Chapter 19 – Shortliffe/Cimino 4th Edition Biomedical Informatics 26 Nov 11

Patient Monitoring Systems

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After reading this chapter, you should be able to answer these questions

1. What is patient monitoring, and why is it used?
2. What patient parameters do bedside physiological monitors provide?
3. What are the major problems with acquisition and presentation of monitoring parameters?
4. In addition to bedside physiological parameters, what other information is fundamental to the care of acutely ill patients?
5. How are patient care protocols used to enhance the care of critically ill patients?
6. Why is real-time computerized decision support potentially more beneficial than monthly or quarterly quality of care reporting?
7. What technical and social factors must be considered when implementing real-time data acquisition and decision support systems?

19.1 What is Patient Monitoring?

Continuous measurement of patient physiologic parameters such as heart rate, heart rhythm, arterial blood pressure, respiratory rate, and blood-oxygen saturation, have become common during the care of the critically ill patient. When accurate and prompt decision making is crucial for effective patient care, bedside monitors are used to collect, display and store physiological data. Increasingly, such data are collected by non-invasive sensors connected to patients in intensive care units (ICUs), new-born intensive care units (NICUs), operating rooms (ORs), labor and delivery (L&D) suites, emergency rooms (ERs), and other hospital care units where patient acuity is increased.

We often think of a patient monitor as something that watches for – and warns about – serious or life-threatening events in patients, and provides guidance for care of the critically ill. Such systems must include continuous observations of a patient's physiological measurements and the assessment of the function of attached life support equipment. Such monitoring is important in detecting life-threatening conditions and guiding management decision making -- including when to make therapeutic interventions and to assess the effect of those interventions.

In this chapter, we discuss the use of computers in collecting, displaying, storing, and interpreting clinical data, making therapeutic recommendations, and alarming and alerting. In the past, most clinical data were in the form of heart and respiratory rates, blood pressures, and vital fluid flows. However, today's ICU monitoring systems integrate data from bedside monitors and devices as well as data from many sources outside the ICU. Although the presentation made here deals primarily with patients who are in ICUs, the general principles and techniques are also applicable to other hospitalized patients and electronic health records (EHR). For example, patient monitoring may be performed for diagnostic purposes in the ER or for therapeutic purposes in the OR. Techniques that just a few years ago were only used in the ICU such as bedside monitors are now used routinely on general hospital wards and in some situations even by patients in their homes.

19.1.1 Case Report

We will use a case report to provide a perspective on the problems faced by the team caring for a critically ill patient: a 27-year-old male is injured in an automobile accident. He has multiple chest and head injuries. His condition is stabilized at the scene of the accident by skilled paramedics using a portable computer-based electrocardiogram (ECG) and pulse oximeter, and he is quickly transported to a trauma center. Once in the trauma center, the young man is connected via non-invasive sensors to a computer-based bedside monitor that displays physiological signals, including his heart rate and rhythm, arterial oxygen saturation, and blood pressure. X-ray and magnetic resonance imaging provide further information for care.

Because of the head injury, the patient has difficulty breathing, so he is connected to a computer-controlled ventilator that has both therapeutic and monitoring functions and he is

transferred to the ICU. A bolt is placed in a hole drilled through his skull and a fiber optic sensor is inserted to continuously measure intracranial pressure with another computer-controlled monitor. Blood is drawn and clinical chemistry and blood-gas tests are promptly performed by the hospital laboratory. Results of those tests are displayed to the ICU team as soon as they are available. With intensive treatment, the patient survives the initial threats to his life and now begins the long recovery process. Figure 19.1 shows a nurse at the patient's bedside surrounded by a bedside monitor, infusion pumps, a ventilator and other devices.

Unfortunately, a few days later, the patient is beset with a problem common to multiple trauma victims—he has a major **nosocomial hospital-acquired infection**, develops sepsis, and acute respiratory distress syndrome (ARDS), which leads to multiple organ failure. As a result, antibiotics and electrolytes are required for treatment and are dispensed via intravenous (IV) pumps. The quantity of information required to care for the patient has increased dramatically.

Multiple patient monitoring computer systems that support this ICU patient are tightly integrated and data are automatically gathered and stored, primarily in a coded format so that real-time computerized decision support can be used. Figure 19.2 shows a schematic of the HELP system at Intermountain Healthcare as an example of such a system. Based on the data available to the HELP system from these multiple data sources, its computerized decision support system makes and displays suggestions for optimum care for the specific problems such as sepsis and ARDS. The system provides audible and visual alerts for life-threatening situations. In addition, the system organizes and reports the large amount of data so that the medical team can make prompt and reliable treatment decisions. The patient's physicians are automatically alerted about life-threatening laboratory and other findings. The Infection Control Department automatically receives emails alerting them of any infections in sterile body sites, new nosocomial infections, and any antibiotic resistant pathogens. The patient's ARDS is managed with the assistance of standardized computer generated protocols. The sepsis is managed with a computerized "antibiotic assistant" that recommends the antibiotic to be given as well as the dose, route, and interval based on specific information in the patient's computerized record.

19.1.2 Patient Monitoring in Intensive Care Units

There are at least three categories of patients who need physiological monitoring:

1. Patients with compromised physiological regulatory systems; for example, a patient whose respiratory system is suppressed by a drug overdose or during anesthesia
2. Patients who are currently stable but with a condition that could suddenly change to become life threatening; for example, a patient who has findings indicating an acute myocardial infarction (heart attack) or immediately after open-heart surgery, or a fetus during labor and delivery
3. Patients in a critical physiological state; for example, patients with multiple trauma or septic shock like the one in our case study

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

1. To acquire physiological data frequently or continuously, such as blood pressure
2. To communicate information from data-producing systems to remote locations e.g., laboratory and radiology departments
3. To store, organize, and report patient information
4. To integrate, organize and correlate data from multiple sources
5. To provide clinical alerts and advisories based on multiple sources of data
6. To function as an automated decision support tool that health professionals may use in planning the care of critically ill patients
7. To measure the severity of illness for patient classification purposes
8. To analyze the outcomes of ICU care in terms of clinical effectiveness and cost effectiveness

19.2 Historical Perspective

19.2.1 The Measurement of Vital Signs

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

In 1896, Scipione Riva-Rocci introduced the sphygmomanometer (blood pressure cuff), which permitted the fourth vital sign, systolic blood pressure, to be measured. A Russian physician, Nikolai Korotkoff, applied Riva-Rocci's cuff with a stethoscope developed by the French physician Rene Laennec which allowed the measurement of both systolic and diastolic arterial pressure. Harvey Cushing, a preeminent U.S. neurosurgeon of the early 1900s, predicted the need for and later insisted on routine arterial blood pressure monitoring in the operating room. At the same time Cushing also raised the following questions – that are still being asked today:

1. Are we collecting too much data?
2. Are the instruments used in clinical medicine too accurate?
3. Would not approximated values be just as good?

Cushing answered his own questions by stating that vital sign measurements should be made routinely and that their accuracy was important (Cushing, 1903). More recently the American College of Critical Care Medicine (Haupt 2003) and the American Society of Anesthesiologists (ASA 2010) have made similar recommendations.

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

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

19.2.2 Development of Intensive Care Units

Until about 1960, if patients had severe cardiac events, there were few treatment options for physicians to care for them. As a consequence, many patients who had life-threatening acute cardiac or pulmonary problems died. However, in the early 1960's two major medical care treatment modalities were developed that provided treatment for heretofore fatal situations. Development of closed chest cardiopulmonary resuscitation (CPR; Kouwenhoven 1960) and closed chest defibrillation (Zoll 1956, Lown 1962) provided means for delivering life-saving treatment. Because of availability of these treatments, the demand for continuous monitoring of high risk patients escalated. Hospitals began to cluster patients with complex disorders together into new organizational units—called ICUs—beginning in the early 1960s. Some of the earliest units were coronary care units where patients were cared for after myocardial infarctions or other acute, life-threatening cardiac events.

SICUs had their beginnings in the late 1950s when post-operative patients were kept in the recovery rooms for extended time periods after cardiac or other high risk surgery for close observation. Initially these recovery rooms did not have the benefit of cardiac monitoring. However, as more sophisticated monitoring became available, special units were created and designated as SICUs or thoracic intensive care units (TICUs).

Intensive care units proliferated rapidly during the late 1960s and early 1970s. The types of units included coronary, thoracic surgery, surgical, medical, shock-trauma, burn, pediatric, neonatal, respiratory, and other multipurpose medical-surgical units. Today there are more than 6 million patients admitted each year into adult, pediatric, and neonatal intensive care units in the United States alone. In the past 3 decades, the demand for ICU services in the United States has risen dramatically. The average life expectancy is rising and estimates of the U.S. Population over 65 (who use ICUs disproportionally more than the rest of the population) will increase by 50% by 2020 and 100% by 2030, continually increasing demand (Kelley 2004, Groves 2008).

19.2.3 Development of Bedside Monitors

A signature feature of each of these early ICUs was the bedside monitor. The original bedside monitors were used primarily to acquire and display the ECG. Soon it became possible to acquire and display arterial and venous blood pressure signals by inserting catheters directly into a patient's vein or artery and connecting them to transducers. In some cases these catheter-transducer systems were already in place when open-heart patients returned from surgery. The bedside monitor could also display the ECG and the arterial waveform (See Figures 19.3A and B). Because of the complexity of care and the increased acuity of these patients, the need for specialized nursing care increased dramatically. In a typical acute patient care situation, one nurse may be responsible for the care of five or more patients. However, because of the observations and care that these acutely ill patients required, intensive care nurses typically are assigned one to three patients.

As a result of the detailed ECG information provided by the new patient monitors, treatment for serious cardiac arrhythmias (heart rhythm disturbances) and cardiac arrest (abrupt cessation of heartbeat)—major causes of death after myocardial infarctions (heart attack) —became possible. Mortality rates from 1960-1970 were about 35%, dropped to about 23% between 1970 and 1980 and to about 20% between 1980 and 1990. During the 1990's reperfusion of the coronary arteries became common and mortality rate dropped to about 5% (Braunwald 1988, Rogers 2000).

In the 1960's bedside monitors were built using analog computer technologies. These systems amplified the electrocardiographic signal and displayed the results on an oscilloscope. Such systems required nurses or technicians to watch the oscilloscope to determine if there was a cardiac arrest or other life threatening cardiac rhythm. Soon after these analog systems were developed, methods for generating high- and low-heart-rate alarm thresholds were included. The alarms were usually audible and very annoying. Unfortunately, since the beginning of the use of these alarms, the false positive rate has far exceeded the true positive rate. As a result, many times alarm systems for bedside monitors are ignored or turned off.

19.2.4 Development of Computer-Based ICU Monitoring

Teams from several cities in the United States introduced computers into the ICU to assist in physiological monitoring, beginning in Los Angles with Shubin and Weil (Shubin 1966) followed by Warner and colleagues (Warner 1968) in Salt Lake City. These investigators had several objectives:

1. To increase the availability and accuracy of the physiological data
2. To compute derived variables that could not be measured directly
3. To increase patient-care efficacy
4. To allow display of the time trends of the patient's physiological data, and
5. To assist in computer-aided decision making

Each of these teams developed their applications on large **mainframe computer systems**, which required large computer rooms and trained staff to keep the system operational 24 hours a

day. The computers used by these developers cost over $200,000 each in 1965 dollars. During that time, other researchers were attacking more specific challenges in patient monitoring. For example, Cox (Cox 1972) at Barnes Hospital in St. Louis, developed algorithms to analyze the ECG for heart rhythm disturbances in real-time. The arrhythmia-monitoring system, which was installed in the CCU in 1969, ran on a relatively inexpensive **mini-computer** rather than a mainframe computer. With the advent of **integrated circuits** and **microprocessors**, affordable computing power increased dramatically. What was considered computer-based patient monitoring by these pioneers in the late 1960s and early 1970s is now entirely built into bedside monitors and is considered simply a "bedside monitor." Clemmer provides an important overview of "where we started and where we are now" (Clemmer 2004) to summarize the four decades since the initiation of computers in the ICU.

19.3 Modern Bedside Monitors

The heart and lungs are crucial to normal body function. For example if the heart stops (cardiac arrest) there is a cessation of normal circulation of the blood. Likewise, if there is a pulmonary arrest there is a cessation of breathing. Each of these situations leads to a reduced delivery of oxygenated blood (hypoxia) to the body, with major physiological hazards. For example, brain injury will occur hypoxia is untreated within 5 minutes. As a consequence, detection of either of these situations is required if life-saving treatments are to be administered. The treatment for cardiac arrest is CPR, which provides circulatory and pulmonary support. Following the application of CPR, if the patient does not regain a normal rhythm, they may have to be shocked with a defibrillator to reestablish a normal rhythm.

Although it is highly desirable to monitor critically ill patients to determine life-threatening events, the process of doing so is very demanding on information systems. For example if a patient in the ICU had a heart rate of 90 beats per minute, that patient would have 5,400 beats each hour and almost 130,000 heart beats each day. With the digitization of the ECG and other physiological signals, it is possible to determine the heart rate and other parameters for each heartbeat. Certainly a computerized monitor should be much better at monitoring such parameters than a human.

19.3.1 ECG Signal Acquisition and Processing

The ECG provides a representation of the electrical activity of the human heart and is a very important tool for the diagnosis of disturbances of heart rate and rhythm. The ECG is derived by placing electrical leads on a patient's chest and limbs and provided one of the first methods for automatically determining heart rate (HR) and detecting irregular rhythms of the heart. Original monitors allowed physicians and nurses the ability to watch the ECG trace on an oscilloscope. Since ECG signal measured on the skin is very small (1 millivolt), it is subject to artifacts (noise) caused by such things as patient movement, electrode movement, and electrical power interference. By using sophisticated analog and digital techniques and presenting data from multiple leads, the quality and reliability of the ECG signals monitored has improved dramatically over the past 3 decades (Weinfurt 1990, Gregg 2008). At the same time, the demand for improved quality of the ECG signal and an increase in the number and types of parameters has increased. Initially, the ECG signal was processed to obtain HR and basic rhythm (periodicity of the beat) while today's monitors can detect signals from artificial heart pacemakers, complex arrhythmias, **myocardial ischemia** and disturbances in the conduction of electrical signals through the heart muscle.

Two types of computerized ECG analysis are in common use today:

1. The 12-lead ECG is typically performed in a physician's office or in the hospital. Usually a technician brings a recording device to the patient's bedside and attaches the leads, and records the signal acquisition during a short interval while the patient is lying quietly in a supine position. From this 12-lead ECG, a wide variety of ECG diagnoses are made. Computer processing of these ECG signals taken at that moment in time has become the definitive practical option for ECG interpretation. Automated ECG analysis has become widespread in clinical practice since the mid-1980s although, in most hospitals, cardiologists will also read them to confirm the automated findings. Automated ECG analysis is quite accurate, especially in normal individuals,

but disagreements with cardiologists are seen and may be clinically important (Guglin 2006, Bogun 2004). On the other hand, cardiologists are not perfect either (Clark 2010)!

Today, physicians expert in ECG interpretation from multiple professional organizations such as the American Heart Association and the Electrocardiographic Society have come to consensus and established standards designed to improve computerized ECG interpretation. In biomedical informatics terminology, these experts have developed the knowledge base for diagnostic ECG interpretation. The detailed pattern recognition and signal processing does not need to occur in real-time. Thus the 12-lead ECG processing can be more sophisticated than with the requirements of real time monitoring situations (Gregg 2008).

