence of arrhythmia-related alarm events. By way of the serial interface linking the AP to the

parameter in alarm for the given patient is highlighted on the WARD STATUS display and remains that way until the value falls within the bedside-set limit or until the alarm is reset.
** PORTSMOUTH NAVAL REGIONAL MEDICAL CENTER PORTSMOUTH, VIRGINIA INTENSIVE CARE UNIT **

SELECT ONE:
1. REGISTER PATIENT
2. DISCHARGE PATIENT
3. PATIENT DIRECTORY
4. ENTER LAB DATA
5. REVIEW LAB DATA

CHOICE: 74

** ENTER LAB DATA **

ENTER BED #: 72
ENTER DATE(MM-DD-YY): 17-FEB-78
ENTER TIME(HH:MM): 12:00

17-FEB-78 12:00
BED: 3 PATIENT: THOMAS, E. ID NO: 67499 SSN: 543-07-3856

OK (Y/N): Y

SELECT ONE:
1. HEMATOLOGY-CONSUMABLES
2. SMH-6: URINE, AND OTHER CHEMISTRIES
3. SMH-12 BLOOD CHEMISTRY
4. RESPIRATORY DATA

CHOICE: 72

** RESPIRATORY DATA **

14-FEB-78 23:39 24:08 24:32

** DISPLAY NEXT 5 RECORDS? (Y/N): Y **

DO YOU WANT TO VIEW ANOTHER CATEGORY? (Y/N): N

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(host processor, the AP sends such information as the number of PVC's per minute, occurrence of bigeminal rhythm, ventricular tachycardia, asystole, etc. This information is processed further by the host processor for display at the central station. Alarm information is also conveyed to the host which can then activate the nurse station chart recorder to document the event.

The analysis algorithm is based on the original work performed at the Biomedical Computer Laboratory of Washington University, St. Louis, Missouri. The algorithm comprises three discrete modules which function as cascaded processors. Each processor works on the output set of the previous processors, with the exception of the first processor which samples the analogue ECG at 250 samples per second. The first processor AZTEC, is primarily a data compression program which allows ARGUS to handle the large amounts of sampled ECG data, gathered as a result of monitoring several patients simultaneously. The processors PRIMITIVE and CYCLE determine the morphology of each beat, on a beat-to-beat basis, and classify them. The following is a brief description of each module:

Fig. 10 Lab data is logged using the background data management feature of the NC-848 system.

Fig. 11 Tabular trends of entered lab data can be generated for incorporation with other patient records.)
1. AZTEC samples the ECG signal every four milliseconds (i.e., 250 times per second) and converts the analogue value to digital code. With digitized data stored in a buffer, Aztec operates on this buffer and compresses the ECG data by transforming the ECG into a series of horizontal and sloping lines. Each horizontal segment of the ECG is described by two digital words, "amplitude" and "duration". Sloping segments are also described by two words, the "amplitude difference" between the two lines that border the slope, and the "duration" of the slope. (Fig. 12)

2. PRIMITIVE scans the Aztec data forward and backward to identify the outstanding portion of the ECG, the QRS complex. Having determined the boundaries of the QRS complex, Primitive goes on to measure its duration, height, area, and offset. This information is passed on to the Cycle processor and forms the basis for the morphological analysis of that beat. (Fig. 13)

3. CYCLE maintains "families" in its memory based upon QRS complexes with similar attributes of duration, height, offset, and area. Basically, this process can be seen to be one of four-dimensional clustering. The family descriptions are constantly updated so as to represent the true population of both normal and abnormal complexes.

Those QRS complexes which are not members of a normal family are classified as abnormal if their family characteristics are grossly different from the characteristics of all existing normal families and if their duration is greater than 80 milliseconds. By further analysis, abnormally shaped QRS complexes are called PVC's if they pass a rather weak prematurity test. The preceding QQ interval must be less than 15/16 of an appropriately selected average of the patient's normal QQ interval. QRS complexes which are found to be neither normal nor abnormal are labelled borderline. These complexes must pass more stringent tests for prematurity and width in order to be called PVC's. (Fig. 14)

Cycle determines normality and abnormality of each beat as a result of a self-learning process whereby it constantly compares each beat with the families of previous beats and makes decisions based upon contextual information it has stored about past as well as present events. No human intervention is required.