2. Continuous, real-time monitoring is required while the patient is in the ICU. Because of patient movement, caregiver activities such as administering medications, bathing and the like, the amount of artifact generated poses important challenges to real-time monitoring. To minimize these effects, filtering of the acquired ECG signal is performed. This filtering slightly distorts the ECG but at the same time makes it possible to process the signals on a beat-by-beat basis. Although standards for interpretation of ECG monitoring are more recent than those for 12-lead monitoring, they are now becoming more common and sophisticated (Drew 2006, Funk 2010), The clinical experts who are establishing the knowledge base now include critical-care nurses, cardiologists, anesthesiologists, and thoracic surgeons (Crossley 2011).

ECG processing in today's vendor-supplied bedside monitors continues to improve and become more reliable. Sophisticated pattern recognition and signal processing techniques are used to allow extraction of key parameters in real-time while adding the ability to measure the utility of new physiological parameters (Crossley 2011). Recently, investigators have created publically available databases of ECG waveforms and other physiological signals as well as other important data from actual patients to allow validation of these monitoring systems (Saeed 2011, Burykin 2011).

19.3.2 Arterial Blood Pressure Signal Acquisition and Processing

Accurate and continuous monitoring of arterial pressure requires insertion of a catheter into an artery. Once the catheter is successfully inserted into an artery the catheter is connected, via a length of sterile fluid-filled tubing, to a stop-cock with a "continuous flush" device and a factory calibrated disposable blood pressure transducer (Gardner 1996). The blood pressure transducer is then connected to an amplifier and the pulsatile signal it detects is displayed on the screen of the bedside patient monitor. With the advent of inexpensive, disposable, accurate pressure transducers, the quality and accuracy of arterial pressure monitoring has improved dramatically. However, two sources of inaccuracy of the arterial pressure signal still depend on medical staff set-up and validation: 1) zeroing is the process by which the monitor is informed when an port on the stopcock is opened to the atmosphere at "mid-heart level" – thus becoming the point from which pressure is measured; 2) since the arterial pressure signal contains pulsatile characteristics with frequencies up to 20 Hz that must be transmitted from the artery through the plumbing system to the transducer, the dynamic response characteristics must be optimized. Optimization is typically done by doing a "fast flush" test (by pushing sterile saline through the tubing) to optimize the system by removing blood and very tiny air bubbles that can dramatically distort the arterial pressure waveform and result in erroneous measures of systolic and diastolic pressure.

At least two types of artifacts in the arterial pressure signal are commonly observed. If a patient rapidly moves or a care giver bumps the tubing, a pressure artifact is generated and transmitted to the transducer and displayed. In addition, when the clinical staff draws arterial blood for laboratory tests, they typically turn off the stopcock connected to the transducer and draw blood through the tubing, causing an immediate loss of the pulsatile arterial pressure signal. The pressure sensed by the transducer then typically rises to that found in the pressurized flush solution. Thus, continuous vigilance on the part of nurses and other care givers is needed for the arterial catheter and monitoring systems to be properly maintained. As a historical note, the continuous flush device was developed over 40 years ago to prevent arterial catheters from clotting and to allow one of the pioneering computerized monitoring systems to become more reliable (Gardner 1970). Since that

time, investigators have developed computerized methods to minimize these “human caused artifacts” (Li 2009, Gorges 2009).Unfortunately, these strategies have seldom been implemented into commercially available bedside monitors.

Since the early 1900’s, efforts have been made to estimate **cardiac output** from the pulsatile pressure in the arterial system by multiplying the HR with an estimates of stroke volume (the volume of blood ejected from the heart during a single contraction) made from the pressure waveform. Warner and his colleagues at the Mayo clinic published some early work in 1953 (Warner 1953) on the topic and followed up again in 1983 further substantiating the feasibility of the method. However, in 1980 Cundick (Cundick 1980) showed that the widely varying mean blood pressures found in critically ill patients adversely affected the reliability of the method. Since that early work, multiple publications and commercially available devices using the pulse-pressure method have appeared. The issue is still active, with such recent publications (Chen 2009, Sun 2009, Gardner 2009B). Other estimates of stroke volume and cardiac output have been made from determining the “Bioreactance” – a measure of the degree of phase-shift in the electrical signal - across the chest. This method shows promise of being a rather simple, continuous and non-invasive method for measuring cardiac output (Keren 2007).

More recently, several investigators have made assessments of delta pulse pressure (DPP), which measures the variability of the peak to peak arterial pressure pulse signal across the breathing cycle to make an estimate of a patient’s fluid balance. The supposition is that if there is larger variability in this DPP marker the patient may require fluid administration (Deflandre 2008).

It is clear that future methods that process available physiological signals will be applied to enhance and improve the availability of important measures of cardiac function – a key parameter for making treatment decisions used by critical caregivers.

19.3.3 Pulse Oximeter Signal Acquisition and Processing

One of the most common technological devices used in hospitals today is the pulse oximeter. The pulse oximeter sensing device is usually placed on a finger and measures oxygen saturation and pulse rate - HR (Clark 2006). The device works by shining red and infrared light generated by 2 light emitting diodes through the tissue. With each arterial pulse there is a variation in the light as it passes through the tissue and is sensed by a light-sensitive photodiode on the opposite side. The more oxygenated the blood is, the more red light is transmitted, with less infrared light passing through. By calibrating these devices, reasonably accurate estimates of arterial oxygen saturation (SpO_2) can be determined. Although the pulse oximeter is convenient and easy to use, it has several important limitations, including motion artifact, when the patient moves, and other physiological considerations such as anemia, low perfusion state and low peripheral skin temperature. If the blood flow to the hand gets disturbed, by perhaps squeezing the arm during blood pressure with a sphygmomanometer, the blood flow to the hand is interrupted and the pulsatile blood pressure signal required for the pulse oximeter is no longer available.

19.3.4 Bedside Data Display and Signal Integration

While colorful and dynamic, the displays on the bedside monitor can be complex – See Figure 19.3 A and B for typical bedside monitor displays from Philips and General Electric (GE) bedside monitor displays. Each vendor of bedside monitors has made a “best effort” at displaying the variety of physiological signals derived. In most cases this consists of three channels: ECG, arterial blood pressure, and pulse oximeter. Additional important physiologic parameters can be derived from these signals, as noted in Table 19.1.

Today’s bedside monitors still present both waveforms and derived parameters in a “single-sensor-single-indicator” format. That is, for each individual sensor attached to the patient there is a single indicator – waveform with derived value presented on the screen (Drews 2008). One of the simplistic consequences of this display strategy is that each indicator is treated as if it had come from a different patient. For example, if ECG, arterial blood pressure and pulse oximeter signals were displayed, they would each have the capability of determining heart rate. Thus, 3 different heart rate

measures might be displayed. Although there are physiological reasons for such differences, the most common situation is that the heart rate should be an “integrated assessment” of the 3 signals since “artifact” is a far more common event than the unusual conditions that would cause the differences in heart rate. Drews and his colleagues suggest that there are better methods for designing hemodynamic monitoring displays (Doig 2011, Drews 2008).

Table 19.1 Bedside Physiological Monitoring Capabilities

Signals	Transducer	Frequency	PARAMETERS			
ECG	Chest Electrodes	Continuous	Heart Rate	Heart Rhythm	Complete ECG Interpretation	Pacemaker Signal
Arterial Blood Pressure Invasive	Catheter & Blood Pressure Transducer	Continuous	Heart Rate	Systolic Diastolic Mean Pressure	Estimates of Cardiac Output	Pulse Pressure Variation & Fluid Loading
Arterial Blood Pressure Non-Invasive	Inflatable Cuff	Intermittent	Heart Rate	Systolic Diastolic Pressure		
Pulse Oximeter	Finger Probe	Continuous	Arterial Oxygen Saturation	Heart Rate		
Temperature	Skin Sensor	Continuous	Temperature			
Respiration	Chest Belt	Continuous	Respiratory Rate			
Bioreactance	Electrodes	Continuous	Cardiac Output	Heart Rate	Stroke Volume	

A more important problem relates to the ’integration of data from multiple bedside devices. Two examples will illustrate the problem:

1. The patient’s pulse oximeter has shown a recent increase of SpO_2. However, the bedside monitor has no knowledge that the respiratory therapist has increased the FiO_2 from 30 to 40% on the ventilator.
2. The patient’s heart rate has recently increased from a dangerously low value of 45 beats per minute to 72 beats per minute. Unfortunately, the bedside monitor has no way of knowing that a nurse has increased the drip rate of a cardio-active medication.

Patients in today’s ICUs can have 50 or more electronic devices attached (Mathews 2011). Many of these electronic devices were developed by independent companies and do not easily interface or communicate with each other. However, even though in recent years the larger monitoring companies have purchased several of the “specialty monitoring” companies, the problems still exist although it was understood more than three decades ago, and standards for bedside data interchange (CEN ISO/IEEE 11073) (Gardner 1989, Gardner 1991) were developed. The **Medical Information Bus** (MIB) is the simple term used to designate CEN ISO/IEEE 11073. So, why has the MIB been a commercial failure to this point? There are multiple reasons; unfortunately, the MIB standard was designed during the time when serial communications via **RS-232** was the norm; there were no **Universal Serial Bus** (USB) interfaces or convenient wireless devices at the bedside. Furthermore, each vendor of bedside devices and ICU data management systems would like to be

the “data integrator” (for a price) and thus has little incentive to adhere to standards that would allow other vendors to compete for the integrator role. The business model apparently has not worked (Kennelly 1997, Mathews 2011).

In spite of the lack of interface standards, the group at Intermountain Healthcare has been actively interfacing ventilators, IV pumps and similar devices for almost three decades (Dalto 1997, Vawdrey 2007). Details of the importance of these interfaces and real-time clinical record capture are discussed later in, Section 19.4.2.

19.3.5 Challenges of Bedside Monitor Alarms

Care of the critically ill is complex and challenging. Most of these patients have medical problems or injuries that are life threatening. They might have heart problems that within minutes could result in sudden death, or they might have breathing problems that require mechanical ventilation to maintain life. As a consequence, each of these situations requires intense minute-by-minute observation with real-time, continuous physiologic monitoring. For those conditions, the requirement for record keeping, monitoring, and alarming is intense.

The requirements for record keeping are not unlike those found in a modern commercial airplane, with its sophisticated flight recorder. Each commercial aircraft has two pilots who serve the function of observers and data collectors; much as nurses, physicians and other care givers do for the critically ill. The modern airplane has sophisticated sensors and measurement systems and a multitude of displays. In addition there are complex alarm systems that warn pilots, and record those warnings about impending problems on the data and voice recorders. It would be ideal if such recording and alarming systems were available to those caring for the critically ill. However, we have not yet developed the capabilities to accomplish the level of care as is provided in a commercial airplane. As complex as flight recorder technology may be, it is not nearly as complex as understanding the systems of the human body – each being a bit different and changing over time.

We are be able to record and process physiological signals with much greater capability than we did just a decade ago, but we are still learning about what data to collect, how to collect those data in a timely manner, and how to generate alerts and alarms that assist care givers to provide optimum patient care. Not only is the human body complex with its multiple internal control systems, but each individual is genetically programmed slightly differently and in many cases those control systems have been injured or rendered partially or completely inoperable by traumatic injury or medical malfunction. Thus, while we may have a few hundred models of commercial aircraft we have billions of models of human patients. Thus, although it is possible to record data minute-by-minute, and even second-by-second (and some have attempted that (Saeed 2011, Burykin 2011)), we are still not able to fully understand all the complex details.

A recent article in the *Boston Globe*, entitled “Patient alarms often unheard, unheeded” (Kowalczyk 2011), presents the clear expectation that bedside physiological monitors, ventilators, IV pumps and similar devices attached to patients should provide “true and valid” alarms and that care givers will be promptly notified and provide the needed care immediately for those patients. On the other hand, a report from the New England Journal of Medicine outlines 24 electronic requirements for classification of a hospital as having a comprehensive electronic record system (Jha 2009), yet recording of data from bedside physiological monitoring systems with their alarming systems and data gathering from other bedside devices such as ventilators and IV pumps were not even mentioned.

So, currently there is a curious and inexplicable set of expectations being generated for care of the critically ill patients. As a consequence there are “nitch” vendors who have built their own data gathering and recording systems and nurse charting systems; in some cases these systems include simple interfaces to allow them to acquire laboratory data and perhaps data from the administrative admissions process. They may even include bedside computers or displays to allow care givers to have access to such things as X-ray images, dictated reports and the like. But, these systems do not typically provide interfaces to *transmit* their physiological data to the hospital’s EHR.

Over the past decade, the number of physiological signals that can and are being monitored has grown. With each signal and derived parameter that is added there is typically a “high” and “low”

alarm added to warn the clinical staff of actual or impending patient crisis. Alarms may be highlighted on the bedside monitor's screen by using a color change or flashing indicators. Most alarms also generate a sound. Over the past 20 years, alarms have become more widespread because of a greater interest in and attention to safety, and also to litigation that may follow when an adverse incident occurs.

Figures 19.4 and 19.5 give examples of the complexity of determining whether an alarm is "true" or "false" based on two life-threatening conditions. Alarms for Ventricular Tachycardia are shown in Figure 19.4. Figure 19.4A shows a true ventricular tachycardia (VT) alarm condition while Figure 19.4.B shows a false VT condition. Figure 19.4B has only a few seconds of ECG artifact, which causes the bedside monitors' alarm detection system to issues an alarm.

Arterial hypotension alarms are shown in Figure 19.5. Figure 19.5A shows a true arterial hypotension alarm condition while Figure 19.5B shows a false condition. If the monitor or human observer only watches the arterial blood pressure (ABP) signal, the two conditions appear similar. However, by simultaneously following the ECG signal, the human observer will note that for some unknown reason the ABP signal displays a false representation of the patient's pulsatile blood pressure. The "unknown reason" is likely related to the catheter and tubing parts of the arterial monitoring system. Alerting the clinical staff to examine the catheter and transducer system is certainly appropriate.

Imhoff and colleagues (Imhoff 2006) noted from 1.6 to 14.6 alarms for each ICU patient each hour. Up to 90% of those alarms were false! "Alarm overload" is clearly a significant issue in ICU monitoring; from clinical informatics professionals working in the ICU is needed to minimize the number of false alarms. Just noting the titles of several Editorials and articles should be informative:

1. Alarms in the intensive care unit: How can the number of false alarms be reduced? (Chambrin 2001)
2. Monitoring the monitors – beyond risk management (Thompson 2006)
3. Alarms and human behavior: Implications for medical alarms. (Edworthy 2006)
4. Alarms in the intensive care unit: Too much of a good thing is dangerous: Is it time to add some intelligence to alarms? (Blum 2010)
5. Intensive care unit alarms – How many do we need? (Siebig 2010)

Biomedical informaticians, biomedical engineers and bedside monitor vendors have recently renewed their efforts to reduce false alarms and improve the relevance of existing alarms. Most of the false alarms are caused by noise or artifacts in the primary signals. To help minimize these problems, two examples are used to illustrate the challenges and opportunities to improve bedside alarms.

1. After observing over 200 hours of alarms from bedside monitors and ventilators in an adult medical ICU, Gorges and his colleagues (Gorges 2009) used the data recorded to recommend a two-step process that would dramatically reduce the number of false alarms. The first step was to add a 19 second delay into the alarming system. That step by itself reduced the number of alarms by 67%. They then noted that by having some method for automatically detecting when a patient was being suctioned, repositioned, given oral care or being washed, there would be a further 13% reduction of ineffective alarms. By using these just these two methods, almost 80% of the false alarms could be eliminated.
2. Using multiple signals to derive identical measures should be an effective method of reducing false alarms. As will be noted in Figure 19.3 A and B, there are five signals that can be used to derive heart rate: ECG 1, ECG 2, ECG 3, Arterial Blood Pressure, and Pulse Oximeter. Since the probability of all those signals having an artifact is smaller than any single physiological signal, "smart alarm" algorithms that are more robust should be possible. Two investigators have developed and tested such algorithms (Zong 2004, Poon 2005). The Zong pressure alarm algorithm reduced false alarms from 26.8% to 0.5%. Poon found that the usual heart rate and rhythm alarm system produced 65.4% false alarms, while an algorithm that integrated multiple signals generated only 31.5% false alarms. Two other findings from the Poon study were also encouraging. By merely delaying the alarms by 10 seconds there was a 60% reduction in false alarms. In addition, he found that default settings for high and low heart rate alarms were not

optimized to prevent false alarms. For example, if a patient had an average heart rate of 65 beats per minute and the default low heart rate alarm was 60 beats per minute; there was an increased likelihood of false low heart rate alarms. Several bedside monitor vendors now provide these more sophisticated alarm algorithms in their newest monitors.

Still other informaticians have found different strategies to provide more accurate arterial blood pressure and cardiac arrhythmias alarm rates (Aboukhalil 2008, Zhang 2008). Having electronic archives of physiological waveforms that are publically available should permit development of even better smart alarm algorithms, which should lead to a reduced number of false alarms generated by bedside monitors (Saeed 2011, Burykin 2011).

19.3.6 Strategies for Incorporating Bedside Monitoring Data into an Integrated Hospital EHR

Three general strategies are currently used to transfer bedside monitoring data into the hospital's EHR. The first is the simplest: nurses observe data presented on the bedside monitor screen and manually "key-in" the observations into an integrated EHR. As simple as this may be to implement, such manual data collection strategy is inefficient and does not collect representative data gathered by the bedside monitor.

The second strategy used by ICU information systems, such as CareVue, iMDSoft or MetaVision, is to acquire vital sign data directly from the bedside monitoring system's network by using an HL7 feed (see Chapter 7). The information is automatically gathered by the ICU information system; nurses have the option of either accepting or modifying the data. In typical clinical settings, nurses perform the selection and transfer of bedside monitoring data from the ICU information system to the EHR about once an hour. These ICU information systems typically retain the high frequency bedside monitoring data and can achieve near-real-time computerized decision support. In many cases, the nurse's notes are also entered into the ICU information system – generally once per shift – and some summary vital sign information may find its way into those notes. Physician progress notes are also entered into ICU information systems in a similar fashion. Unfortunately, data in the ICU information system "EHR" may never find its way into the hospital's EHR. For these systems, the ICU data are usually archived separately. As a consequence, these data cannot be used for real-time decision making by the hospital's EHR.

The third strategy is to have the ICU information system or the hospital's EHR automatically transfer vital sign data from the bedside monitoring system to the EHR. Most systems that automatically gather data with this strategy take a "median" of the vital sign data over a 15 minute time interval to smooth the data (Warner 1968, Gardner 1991, Vawdrey 2007). This strategy provides real-time data for computations and computerized decision support for the hospital's EHR and is the preferred strategy.

There are opportunities to improve the automated data gathering from bedside monitors, especially if the false alarm rate can be minimized. In addition to acquiring 15 minute median data, one may wish to detect bedside alarms and record data in the intervals just before and just after these alarms. Thus, there is still opportunity for informaticians to make major improvements in both data recording and bedside monitoring alarms.

19.4 Information Management in Intensive Care Units

19.4.1 Early Pioneering in ICU Systems

A good way to understand the implementation and use of computerized intensive care monitoring systems is to follow the development of a system that was begun 40 years ago at Intermountain Healthcare's LDS Hospital. There, a team of people developed what was known as the HELP System (Pryor 1983, Kuperman 1991, Gardner 1999). Initially only physiological data were acquired from the bedside monitors. Nursing note charting promptly followed with ability to chart medications ordered and given, including IV drip rates. Soon, it became apparent that much of the data needed to care for these critically ill patients came from the clinical laboratory and other sites such as radiology (X-rays). As a consequence, multiple modules were added to the HELP system to support the ICUs.

About five years after this initial computerization of the ICUs, studies were made during structured “teaching rounds” where physicians, nurses, respiratory therapists, pharmacists and others evaluated each patient. Since the early motivation was to use the computer as a decision support system, observations were made on 63 patients during morning ICU rounds to determined what data were used by the critical care team to make clinical care decisions (Bradshaw 1984). Table 19.2 outlines the data types evaluated with the percentage of time that each type of data was used to make a care decision. In addition, the source of each of the data elements was noted. Many of the data came from automated instruments in the laboratory, but a large number came from nurse observations and actions that were manually charted into the computerized record.

Table 19.2 Data Used for ICU Decision Making (Adapted from Bradshaw 1984)

Data Types	%	Data Source
Clinical & Blood-Gas Laboratories	42	Laboratory Interfaces
Drug I/O IV	22	Nurse Charting & IV Pump Interface
Observations	21	Nurse Charting & Physician Notes
Physiological Data	13	Bedside Monitor Interface
Other	2	

Finding that data from the physiological monitor accounted for only 13% of the data was used to make treatment decisions was a surprise to the investigators. However, as described earlier, the physiological monitor serves a very crucial function during critical situations such as cardiac arrest. The observations showed the crucial need for a fast and reliable laboratory interface *and* the importance of data that came from nurse charting. Knowing which drugs the patient was receiving, when those drugs were given, and the types and administration rates of IV medications were crucial to clinical decision making. In addition, the observations made by nurses and physicians were important for making many decisions.

As a consequence of these observations, obtaining real-time computerized nurse charting became a top priority. With paper charting systems, there is little ability to audit and improve the timeliness of nurse charting. To enhance the ease and timeliness of bedside charting, terminals were installed at each bedside. Studies were conducted and nurses were trained to chart in real-time – e.g., within 1 minute of when a medication was given or a procedure was performed. As a result of these actions, the computer record became a more real-time representation of the patient’s status (Oniki 2003, Nelson 2005). Thus, nurses, physicians, therapists, and the computerized decision support modules could reliably act on the data stored in the computer. It is surprising that even today, almost 30 years later; many computerized ICU systems do not store real-time physiological data and nurse charting information. Having made recent observations at several computerized ICUs it is surprising that the old standard of having the chart “up-to-date at the end of the shift” is still the norm. Clearly, with that philosophy and operational mode, computerized decision support and access to data by the clinical staff is sub-optimal and as a result, medical errors can and do occur.

19.4.2 Clinical Charting Systems (Nurses, Pharmacists, Physicians, Therapists)

Table 19.2 clearly shows that a major part (43%) of the data used at LDS Hospital for decision-making during rounds came from data charted by nurses and other clinicians (Bradshaw 1984). In a more recent study in the ICU at the Mayo Clinic, the team found that as they developed what they referred to as their “novel presentation” of ICU data, they required similar data content (Pickering 2010).

At LDS Hospital the computerized nurse charting module allows nurses to enter patient care tasks, qualitative and quantitative data and a patient’s response to therapy (Willson 1994A, Willson 1994B, Nelson 2005). In addition, nurses interact with a pharmacy module to chart all given

medications including IV drip rates (Pryor 1989, Kuperman 1991). Initial nurse charting at LDS Hospital was done at a central station, since at that time large cathode ray tubes were used as display devices making bedside installation of terminals inconvenient and expensive. Now, virtually all clinician charting is done at bedside terminals, primarily with a bar code scanner.

Soon after the nurse charting was implemented at LDS Hospital, respiratory therapists chose to enter their qualitative and quantitative ventilator data and care given to patients (Andrews 1985, Gardner 2004). The motivation for the on-line charting was to provide clinicians with access to timely and accurate data to make patient care decisions. In addition, these data could be used to implement protocol-controlled ventilator weaning systems (East 1992, Morris 2001).

To optimize the performance of routine care deemed essential for ICU patient recovery, computer "reminders" were generated (Oniki 2003). For example, one of the goals of the reminders was to provide assistance in determining the required level of sedation while avoiding over-sedation. By providing the computerized reminders to nurses, charting deficiencies were reduced by 40% and the number of deficiencies at the end of the shift was improved. To optimize care provided by the reminders, real-time charting was required. However, during a quality improvement process, it was determined that 29% of the medication errors that should have been prevented by on-line nurse charting were still present. A careful evaluation revealed that the actual nurse charting workflow was different than that envisioned by the system planners. Instead of charting the given medication using a bedside terminal, nurses administered the medication and then at some later time, at the central nursing station, charted that the medication had been given. As a consequence errors were occurring. After careful training and feedback with the nursing staff, the real-time charting rate increased from 40% to 75% and remained at that level a year later. This example shows that having computerized decision support systems in place without having real-time data entry was ineffective. Conceptually, one could make the same logical observation if the ICU were operating as a tele-ICU as discussed later in this chapter.

For generations, nurses and other care givers who have used conventional paper records have had the notion that if their paper chart was up-to-date at the end of the shift then they had met their requirements for good patient care. Clearly, the above example shows that such a strategy is flawed. However, it is interesting that even today reports are being made about charting and use of data for end-of-shift nursing care exchanges and patient "handovers", suggesting that the EHR still may not be real-time (Hripcsak 2011, Collins 2011). Collins and associates found that clinicians preferred oral communications compared to EHR documentation and stated that the perceptions that the EHR was a "shift behind" might have only been a manifestation of the lack of real-time charting by nurses and acquisition of real time data from bedside monitors in their ICU (Collins 2011).

An early survey of nurses and physicians use of the HELP clinical expert system was conducted in 1994 (Gardner 1994). The investigators were encouraged by a positive response from both nurse and physician users who appreciated having the data available with interpretation and alerting features provided by the HELP system. At the time the survey was conducted, ICU charting and decision support was a major feature of the HELP system. It is exciting to note that recently, other institutions have begun to assess factors related to acceptance of an EHR in critical care (Carayon 2011). The Carayon study showed that ease of use as well as data presentation strategies were major determinants of acceptability of their system.

19.4.3 Automated Data Acquisition from All Bedside Devices

As noted in Table 19.2 and from the HELP System Diagram shown in Figure 19.2, much of the information required for patient care comes from laboratories and devices that automatically acquire data. In the upper right hand corner of the diagram, shown in block diagram format, data from the ventilator, IV pumps and the bedside monitor are noted. While most of the physiological bedside monitor vendors now acquire ECG, blood pressure, and pulse oximetry data, they do not provide access to data from ventilators or information from IV pumps. As a consequence data from these devices must be obtained by developing hardware and software interfaces (Gardner 1991, Dalto 1997, Kennelly 1997, Vawdrey 2007).Based on studies by these investigators, it is clear that

automatically collecting data from all of these devices in real-time is more timely and accurate than manually charted data collected by nurses or respiratory therapists. Although data from these devices can contain artifacts, methods for minimizing those artifacts have been implemented in operational systems.

It is unfortunate that the Medical Information Bus (MIB) standard (CEN ISO/IEEE 11073), designed to help gather data from bedside devices has not been more widely implemented (Mathews 2011). Section 19.3.4 gives the background of the issues. Fortunately, battery power and wireless communications with IV pumps are now widely available. By using wireless technology, interfaces with the IV pumps are fast, mobile and easy for nurses to implement and tangled wires are no longer an issue with the IV pumps. In addition, communications with IV pumps can be carried throughout the hospital – in the operating room, while on transport and in the ICU.

Although early studies of nurses and therapists showed that computerized charting took longer than manual charting, it is almost certain with automated acquisition available today that charting takes less time and is more accurate. As a consequence, in institutions that have historically collected IV pump and ventilator data automatically, there is a commitment to collect data from every bedside monitoring device. These include, measures of urine output, fluid drainage and similar measures.

19.4.4 Establishing Collaborative Care Processes

. The care of critically ill patients in the ICU requires collaboration among a diverse team of very competent care givers to achieve the best care (Clemmer 1998). The teamwork and communications required in this complex care process are unusual. Establishing a collaborative “care society” does not occur without thoughtful effort, with appreciation and respect for every team member. In the early years of working with the collaborative teams of nurses, therapists, pharmacists, physicians, and informaticians and attempting to implement complex computerized charting with decision support in the ICUs, Dr. Gardner often said “this process is 80% sociology and 20% technology”. Those observations are likely still true today - over 40 years later.

The rounds activity at LDS Hospital is an exemplar of the collaborative process. Figure 19.6 shows the clinical care team during rounds. There are physicians, house officers, advanced practice clinicians, nurses, pharmacists, respiratory therapists, dieticians, case managers, and others who gather each day to assess each patient and make key care decisions. The rounds leader is usually a physician, but each team member is considered an equal partner, providing key information (most of it stored in the computer record) and given the opportunity to discuss their interpretation and make recommendations about the patient’s care. Over decades, the social process of conducting these rounds has created a very open and cooperative environment. The purpose of rounds is to reduce errors from human factors, to give structure to the evaluation, and to make sure all sides of the decision process are considered as each member considers the decisions from their point of view. The information from the computer system is organized to support the process. The computerized record is *the* patient record. Information from other sources such as X-ray images and “free-text” reports are also readily available (Gurses 2006).

19.4.5 ICU Change-of-Shift and Handover Issues

Recently, cognitive scientists have taken an interest in and studied the dynamic and distributed work environment in critical care medicine (Patel 2008A, Patel 2008B, Ahmed 2011). They have studied issues such as provider task load, errors of cognition, and performance of clinicians involved in these complex tasks. The “change-of-shift” and “handover” times are especially critical and require complex exchanges of information that must occur rapidly and efficiently. These investigators have found that errors can occur during this time because of corruption of information and a failure to transfer crucial care facts. Having the majority of the patient record in electronic form and having that data timely and accurate should allow optimization of computerized decision making tools and methods for sharing the patient data. The Rounds Report developed at LDS Hospital three decades ago (Figure 19.8) and recent developments at the Mayo Clinic provide laboratory models for better

understanding the issues and improving efficiency and eliminating medical errors for ICU patients during shift changes and patient handover times (Pickering 2010, Ahmed 2011).

19.5 Computerized Decision Support in Intensive Care

In addition to the alarms from bedside monitors, there are many other types of alerts and decision support tools that can be helpful for the care of hospitalized patients. A sampling of the types of decision support mechanism that have been reported is provided below to give the reader a sense for the breadth of capabilities that have been applied in intensive care as well as other care settings of hospitals. Key to the application of such computerized decision support tools is having access to an integrated, real-time, accurate and coded EHR. Most of the examples noted are from the HELP system (Gardner 1999). A key function of the HELP system is that the computerized decision support system is activated when new patient data are added to the patient's database, the process is called "data-driven" decision making. An example would be when the pO2 is put into the medical record an instruction is given to the respiratory therapist to modify the FiO2 or PEEP accordingly. Some functions of the HELP system such as alerts require that computerized decision support be activated at specific times and that process is called "time driven" decision making. An example would be to remind the nurse the next glucose check is due when on an insulin drip, or instructing the computer to automatically calculate today's APACHE score and update all the reports at 06:00.