Periodically, the host processor polls the arrhythmia preprocessor and initiates a transmission of current arrhythmia-related parameters and alarm status information for each monitored bed. This data, also transmitted in standard serial ASCII format, is combined with data acquired from the bedside monitors, stored into the patient files on disk and trended.

Fig. 12 The data compressing transformations performed by the Aztec processor.

Fig. 13 Measurements performed by the Primitive processor.
FIG. 14 Schematic representation of the algorithm used by Argus for PVC detection. QRS complexes detected by the Primitive processor are classified into six categories according to the presence of artifact, their shape, width and prematurity.

Respiratory Monitoring Option

An additional hardware/software option to the NC-848 system is in-depth Respiratory monitoring for all patients. Such monitoring is divided into two categories: Respiratory mechanics and Respiratory gas monitoring. The analysis algorithms are implemented on an LSI-11 preprocessor, with 28K words of memory, a 64-channel analog-to-digital converter and a serial interface.

In deriving Respiratory mechanics data for an artificially ventilated patient, the Mennen Greatbatch system monitors respiratory flow during expiration only as extracted from the expiratory flow signal and is designed to function with any airway pressure and expiratory flow measuring equipment available. The algorithm consists of three major sections: Airway Pressure Analysis, Expiratory Flow Analysis and Derived Parameter Calculations.

The major work of the airway pressure phasic analysis program is to divide the airway pressure waveform into "airway pressure cycles" which correspond to individual breaths. For each cycle found, the following parameters are calculated:

1. Peak Pressure
2. End-Expiratory Pressure

In the same fashion, the expiratory flow phasic analysis program divides the expiratory flow waveform into units called "flow cycles" corresponding to individual breaths. The algorithm searches for a minimum and maximum flow point. Using this information, the algorithm derives:

1. Tidal Volume
2. True Maximum Expiratory Flow
3. Respiration Rate
4. Minute Volume

Once both analysis algorithms run to completion, the system then runs the Derived Parameter Calculations Program which calculates respiratory system compliance and expiratory resistance.

The Respiratory gas concentration monitoring is based on the analysis of two types of signals: Oxygen and Carbon Dioxide concentration in the patient's breathing during both inspiration and expiration. The Mennen Greatbatch system is designed to work with any O2 and CO2 gas concentration measuring equipment available.

Once again, the Respiratory Gas Concentration algorithms consist of three programs: O2 Concentration Analysis, CO2 Concentration Analysis and Derived Parameter Calculations.

The O2 Concentration Analysis program divides the O2 concentration waveform into units called "oxygen cycles" corresponding to individual breaths. After determining oxygen maximum and minimum points in a given cycle, the following parameters are calculated:

1. Inspired Oxygen Concentration
2. End-Expired Oxygen Concentration
3. Average Expiratory Oxygen Concentration

In a similar fashion, the CO2 concentration analysis algorithm identifies "CO2 cycles" and calculates the following parameters:

1. Inspired CO2 concentration
2. End-Expired CO2 concentration
3. Average Expiratory CO2 concentration

Once both algorithm run to completion, the derived parameter calculations algorithm runs and derives the following parameters:

1. Oxygen Minute Consumption
2. Carbon Dioxide Minute Consumption
3. Respiratory Quotient

All data derived from both the Respiratory mechanics and Respiratory gas monitoring programs is available for transmission in ASCII format to the Host processor via a serial link. The Host processor can then display and trend the remotely derived data.

CLINICAL APPLICATION

The NC-848 offers the medical staff in the ICU capability for closely monitoring the critically ill patient which exceeds that facilitated by conventional monitoring equipment. While it does not necessarily relieve the staff of their manual record keeping duties, it does provide relevant outputs which complement the patient record.

The ability to be able to view, in depth, the current status of each patient in the unit from one central location at the nurse station has been proven quite effective. The observer can determine not only current patient status by viewing the WARD STATUS display, but can also note whether the bedside monitor itself is set up properly without
having to "make rounds" of the instrumentation. In many cases, this feature has resulted in the more effective utilization of the bedside monitors (ie. Heart rate modules not left in the "STANDBY" mode for long periods of time.)

The interactive display adds yet another dimension to the management of the critically ill - that of being able to view past data acquired by the system, in graphical form. The high-resolution of the trends together with the unique feature of being able to "window" over the 72 hour period of stored data aids in detecting slow transient changes in any of the monitored parameters. This together with the ability to correlate drug administration with the trends provides a powerful tool to the medical staff. A hard copy device attached to the system allows the user to make exact reproductions of the interactive display onto 8½ x 11" paper.

In the Naval Regional Hospital at Portsmouth, for instance, complete set of trends for all monitored parameters for all patients in the Anesthesiology unit are made daily. This data, together with outputs from the LAB DATA LOGGER are attached to the patient record. A summary of two clinical cases, as shown by trends taken from the system, follows:

1. Case 1: An eight-hour trend plot of arterial and pulmonary artery pressure during the time period 15:00 to 23:00 was requested. At about 21:00 a rise in blood pressure is noted. This was a time of sudden hypertensive crises for this patient. Next, examination of the time period from 20:00 to 21:00 by requesting a one-hour plot of heart rate with arterial pressure and a plot of arterial with pulmonary artery pressure gives further information. One notes that in this hour, the heart rate went from 100 to 165, the arterial pressure went from 40/10 to 90/20. These were unexplained cardiovascular crises but may have been secondary to a pulmonary embolus. One can see from the eight-hour trend that therapy was initiated quickly to reduce the blood pressure and the problem lasted less than two hours. (Fig. 15)
2. **Case 2**: An eight-hour trend is shown of heart rate with arterial blood pressure and heart rate with pulmonary artery pressure for a patient in atrial fibrillation with a ventricular response rate of about 135 per minute. He spontaneously converted to a sinus rhythm with a heart rate varying from 105 to 115. Note that there was no change in blood pressure or pulmonary artery pressure after conversion. (Fig. 16)

At the Naval Hospital, the trending/MARK facility of NC-848 is routinely used not only for the clinical management of patients but for a teaching tool as well.

**CONCLUSION**

The NC-848 system as presented in this paper has indeed met our initial design goals. The system has presently reached a level of cost-effectiveness which does not restrict its usage in only large hospitals but has been successfully employed in the small community hospital as well. Technological advances by Digital Equipment Corporation in their LSI-11 processor product line has not only contributed significantly to the reduced cost but has also greatly impacted the reliability and maintainability of the system. Adoption of a serial ASCII communication protocol for transmission of data between bedside and processor, as well as between processors, has offered significant flexibility in system development and further system enhancement. Lastly, the design of a simple function keyboard for user-interaction at the control station resulted in greater system acceptability.

Though the system does not totally eliminate the need for manual record keeping in the ICU, we feel that it has contributed to better patient care by providing primary monitored patient data at a central location, consistently formatted and neatly presented, for review by the medical staff. Trending of monitored parameters over 72 hours as well as correlations with drug administration presents a more reliable picture of patient progress. Where employed, the background programming feature of the system allows the user to identify a specific data management need for his particular unit and develop a unique software package to run on the system to meet that need.

In conclusion, we have described a micro-computer based system for the management of the critically ill. By virtue of its modular design, both hardware and software, usage of serial ASCII communication between major elements, and application of distributed processing techniques to expand the system to include arrhythmia and respiratory monitoring, a clinically viable system is provided to meet the monitoring and management requirements of the typical intensive care units.

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**Fig. 16** a) Eight-hour plot of heart rate and pulmonary artery pressure for a patient in atrial fibrillation who spontaneously converted to a sinus rhythm. b) Eight-hour plot of heart rate and arterial pressure for same patient.
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