19.5.1 Laboratory Alerts

During the developmental period of the HELP system in the 1980's, it became apparent that on occasion life-threatening laboratory results were not being acted upon promptly. On acute care nursing floors, the initial alert response time averaged from 5.1 to 58.2 hours (Bradshaw 1989). By posting alerts on computer terminals on nursing floors, the average response time was reduced to 3.6 hours. Then a flashing light, similar to those found on road maintenance vehicles, was installed on each nursing floor. The average response time then decreased to six minutes but the light was very annoying to the nursing staff (Bradshaw 1989). Later, a sophisticated nurse paging system was set up that paged the particular nurse caring for the patient with the laboratory alert and required nurses to acknowledge the alerts (Tate 1995). The new pager system was equally effective and less annoying. Similar work was done by Shabot and associates at Cedars-Sinai Hospital in Los Angeles using a Blackberry pager (Shabot 1995). Since that time, wireless communications technology has improved dramatically and a variety of even better feedback mechanisms are now available. As a result of the early computerized laboratory alerting experiences, it was surprising to find a 2011 review article on the topic which concluded "The existing evidence suggests that the problem of missed test results is considerable and reported negative impacts on patient's warrants the exploration of solutions. Attention must be paid to integration of solutions, particularly those which involve information technology, into clinical work practices." (Callen 2011)

19.5.2 Ventilator Weaning Management and Alarm System

Weaning patients from ventilators was one of the first applications of a computerized expert system to routine patient care at Intermountain Healthcare's LDS Hospital. As a result of the nurse and respiratory therapist charting described earlier, it was possible to develop and test computerized ventilator management protocols. Patient therapy was controlled by protocol 95% of the time and 90% of the protocol instructions were followed by clinicians. Several of the computerized instructions not followed were due to ventilator charting errors. Patients cared for with the computerized protocol had required less positive pressure in the ventilator system, and physiological measures were disturbed less. The investigators concluded that such protocols could make the ventilator weaning processes "less mystifying, simpler, and more systematic" (East 1992). Since that early work, several other investigators have implemented similar ventilator weaning algorithms.

In the process of implementing automated charting of ventilator parameters at LDS Hospital (Vawdrey 2007), it became clear that critical ventilator alarms were being missed. As discussed

earlier, alarm sounds emitted from ventilators were blended with bedside monitor alarm sounds. As a consequence, when a patient became disconnected from a ventilator the alarms could be missed (Evans 2005). Once this situation was recognized, an enhanced notification system was implemented. Figure 19.9 illustrates a ventilator disconnect alarm presented on the patient's bedside display and on every other computer display in the same ICU. The efficacy and user acceptance of the new alarm system has enhanced patient safety and allowed documentation of this important clinical event.

19.5.3 Infectious Diseases Monitoring – Antibiotic Assistant

Early data available to the HELP system at LDS Hospital included microbiology culture results. Several programs were developed to present these results and predict pathogens and list most likely empiric antibiotic regimens. Based on the physician use of and approval of computerized **antibiograms**, empiric antibiotic suggestions, and a therapeutic antibiotic monitor, an anti-infective agent management program known as the "antibiotic assistant" was developed (Evans 1998). Figure 19.12 shows an example screen display from the program. The screen display was designed by infectious disease and critical care physicians who wanted a one-screen display of relevant data and recommendations. The upper section displays pertinent patient data, the middle sections displays suggested anti-infective agents along with dose, route and interval, and the lower panel provides quick and easy access to other relevant patient information. Over the past decade this antibiotic assistant has been implemented in Intermountain Healthcare's Primary Children's Medical Center (Mullett 2001) and 10 other large hospitals operated by Intermountain Healthcare.

19.5.4 Adverse Drug Event Detection and Prevention

Detection and prevention of **adverse drug events** (ADEs) has been a long term goal of care givers, the World Health Organization (WHO), and the U.S. Food and Drug Administration (FDA) (Classen 1991). Physicians, pharmacists, and informaticians at Intermountain Healthcare's LDS Hospital developed a computer-based ADE monitor that detected a variety of "triggers" in the EHR that could indicate potential ADEs, such as sudden medication stop orders, medication antidote ordering, and specific abnormal laboratory and physiologic results. Pharmacists followed up on each ADE alert and each was verified and categorized. During an 18 month period, 36,653 hospitalized patients were monitored and 731 true ADEs occurred in 648 patients -- 701 were classified as moderate or severe. Only 92 of the ADEs were identified by traditional voluntary reporting methods. Using this knowledge, the investigators developed methods for preventing ADEs. An example is the nurse charting work of Nelson (Nelson 2005). Figure 19.11 shows a printout of "possible Adverse Drug Events ADE for two days in the Thoracic ICU (TICU) at Intermountain Healthcare's Intermountain Medical Center.

Classen and colleagues followed up their earlier surveillance system for adverse drug events. They found that the attributable length of stay and costs of hospitalization for ADEs were substantial. If a patient had an ADE there was an increased length of stay of 1.74 days, an increased cost of $2,013, and an increased risk of death of 1.88 (Classen 1997).

Even with the enhanced computerized methods for detecting, preventing and monitoring adverse drug events, there is still room for improvement (Petratos 2010). Critically ill patients are particularly susceptible to ADEs due to their unstable physiology, complex therapeutic medications, and the large percentage of IV medications (Hassan 2010). Better systems must be developed and implemented to prevent ADEs.

19.5.5 IV Pump and Medications Monitoring

Intravenous medication administration occurs in 90% of hospitalized patients; virtually every ICU patient is connected to an IV pump to receive fluids, nutrients, and medications. Although so called "smart pumps" have been developed to minimize errors, those pumps are not yet integrated with the EHR and as a result are not capable of helping to prevent IV administration errors. Evans and associates at LDS Hospital have recently used cabled or wireless IV pumps integrated with the

HELP system to enhance notification of IV pump programming errors (Evans 2010).The medication charting system can detect and provide real-time alerts whenever an initial or potential pump rate programming error occurs. A set of 23 high-risk medications are monitored by the HELP system. Whenever IV pump flow rate for one of these medications is outside the acceptable range, a visual alert such as that shown in Figure 19.12 is presented on the bedside display and on all other computer displays in the same ICU. Over a two year period, they found that there were alerts on 4% of the initial or dose rate changes or about 1.4 alerts per day. Of those alerts, 14% were found to have prevented potential patient harm.

Clearly the monitoring and alerting system for ICU patients involves quite a different process and strategy than the usual bedside monitoring alarms. However, by having the integrated clinical record and the computerized decision support system available, these investigators have made major advances in minimizing ADEs and providing higher quality patient care.

19.5.6 Predictive Alarms and Syndrome Surveillance

In recent years a series of **machine learning** and surveillance methods have been developed to assist clinician decision makers in the care of complex care situations. The work of Lee and Mark at Harvard/MIT presents a methodology that has great promise (Lee 2010). These investigators used machine learning to see if they could use pattern recognition approaches to predict impending hypotension in intensive care patients. Using the high-resolution vital sign trends from the **MIMIC II Database**, they trained their system to predict impending hypotension. Although the results were not perfect, they were able to identify patients at higher risk for developing hypotensive episodes within the subsequent two hours, thus alerting busy clinicians to be vigilant to impending events. As of this writing, the system still needs to be tested in a clinical environment.

Herasevich and his associates at the Mayo Clinic have mined their Multidisciplinary Epidemiology and Translational Research in Intensive Care Data Mart to explore the ability to detect high-risk syndromes in the critically ill and to alert clinicians if therapy has not yet been started (Herasevich 2009, 2010, 2011). These investigators have provided excellent recommendations for development and use of large databases to allow better understanding of the complexities of patients who are critically ill.

19.5.7 Protocols versus Guidelines

Computerized decision support tools are intended to aid clinicians and enable them to deliver evidence-based care consistently. Several terms, including guidelines and protocols are used to describe these decision support tools. Protocols (also called algorithms) are detailed and provide explicit instructions for each clinical decision. In contrast, guidelines are more general statements of concepts and provide less instruction about specific clinical decisions (Morris 2003). Computerized protocols can be configured to contain much more detail than textual guidelines or paper-based flow diagrams. Several case studies of computerized protocols such as mechanical ventilation and management of intravenous fluid and hemodynamic factors in patients with acute respiratory distress syndrome have been studied. Protocols currently used at Intermountain Healthcare's Salt Lake City Hospitals are:

Computerized Protocols:
- Insulin infusion for glucose control,
- Ventilator management and weaning,
- Blood ordering,
- Antibiotic assistant,
- Total Parenteral Nutritional,

Paper Based Protocols:
- Potassium replacement,
- Magnesium replacement,

Phosphate replacement,
Subcutaneous insulin correction factor,
Heparin anticoagulation,
Fluid optimization,
Lasix Drip
Intracranial pressure control,
Sepsis treatment,
Enteral Nutrition
Pneumonia antibiotic selection

Although the paper based protocols could be computerized most are very simple consisting of one or two pages usually containing a simple look-up table. The reason they have not been computerized is for convenience, it is easier and faster for the nurse to have the protocol on their clip board and use the table rather than to log onto the computer to get the recommendation. When the protocols are more complex and require following complex flow diagrams or performing a set of calculations, the computer does a better job with fewer errors.

19.6 Tele-ICU Development

Tele-ICU is defined as the provision of care to critically ill patients by health care professionals located remotely. Tele-ICU clinicians use audio, video, and electronic links to assist the bedside caregivers in monitoring patients to help provide best practice and to help with the execution of optimized patient care plans. These types of systems have the potential of improving patient outcomes by having shorter response times to bedside monitor alarms and to abnormal laboratory values, initiating life-saving therapies, providing best practice more frequently, and providing expertise to smaller or remote ICUs where subspecialists are not readily available (Lilly 2011). Historically Tele-ICU concepts date back to the mid-1980s, but it was not until the early 2000's that there was a dramatic increase in the use of such systems (Breslow 2007).

19.6.1 What is Tele-ICU and how does it work?

Tele-ICU has built on the concepts of computerized patient monitoring discussed earlier in this chapter. The real-time, electronic patient record is fundamental to making Tele-ICU care practical. The clinical information system is one of the keys to allow clinicians not physically present in the ICU to be able to suggest appropriate care. The HELP system provides an example of such a clinical information system. Enhanced bedside data acquisition and alarm systems, as well as clinical decision support systems (such as those described above) are required if remote clinicians are to provide practical and effective care for patients located in multiple remote ICUs (Rosenfeld 2000, Celi 2001, Breslow 2007, and Lilly 2011). Table 19.3, gives an overview of the differences between a typical ICU with no electronic record compared with a Tele-ICU.

Table 19.3 Comparison of Typical ICU Care Processes with Tele-ICU Care Processes (Adapted from Lilly 2011)

Typical Current ICU	Tele-ICU
Bedside Monitor Alarms	Physiological trend alerts Abnormal laboratory value alerts Review of response to alerts Off-site team rounds
Daily Goal Sheet	Electronic detection of non-adherence Real-time auditing Nurse manager audits Team audits

Telephone case review initiated by house staff or affiliate practitioner	Workstation review initiated by intensivists including electronic medical record, imaging studies, interactive audio and video of patient, integrated with nurse and respiratory therapist and assessment of responses to therapy

19.6.2 Future Informatics Impact on Tele-ICU Care

Recent findings of the impact of Tele-ICU are encouraging and exciting. Patients receiving such care have lower hospital and ICU mortality and shorter hospital and ICU lengths of stay. Measures of adherence to best care practices are increased and complication rates are decreased (Lilly 2011). However, the investigators pointed out that they had to implement major process and culture changes in their "reengineering" activities to make their system work (Lilly 2010). An editorial accompanying the Lilly article outlines challenges still to be studied and understood about Tele-ICU (Kahn 2011). Since many changes were made from the typical ICU to the Tele-ICU intervention, simply adding better electronic data recording, electronic physiological surveillance and computerized decision support may have provided the same benefit – independent of the telemedicine feature. Informaticians clearly have exciting opportunities to improve care of critically ill patients and answer important process and intervention questions.

19.7 Implementation Strategies for ICU Systems with Computerized Decision Support

In the process of developing, testing, evaluating, and maintaining the HELP system for several decades, we have come to realize the complexity and challenges of implementing a sophisticated computerized medical decision support system (Gardner 2004). Five steps describe the primary issues and challenges. Those steps are illustrated in Table 19.4. A brief discussion of each of the steps is outlined below.

Table 19.4 ICU & Patient Monitoring System
Clinical Computerized Decision Making Strategy
(Adapted from Gardner 2004)

#	Step	Activities & Issues	Implementation Time
1	Acquire the Required Clinical Data	Decide WHAT data is required. Issues such as free-text with Natural Language Processing (NLP) vs. coded data. What coding system to use. Deciding WHO, WHEN, WHERE, HOW and HOW MUCH data will be entered.	5+ Years & Continuous Update
2	Establishing the Quality and Timeliness of the Required Data	Is the data accurate? Is the data entered promptly? Is the data representative?	2+ Years & Continuous Update
3	Decide How & Where to Present the Data	Display media - Printer, Terminal, Hand Held Device (cell phone, iPhone, iPad) Format, (e.g. numbers vs. graphics), Who gets to see the data and how. (Patient, Insurer, etc.) How to handle life-threatening Alert notifications?	6 Months & Continuous Update

4	Decide on the Decision Rules	Who is the Expert? Simple rule structure (IF, THEN, ELSE) vs. Complex structures such as Neural Nets, Bayesian, Logistic Regression, etc. How to implement alerts, alarms and protocols?	6 Months & Continuous Update
5	Executing the Decision Presenting the Results	Decision Support Computer System executes the Decision Rules based on the Data in the EHR and presents the decisions	Seconds

19.7.1 Acquiring the Data

A fundamental part of any computerized decision support system, just as with any human clinical decision support system, is the acquisition of data. Clinicians develop observational, interpersonal and technical skills as they collect accurate patient data. Likewise, a computerized decision support system depends on high-quality, timely data. In a typical ICU today, most medical data continue to be collected on paper flow sheets. Some of the data on those flow sheets are now being entered into computerized patient records in a structured and coded format while others (such as the progress note) are be stored in a free text format (either handwritten or typed) (Celi 2001, Pickering 2010, Ahmed 2011, Hripcsak 2011). As noted in Chapter 8, natural language processing of free text to obtain coded and structured information has seen dramatic improvement over the past decade; however, the process is still not perfect.

As system implementers look at acquiring and entering clinical data for computerized decision support they must decide:

- *Who* should enter the data: automated acquisition from electronic instruments (such as the bedside monitor) versus Manual entry using a keyboard, bar code reader, touch screen, voice input or some similar method
- *When* to enter the data: accurate ICU decision making often requires data to be acquired in a timely manner, sometimes within 1 minute of an event The decision about
- *Where to enter the data: this* automated data will naturally be acquired from the bedside monitor or instrument located at the bedside; manual data entry should optimally occur at the bedside as well
- *How* data should be collected: methods should take into account the occurrence of artifacts in the patient data; many EHR systems allow nurses to review and validate bedside vital sign data minutes to hours after they are collected, although this process does not meet the requirement for real-time data collection and can lead to “human” and computerized decision support errors (Nelson 2005, Vawdrey 2007)
- *How much* to collect: this is particularly an issues with systems such as bedside monitors that *can* generate a heart rate, systolic and diastolic blood pressure value for each heartbeat, resulting in hundreds of thousands of values per day; except for very special situations, the collection of such intensive data collection is inappropriate, but deciding on the appropriate amount to collect is not a trivial consideration and depends on the individual patient and the stage of their medical care

The process of developing and implementing the systems for acquiring data involves not only technology, but adapting that technology to the human users; training those users to properly use the system is complex and difficult. Consequently, developers and adopters of such systems should plan for and be prepared for challenges that may take five years to implement and optimize, with continuous monitoring and updating after the initial implementation required.

19.7.2 Establishing Quality and Timeliness of the Required Data

There are still major problems with acquiring ICU data either automatically or manually (Gardner 1989, Gardner 1991, Dalto 1997, Nelson 2005, Vawdrey 2007). Data from bedside monitors, ventilators and IV pumps should be acquired automatically with a real-time technology such as the Medical Information Bus. Data thus acquired is timely and by appropriate signal processing

methods can be validated (Dalto 1997, Vawdrey 2007, Ahmed 2011, Lilly 2011). Changes in ventilator settings such as FiO_2 may only be present for a few minutes, but blood-gas measurements taken during that time interval will be misinterpreted if only manual electronic charting is used. Similar interpretation errors were found to occur with IV Pump drip rate charting when manual charting methods were compared to automated acquisition. Gathering accurate, representative and timely computerized ICU data requires attention to detail and careful planning to assure its quality. When transitioning from a manual, on-paper charting system to a computerized system, the processes of gathering and recording data must change dramatically. As a consequence, establishing mechanisms to gather appropriate data may take two or more years, with continuous effort directed at updating quality processes.

19.7.3 Presentation of Data

Once data have been collected, their quality verified, and the results stored, one must decide how the data should be presented. Currently, most data are presented on a colorful screen similar to that shown in Figure 19.7. However, some care givers will still prefer a paper copy, so the Rounds Report shown in Figure 19.8 might be required. Still others will prefer to view these reports on their iPhones, iPads or other mobile devices. For ICU patients, it is clear that specialized reports must be developed. The traditional method of segmented reporting (separate reports for laboratory data, vital signs reports, medication lists, etc.) has proven inadequate (Clemmer 2004, Ahmed 2011). The ICU group at Mayo Clinic has recently presented their “ICU Summary Report” (Pickering 2010), which they have sought to patent. Thus, one can see there is value in the integration of and presentation of data. As of this writing, there is probably not a single ICU summary report that will satisfy all ICU users. Thus, such reports will require special effort for each institution and perhaps even each ICU within that institution. For example, the report generated for a thoracic ICU is unlikely to be identical to that required by the neonatal ICU. Accomplishing such tasks typically requires six months or more, with continuous ongoing effort to update the report as new data are acquired and care givers needs evolve.

19.7.4 Establishing the Decision Rules and Knowledge Base

Deciding on the decision rules that should be installed in a computerized ICU decision support system is difficult. Health care is currently driven by implementing evidence-based protocols. However, few of these protocols have been computerized. The long-standing work with the HELP system and some recent exciting work being done at the Mayo Clinic and at the University of Massachusetts are exceptions (Clemmer 2004, Morris 2000, East 1992, Ahmed 2011, Lilly 2011). Using a consensus process to develop treatment-decisions is essential. However, generating a consensus is a tedious, difficult and slow process. At the moment, the consensus process involving all the clinical care-givers in the ICU is the best approach, as rules developed by individuals are often not widely accepted or used. However, in some departments there may be trusted clinical leaders who become the “agreed to” local expert. Developing the rules for clinical decision support is complex and those rules are always subject to change. Development of appropriate rules can take up to 6 months and the rules will need to be continuously reviewed and updated (Gardner 2004, Ahmed 2011, Lilly 2011).

19.7.5 Execution of Computerized Decision Support Rules and Measuring Care Improvement

Once the four earlier steps have been completed, the rules must be included in the institution’s ICU system. In the past, commercially available ICU EHRs and stand-alone ICU systems did not have convenient methods for programming and execution of computerized decision support rules. However, recent surveys by Sitting and Wright have shown that more and more commercial vendor systems have improved capability for providing clinical computerized decision support (Sittig 2011, Wright 2011).

Once computerized decisions are made, they must be used to notify clinicians so that the feedback can be used to more effectively care for patients. The most common notification method is

presentation on the computer screen when a clinician is interacting with the computer in some task such as order entry or charting. However, as noted in some earlier examples such as laboratory alerting and ventilator disconnect alerts, the issues of *how* to notify and *who* to notify are much more challenging (Tate 1995, Shabot 1995). Further, verifying that such feedback results in the appropriate care is becoming ever more important. Research continues on identifying the most efficient and effective notification methods. Just as with the false alarms generated by bedside monitors, alarm feedback from computer systems must present timely and accurate recommendations with a minimum number of false alarms.

19.8 Opportunities for Future Development

Throughout this chapter, we have discussed many challenges and opportunities that remain in the field of "patient monitoring systems. There are still important opportunities in the development of better and more effective bedside monitoring systems, especially in the area of maximizing true alarms and minimizing false alarms. Integrating clinical data from a broad variety of hospital and personal records is still challenging and important. Being able to apply computerized decision support systems to warn of life-threatening situations or advise care-givers about optimum patient treatment strategies is still a relatively new aspect of health care. Development of patient care protocols and then having them be "executable" by computers, especially for ICU patients, is also a new and exciting field of endeavor. Below are other areas of opportunity for informaticians to enhance the field of patient monitoring. Enjoy the challenges and opportunities that these and similar tasks will give you. We still believe that applying informatics in the ICU is a "contact sport" – that is you must be involved at the patient care level and work with the incredibly talented clinical teams to maximize the benefits that biomedical informaticians can provide.

19.8.1 Evaluation of Value of Computerized ICU Care Processes

Challenges and opportunities lies in proving the value of health information systems. A recent review by Chaudhry and associates assessing the impact of health information technology on the quality, efficiency and cost of medical care is illustrative of the challenge (Chaudhry 2006). An even more sobering report was presented by Karsh and associates (Karsh 2010). These investigators suggest that not only is rate of adoption of health information technology low but in addition such technology may not have the benefits on improved quality of care or cost reductions touted.

19.8.2 Genomics Applied to the Critically Ill

The application of computational biology and new biomarker testing technologies to the critically ill and injured has exciting potential. The ability to detect the appropriate biomarkers of changes in gene expression induced by infection, shock, trauma or other inflammatory triggers is moving forward rapidly (Cobb 2008). Today, the diagnosis of infections uses genomic data to detect bacterial DNA and rapidly assist in the selection of the most appropriate antibiotics.

19.8.3 Closed-Loop Therapy

Since the early 1950's, when physicians began to understand control system theory, there has been a fascination with having control systems that "closed the loop" without the need for any human intervention. Implantable defibrillators and pacemakers are examples closed-loop devices. The natural outcome of the remarkable developments discussed in this chapter would seem to lead to closed-loop control of physiological processes. While many of the problems discussed earlier in this chapter continue to hamper efforts to develop such systems, we believe that the opportunity to do so is drawing near (Gardner 2009C).

19.8.4 Sharing Decision Support Rules – Alerts, Alarms and Protocols

Once alerts, alarms and protocols are developed that are shown to be effective in improving patient care, it will be incumbent on care givers to use those tools. Unfortunately, many of these decision support rules being developed have not been designed to use computerized decision

making systems. As a consequence, the biomedical informatics community will need to be much more active in the development and implementation process of sharable decision support rules for ICU patient care (see Chapter 22).

19.8.5 Commercialization of Patient Monitoring Systems

Initially patient monitoring systems such as the HELP System (Gardner 1998) were "home grown" by informatics research centers. Later, several hardware and software vendors began to supply specialty systems designed to interface with bedside monitors and other bedside devices. More recently, vendors of large hospital information systems have begun to adapt their systems to allow automatic acquisition of data from bedside monitors and also provide the level of nursing charting that meets the needs of the ICU patient. Today, companies like Philips, General Electric, Siemens and others have not only developed bedside monitors, but have also developed primarily stand-alone charting systems.

At the moment, there are a variety of alternative options for critical care units as they seek to have Patient Monitoring Systems. These include the following:

1. Local Development – Home grown
2. Vendor developed ICU System – Stand-alone
3. Vendor developed ICU System – Integrated with laboratory and Hospital EHR
4. Software interface applications from bedside monitors to existing Hospital EHR
5. Mixture of existing Hospital EHR systems with planning to have an integrated ICU system

One of the opportunities for clinical informaticians will be to help their hospitals select systems that enhance patient monitoring by not only enabling automated and real time acquisition of data from bedside monitors and bedside care devices such as IV pumps, but that will also enable clinicians to chart in real time such that computerized decision support systems will be available to optimize patient care.

19.8.6 Establishment of the Subspecialty of Clinical Informatics

With the leadership of the American Medical Informatics Association (AMIA), recommendations for the content of and the "fellowship" education for the medical subspecialty of clinical informatics has been established (Gardner 2009A, Safran 2009). Initially this subspecialty will only be for physicians. However, plans are under way to allow engineers, computer scientists and informaticians to eventually be able to achieve a clinical informatics certification. The opportunity to receive training and practice in the field of clinical informatics will provide a major boost to the profession and will have an energizing effect on advancing the implementation of and improvement of patient monitoring systems.

Suggested Readings

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Questions for Discussion

1. Describe how the integration of information from multiple bedside monitoring signals, the pharmacy and clinical laboratory data can help improve alarm systems used in an ICU.

2. How would you decide whether to buy a “stand-alone” ICU patient monitoring system versus an integrated EHR system?
3. How do care providers impact the installation and optimization of real-time data collection and real-time decision support?
4. Perhaps “real-time data collection” and “computerized decision support” are not necessary. How would you assess these issues? Is there sufficient literature to validate or disprove your supposition? If not, what is missing?
5. How would you go about selecting the optimum data for monitoring and improving the care of a critically ill patient?
6. How would you optimize a patient monitoring system that you were building or buying to provide the most accurate, timely and helpful computerized decision support capabilities? Be specific and give literature references to support your optimization plan.
7. If you were the Chief Clinical Information Officer of a large hospital without data from the ICU integrated into your EHR system, what factors would you have to consider to implement such a system AND to apply computerized clinical decision support to optimize such a system? How long do you think it would take to implement such a system?

TABLES

LEGENDS FOR FIGURES

Figure 19.1 Overall view of an ICU Patient’s room. Shown is a nurse standing at the bedside computer screen a ventilator (center) with a respiratory therapist suctioning the patient. The patient is connected to the ventilator, bedside monitor (upper right) and to three IV pumps (lower right).

Figure 19.2 Diagram of HELP the System used by Intermountain Healthcare’s Hospitals (including LDS Hospital in Salt Lake City). At the center is the database for the electronic health record (EHR). Data from a wide variety of clinical and administrative sources flow into the EHR. As the data flows into the EHR, the Data Driver capabilities of the HELP Decision Support System are activated. In addition Time Driven decisions are also made. Shown schematically, in the upper right hand corner of the diagram are blocks representing ICU bedside devices including the physiological monitor, ventilator, IV pumps and barcode scanner.

Figure 19.3 - Waveforms on Two Types of Bedside Monitors. Displays from the Philips (19.3A) and General Electric (19.3B) show the real-time beat-by beat from a patient’s bedside monitor with multiple channels of ECG along with the arterial blood pressure and pulse oximeter signals and their derived variables.

Figure 19.4 Ventricular Tachycardia (VT) Alarm Conditions. Figure **A** shows a true alarm; note that the ventricle is still pumping but that the arterial pulse pressure is dramatically reduced. Figure **B** shows a false alarm caused by artifact in the ECG signal; note the arterial blood pressure waveform is stable during the same time interval. ECG = Electrocardiogram, ABP = Arterial Blood Pressure.

Figure 19.5 Arterial Hypotension Alarm Conditions. Figure **A** shows a true alarm; note the normal ventricular beats followed by ventricular fibrillation that causes the renders the heart unable to generate an effective blood pressure. Figure **B** shows a false alarm; note for some non-physiological reason the arterial pressure signal loses its pulsatile characteristics and then eventually it returns.

Figure 19.6 ICU Rounds room at LDS Hospital in Salt Lake City. The compuerized ICU "rounds report" is displayed by a projector on the wall to physicians, a nurse practitioner, medical students, a respiratory therapist, a pharmacist, and a patient's family member. An important laboratory result is highlighted in red by the rounds director. Note several laptops *and* paper notes used by each of the participants.

Figure 19.7 Close-up of the Rounds Report. A set of laboratory tests is highlighted by the Rounds Director to draw attention to the abnormal findings. See Figure 19.6 for the context of the "Rounds Room" configuration.

Figure 19.8 Printed 24 Hour Rounds Report from Intermountain Healthcare's LDS Hospital

Figure 19.9 Ventilator Disconnect Alarm. This is for the patient in Room #645, but it is displayed on every computer screen in that particular ICU.

Figure 19.10 Screen Display of "Antibiotic Assistant". The display provides relevant patient data, current antibiotics, and antibiotic therapy suggestion for this particular patient as well, at the bottom of the screen is a list sites for review of other important patient information.

Figure 19.11 Possible Adverse Drug Event (ADE) for two days for the TICU at Intermountain Healthcare's Intermountain Medical Center.

Figure 19.12 IV Pump Alert. This is for Pump #305 located in Room E601, but it is displayed on every computer screen in that particular ICU.

Chapter 19 – REFERENCES Alphabetic by Year 26 Nov 11

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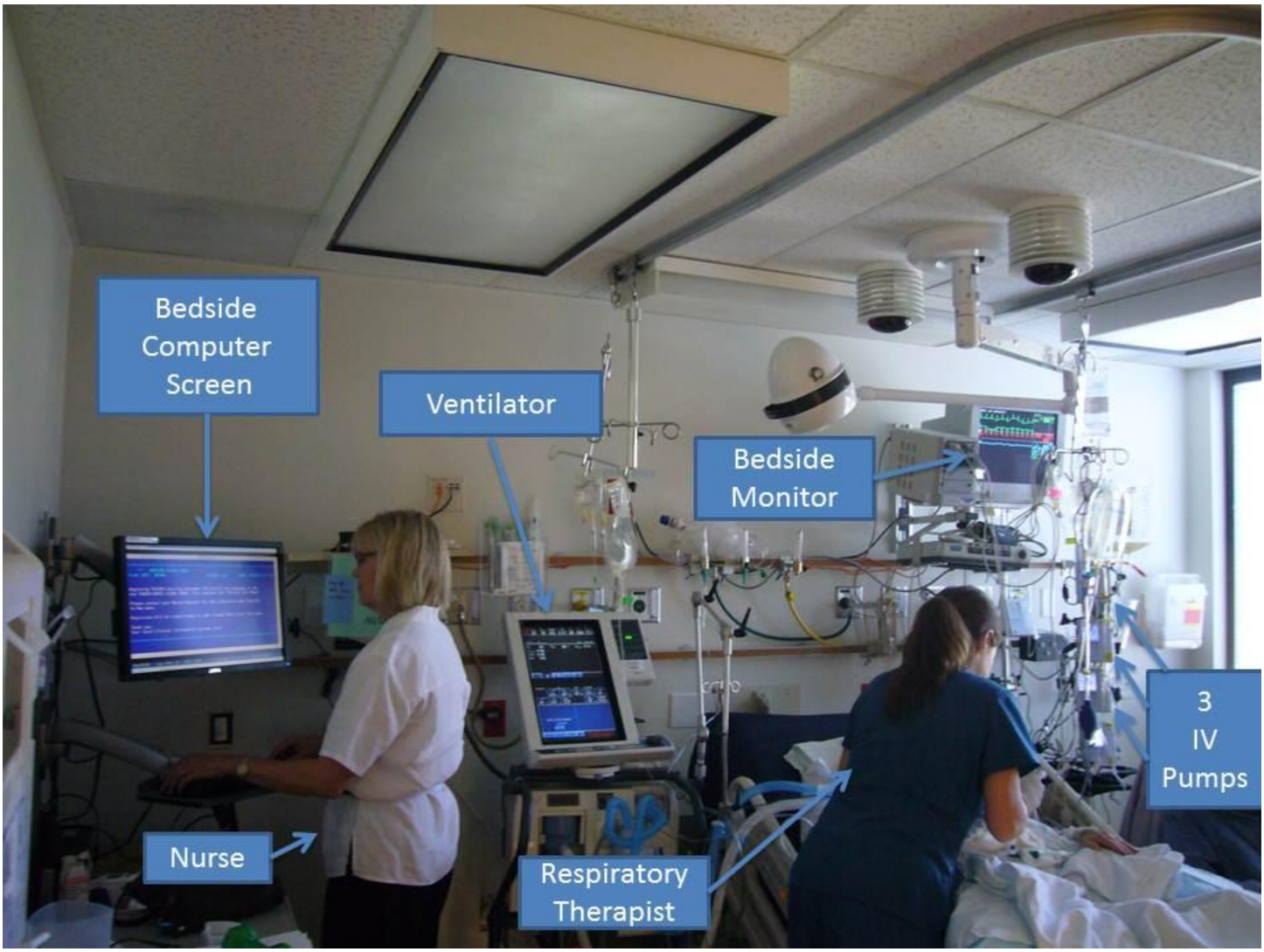


Figure 19.1 Overall view of an ICU Patient's room. Shown is a nurse standing at the bedside computer screen a ventilator (center) with a respiratory therapist suctioning the patient. The patient is connected to the ventilator, bedside monitor (upper right) and to three IV pumps (lower right).

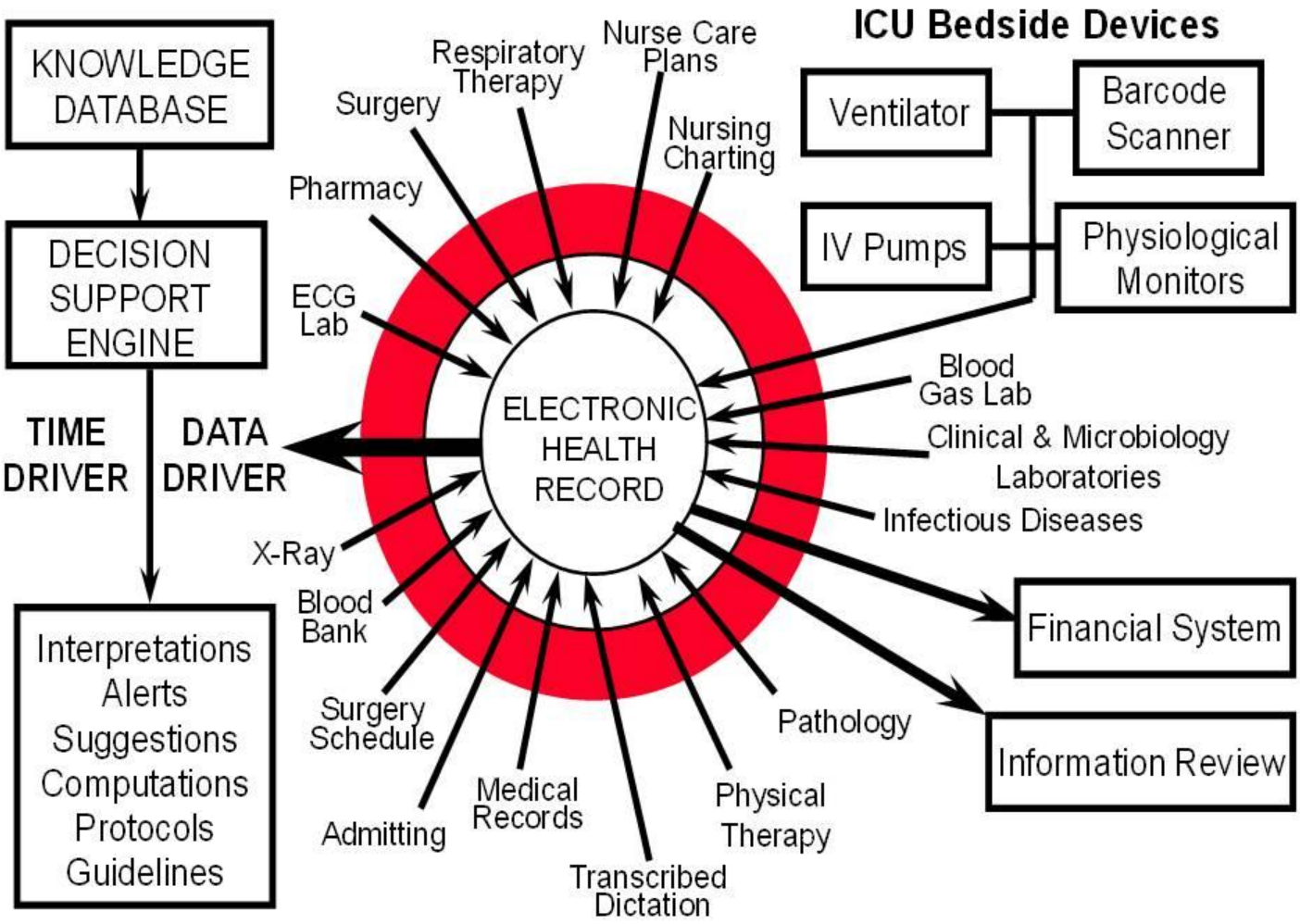
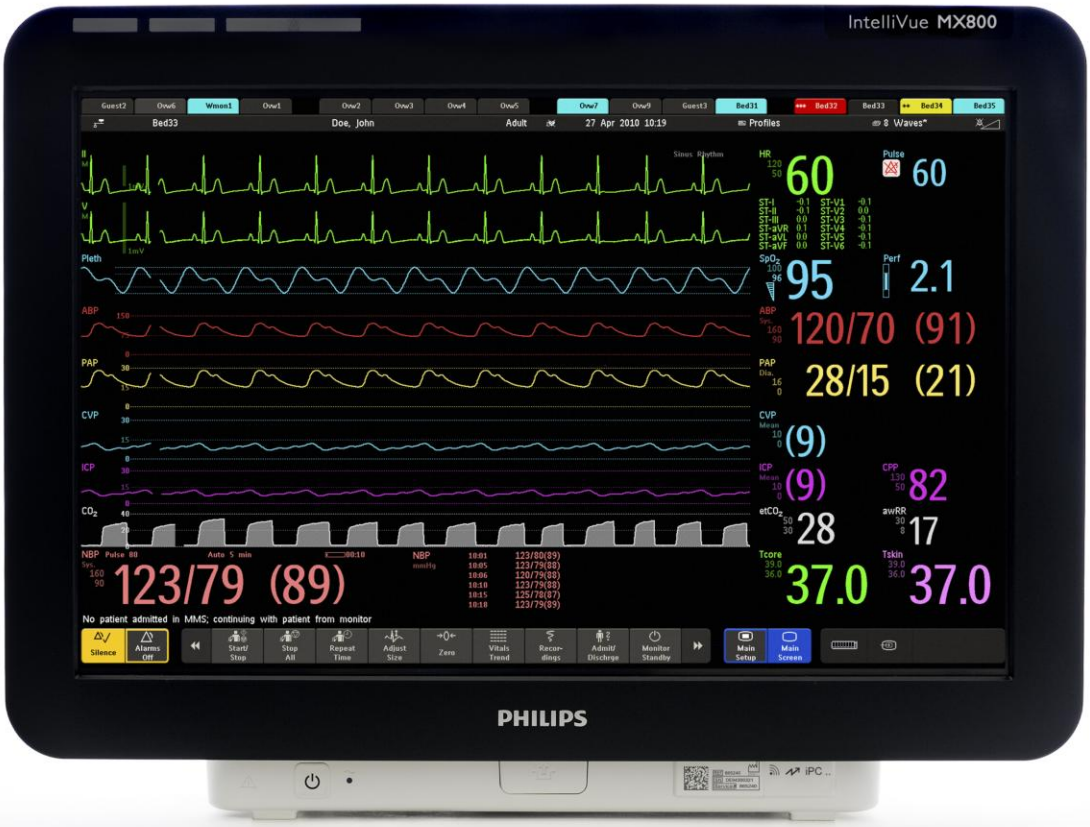
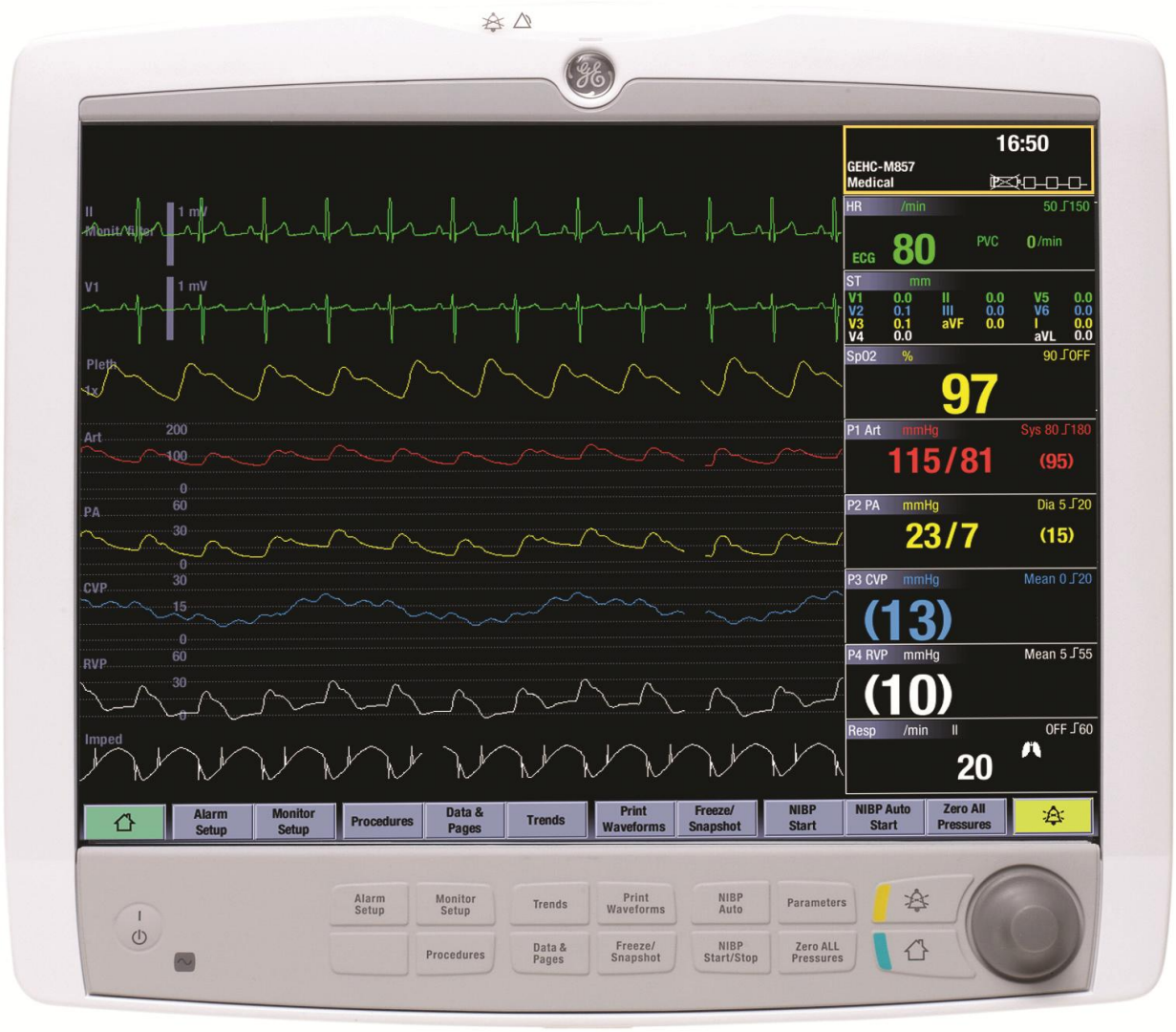


Figure 19.2 Diagram of HELP the System used by Intermountain Healthcare's Hospitals (including LDS Hospital in Salt Lake City). At the center is the database for the electronic health record (EHR). Data from a wide variety of clinical and administrative sources flow into the EHR. As the data flows into the EHR, the Data Driver capabilities of the HELP Decision Support System are activated. In addition Time Driven decisions are also made. Shown schematically, in the upper right hand corner of the diagram are blocks representing ICU bedside devices including the physiological monitor, ventilator, IV pumps and barcode scanner.



A

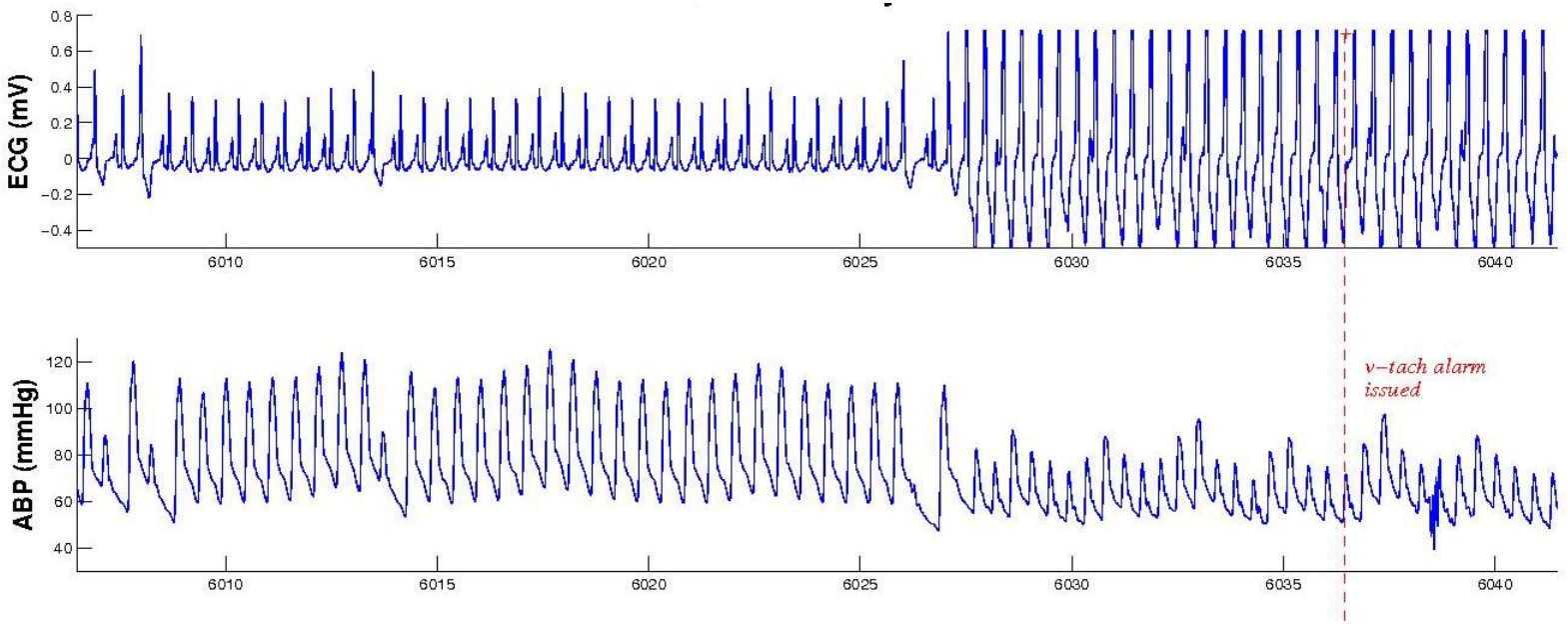
Figure 19.3 A



B

Figure 19.3 - Waveforms on Two Types of Bedside Monitors. Displays from the Philips (19.3A) and General Electric (19.3B) show the real-time beat-by beat from a patient's bedside monitor with multiple channels of ECG along with the arterial blood pressure and pulse oximeter signals and their derived variables.

A



B

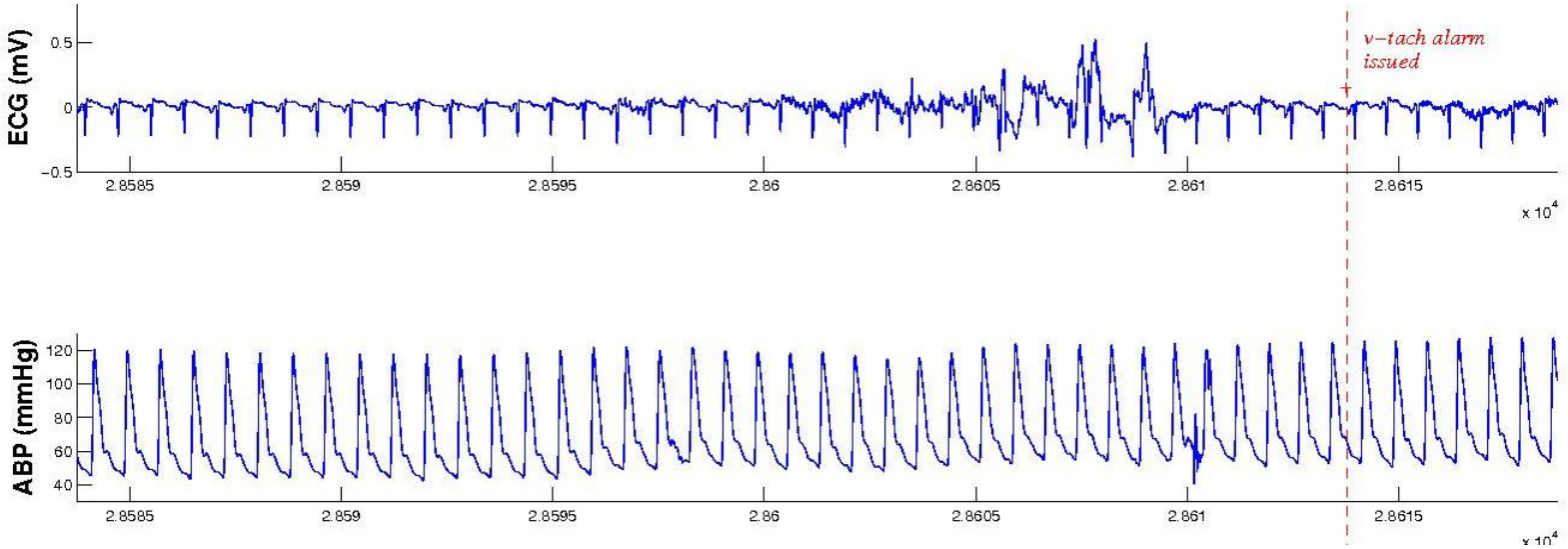
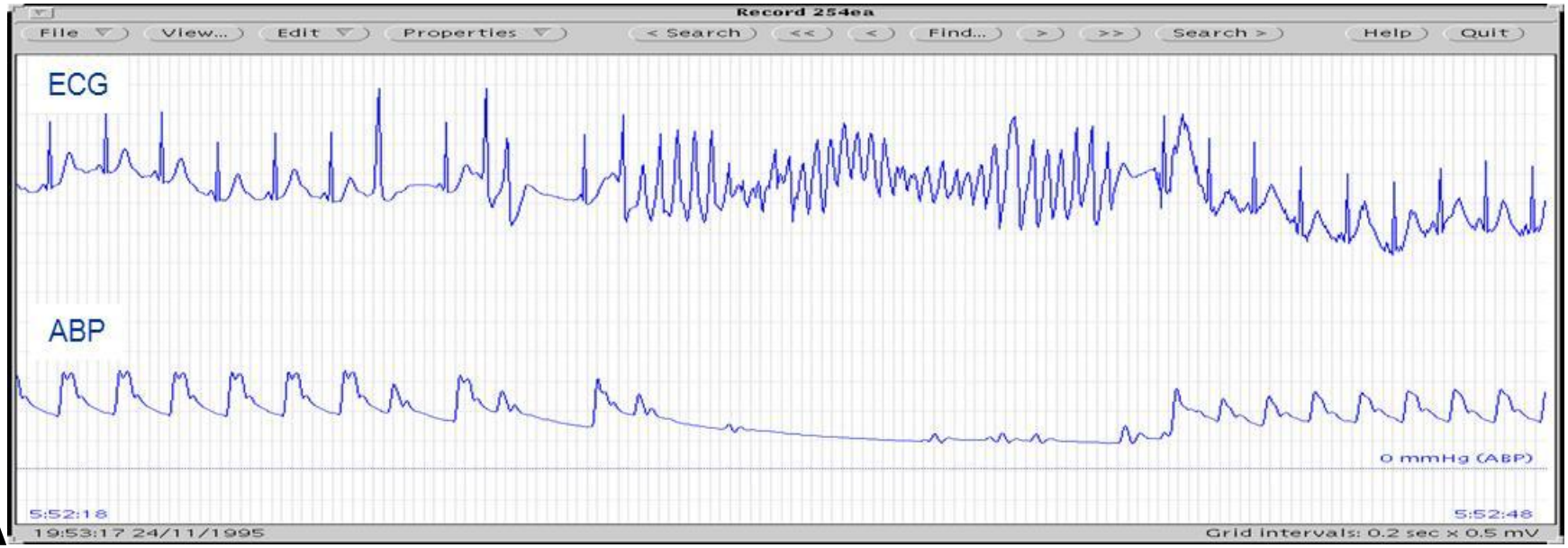
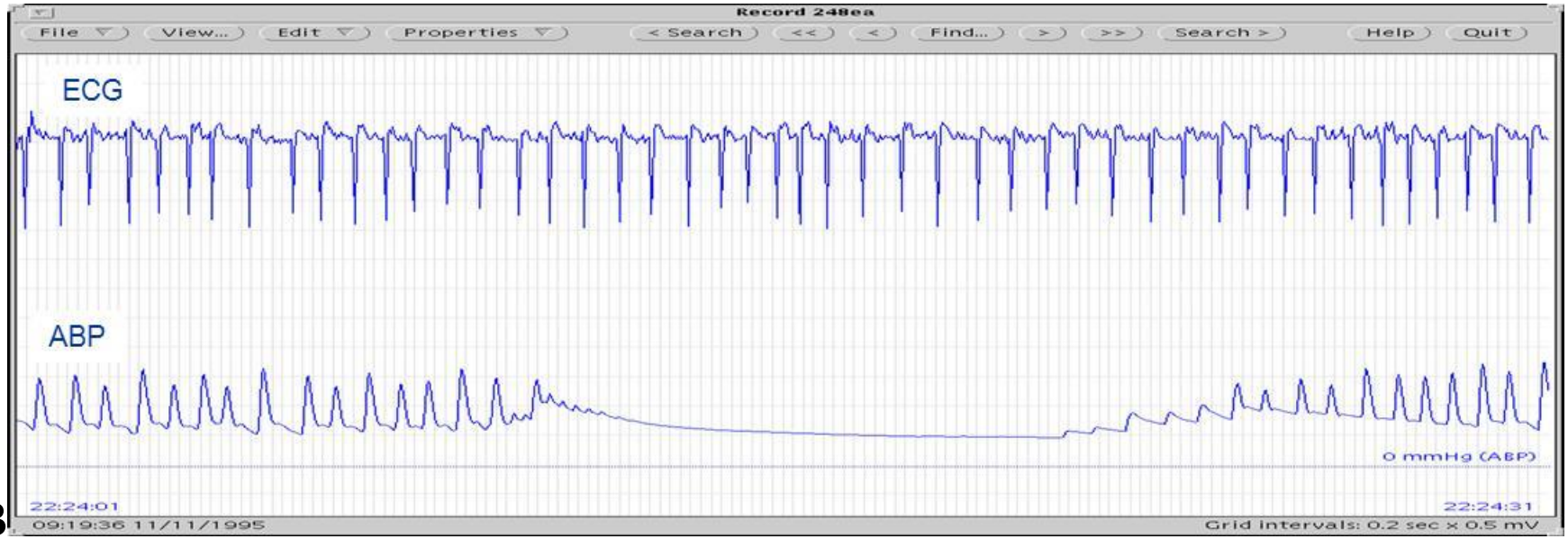


Figure 19.4 Ventricular Tachycardia (VT) Alarm Conditions. Figure **A** shows a true alarm; note that the ventricle is still pumping but that the arterial pulse pressure is dramatically reduced. Figure **B** shows a false alarm caused by artifact in the ECG signal; note the arterial blood pressure waveform is stable during the same time interval. ECG = Electrocardiogram, ABP = Arterial Blood Pressure.



A



B

Figure 19.5 Arterial Hypotension Alarm Conditions. Figure **A** shows a true alarm; note the normal ventricular beats followed by ventricular fibrillation that causes the renders the heart unable to generate an effective blood pressure. Figure **B** shows a false alarm; note for some non-physiological reason the arterial pressure signal loses its pulsatile characteristics and then eventually it returns.

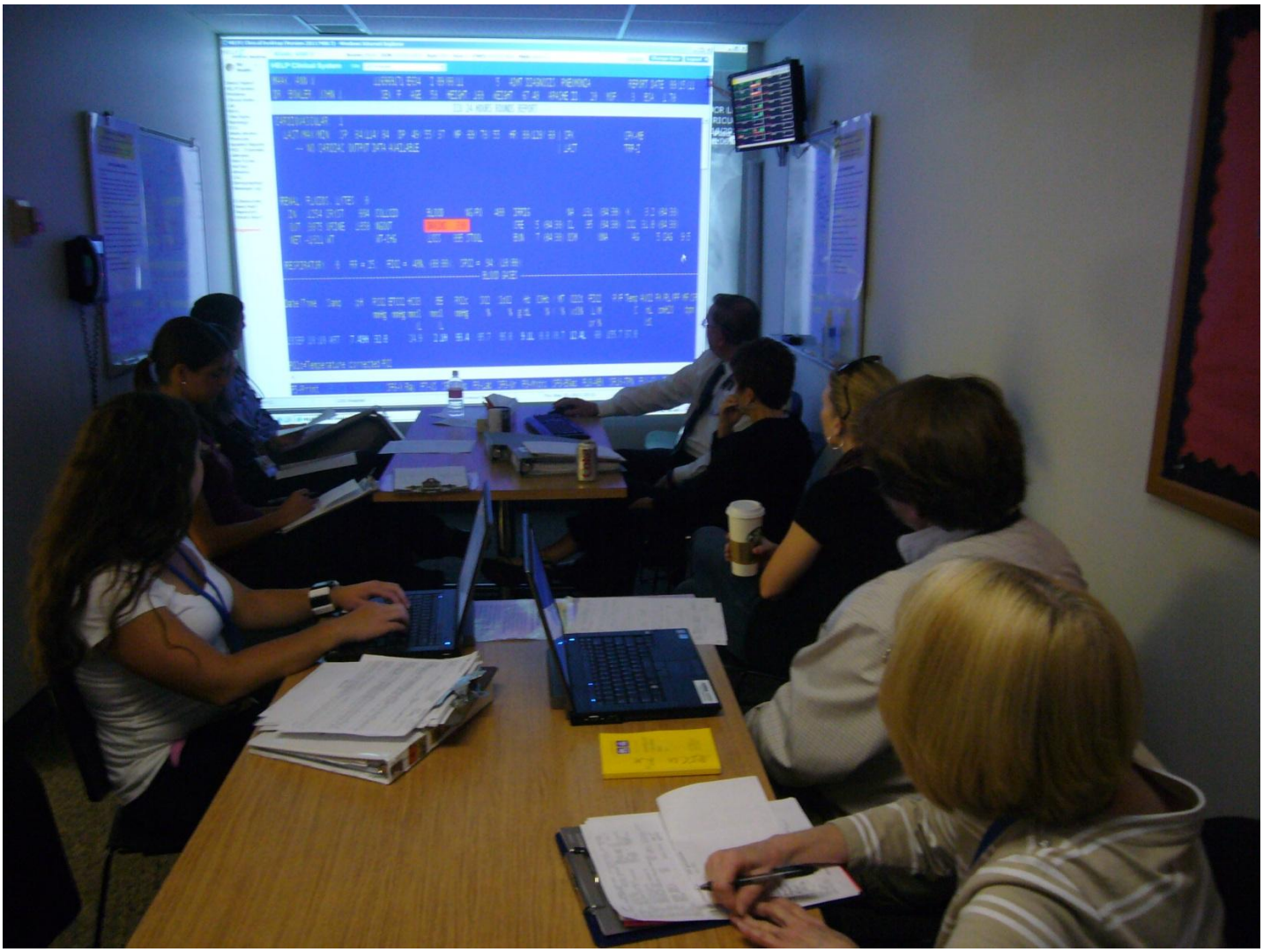


Figure 19.6 ICU Rounds room at LDS Hospital in Salt Lake City. The compuerized ICU “rounds report” is displayed by a projector on the wall to physicians, a nurse practitioner, medical students, a respiratory therapist, a pharmacist, and a patient’s family member. An important laboratory result is highlighted in red by the rounds director. Note several laptops *and* paper notes used by each of the participants

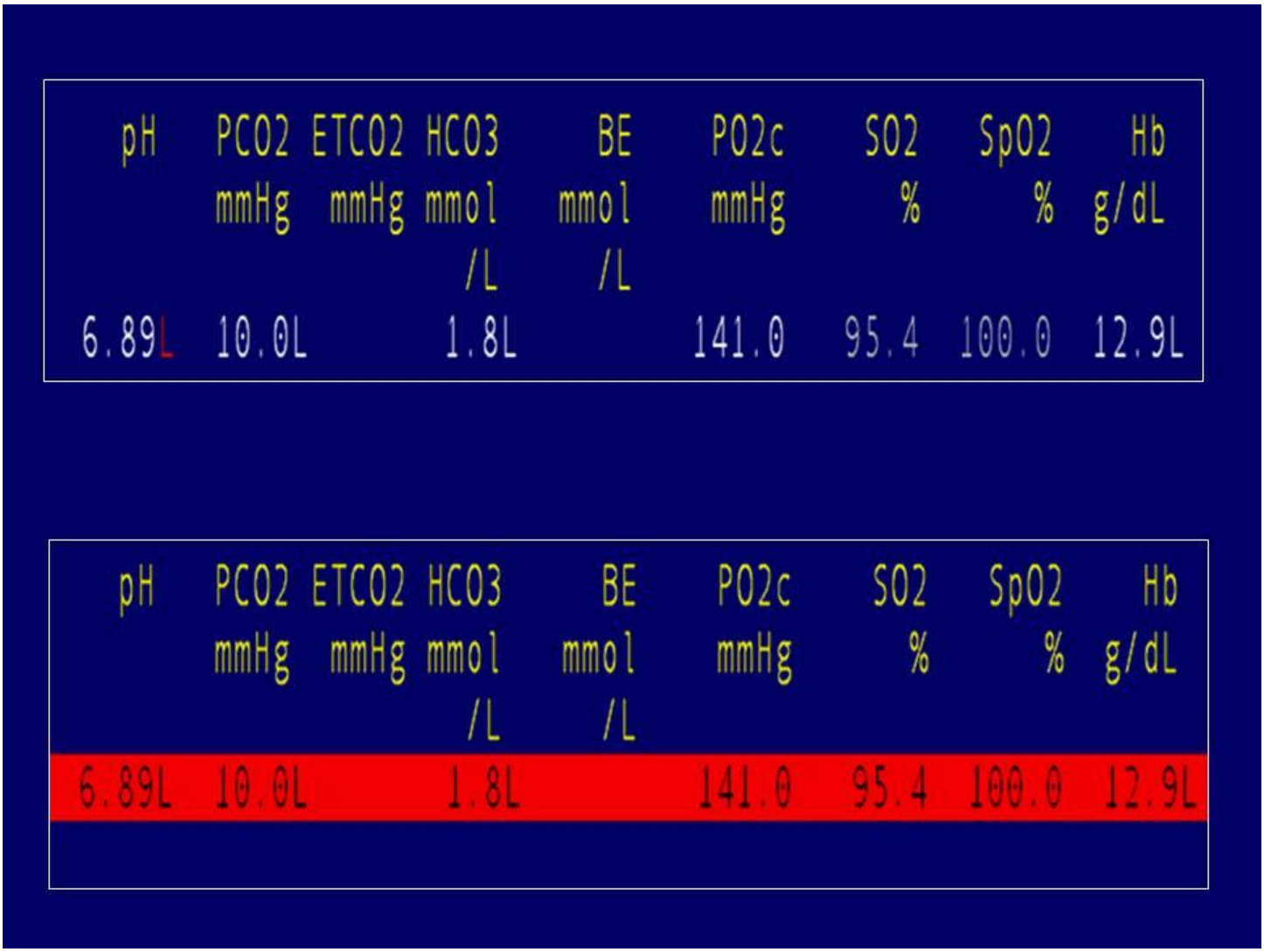


Figure 19.7 Close-up of the Rounds Report. A set of laboratory tests is highlighted by the Rounds Director to draw attention to the abnormal findings. See Figure 19.6 for the context of the “Rounds Room” configuration.

Doe, Jane Q 000000000 T599 I 07/19/11 4 ADMT DIAGNOSIS: SEPSIS, PNA, ESRD REPORT DATE: 07/29/11
DR. KRAFT, ADAM M. SEX: F AGE: 45 HEIGHT: 167 WEIGHT: 112.40 APACHE II: 18 MOF: 7 BSA: 2.18

CARDIOVASCULAR: 1
LAST/MAX/MIN SP: 96/110/ 79 DP: 47/ 55/ 22 MP: 59/ 65/ 44 HR:110/110/ 45 | CPK 60 (08:46) CPK-MB 3 (08:46)
-- NO CARDIAC OUTPUT DATA AVAILABLE CVP 6 (14:00) | LACT 5.4 (09:35) TRP-I 1.13 (08:46)

RENAL, FLUIDS, LYTES: 1
IN 4271 CRYST 2996 COLLOID BLOOD NG/PO 1170 IRRIG NA 139 (09:35) K 4.2 (09:35)
OUT 5301 URINE 1650 NGOUT DRAINS 3175 CRE 1.1 (03:09) CL 117 (09:35) CO2 19.0 (03:09)
NET -1030 WT WT-CHG LOSS 476 STOOL BUN 48 (03:09) OSM UNA AG 3 CAG 9.0

RESPIRATORY: 0 RR = 11; FIO2 = 2.0; (28 22); SPO2 = 94; (14:15);

---------- BLOOD GASES ----------

Date/Time	Samp	pH	PCO2 mmHg /L	ETCO2 mmHg /L	HCO3 mmol	BE mmol	PO2c mmHg	SO2 %	SpO2 %	Hb g/dL	COHb / MT % / or %	O2Ct % vol%	FIO2 L/M	P/F	Temp C	AVO2 mL /dl	PK/PL/PP cmH2O	MR/SR bpm
29JUL 09:35	MIXV	7.31L	35.7		17.3L	-7.8	57.7	86.7		11.4L	2.4H/0.4	13.9	2		36.0			
28JUL 21:10	ART	7.38L	29.0		16.7L	-7.0	110.0	95.8	98.0	11.6L	2.6H/0.6	15.8	2	5500.0	37.0			
27JUL 11:55	ART						96.0					21			37.0			

PO2c=Temperature corrected PO2

-- NO SPONTANEOUS PARAMETERS WITHIN THE LAST 24 HOURS –

NEURO AND PSYCH: 0 SLEEP 6 07/29 06:00 LAST EYE OPENING 4 LAST MOTOR 6 LAST VERBAL 4 07/29 14:00

	6	12	18	0	6
GCS [3-15]	15		15	15 14 13 15 14	
RASS [-5 to 4]					
CAM-ICU[+/-/S]					
PAIN [0-10]	0		3	5 8 7 7 7 10 6	
ICP [0-99]					

COAGULATION: 2
PT 38.9 (03:09) INR 4.0 (03:09) PTT 75 (11:28) PLATELETS 30 (03:09) FIBR 172 (11:25) D-DIMER
B-TYPE NATRIURETIC PEPTIDE:
BNP

METABOLIC --- NUTRITION: 0 BEE 1806
KCAL 0 GLU 165 (03:09) ALB 1.6 (03:09) CA 7.2 (03:09) TRG
KCAL/N2 0 UUN I-CA 1.2 (09:35) PO4 4.3 (08:46) MG 3.1 (03:09) CHOL

GI, LIVER, AND PANCREAS: 3 / 0
HCT 33.0 (03:09) TOT BILI 5.7 (03:09) ALT 65 (03:09) ALKPO4 102 (03:09) LDH LIPASE AMONIA
GUAIAC DIR BILI AST 40 (03:09) GGT AMYL GAST Ph

INFECTION:
WBC 13.0 (03:09) TEMP 36.7 (28 21) DIFF: EARLY FORMS 0, P 88, L 3, M 4, E 5(03:09)
Positive Micro Results, F10 for more information

SKIN AND EXTREMITIES: Braden Score 15 (28 22)

PALLIATIVE CARE:
Symptom Rx: Last Family Conference: Goals of Care:

ICU ROUTINES:
DVT Prophylaxis: Stress Ulcer Prophylaxis:PANTOPRAZOLE (ProT Activity / Fall Risk:

PROTOCOLS:
Feed___ Vent___ Oxygenation___ Insulin___ Fever___ Sed___ Heparin___ K___ Brain___

MEDICATIONS:

HYDROmorphOne (DILAUDID) 1.9 MG	LACTULOSE, SOLUTION 60 GM	URSODIOL (ACTIGALL), CAP 900 MG
ASPIRIN, TABLET CHEWABLE 324 MG	SODIUM CHLORIDE 0.9%, IV 1300 ML	OMEPRAZOLE (PriloSEC), C 20 MG
CefTAZIDime (FORTAZ), AD 6000 MG	POTASSIUM CHLORIDE (10%) 20 MEQ	INSULIN ASPART (NovoLOG) 3 UNITS
LINEZOLID (ZYVOX), IV SO 1200 MG	SODIUM CHLORIDE 0.9% (SA 8 EA	**INJ** HydrocorTISone (50 MG
RiFAXimin (XIFAXAN), TAB 1100 MG	LACTATED RINGERS, IV SOL 1000 ML	BIVALIRUDIN (ANGIOMAX), 32 MG
SODIUM CHLORIDE 0.9%, IV 25.6 ML	MESALAMINE (PENTASA), CA 4000 MG	
POTASSIUM PHOSPHATE/NACL 10.1 MMOL	ONDANSETRON (ZOFRAN), VI 4 MG	

INVASIVE LINE: TYPE SITE/.../DAY Central line: R/ 9;

--- End of Report ---

Figure 19.8 Printed 24 Hour Rounds Report from Intermountain Healthcare's LDS Hospital

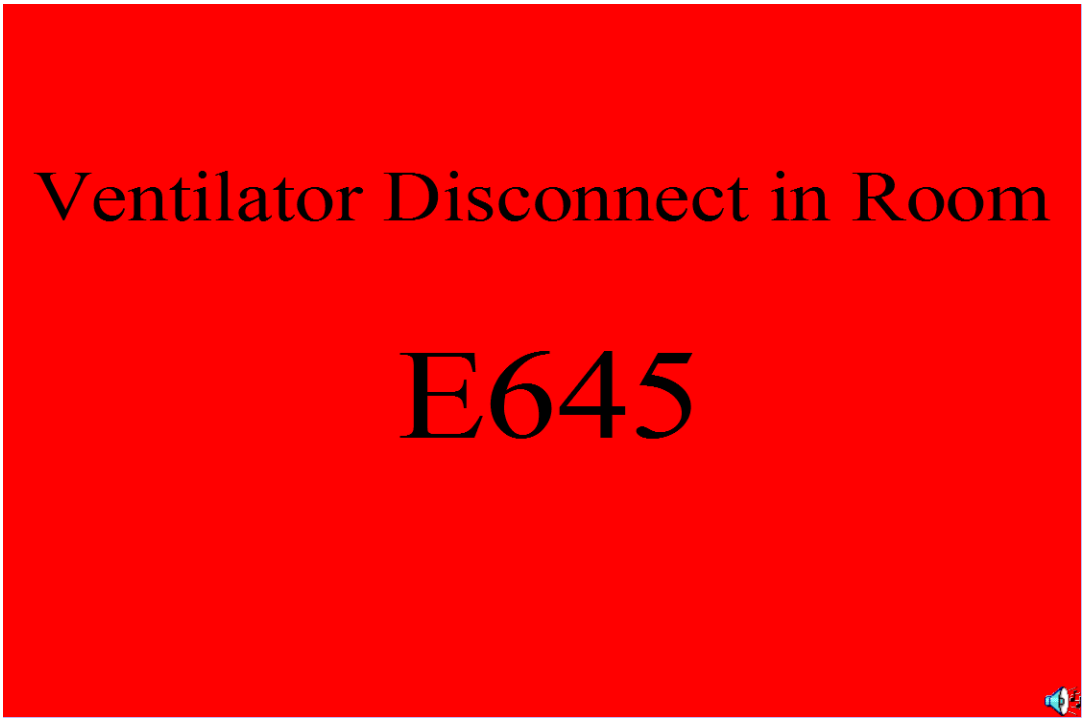


Figure 19.9 Ventilator Disconnect Alarm. This is for the patient in Room #645, but it is displayed on every computer screen in that particular ICU.

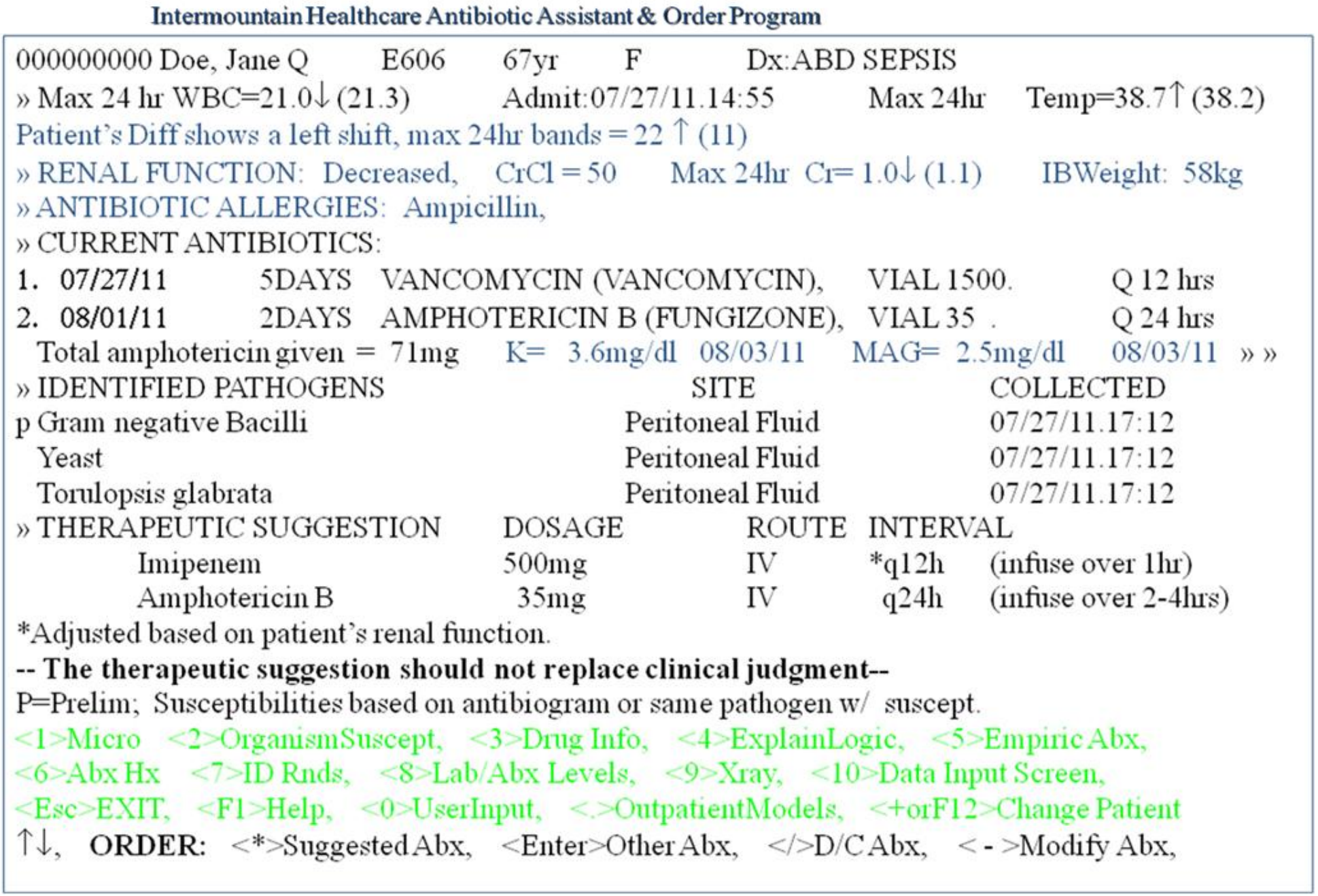


Figure 19.10 Screen Display of "Antibiotic Assistant". The display provides relevant patient data, current antibiotics, and antibiotic therapy suggestion for this particular patient as well, at the bottom of the screen is a list sites for review of other important patient information.

INTERMOUNTAIN MEDICAL CENTER
POSSIBLE ADVERSE DRUG EVENT REPORT
FOR 29 AUG 2011
FOR 2 DAYS BACK ON TICU
PRINT TIME: 8/29/11.10:51

***** 08/26/11.17:55 SBP < 90, DOWN 20 WITHIN 48HR & ON HYPOTENSIVE DRUG
@PAT: 000000001 Doe, Roger Q. 82Y M S999 MR#: 111111
DOC: 00009 Jones, John L.
ADMITTED: 08/21/11.20:15 ADMIT DIAG: SYCOPE

***** 08/27/11.00:10 PATIENT W/ DOUBLING OF CR
@PAT: 000000002 Lake, Brent H. 64Y M S999 MR#: 111121
DOC: 00008 Smith, James Q.
ADMITTED: 08/13/11.00:40 ADMIT DIAG: VASCULAR INSUFFICIENCY

***** 08/27/11.01:25 GLUCOSE > 350 mg/dL
@PAT: 00000003 Wright, Ruth P. 73Y F S999 MR#: 111131
DOC: 00007 Young, Andrew R.
ADMITTED: 08/23/11.00:09 ADMIT DIAG: PULMONARY EDEMA

Figure 19.11 Possible Adverse Drug Event (ADE) for two days for the TICU at Intermountain Healthcare's Intermountain Medical Center.

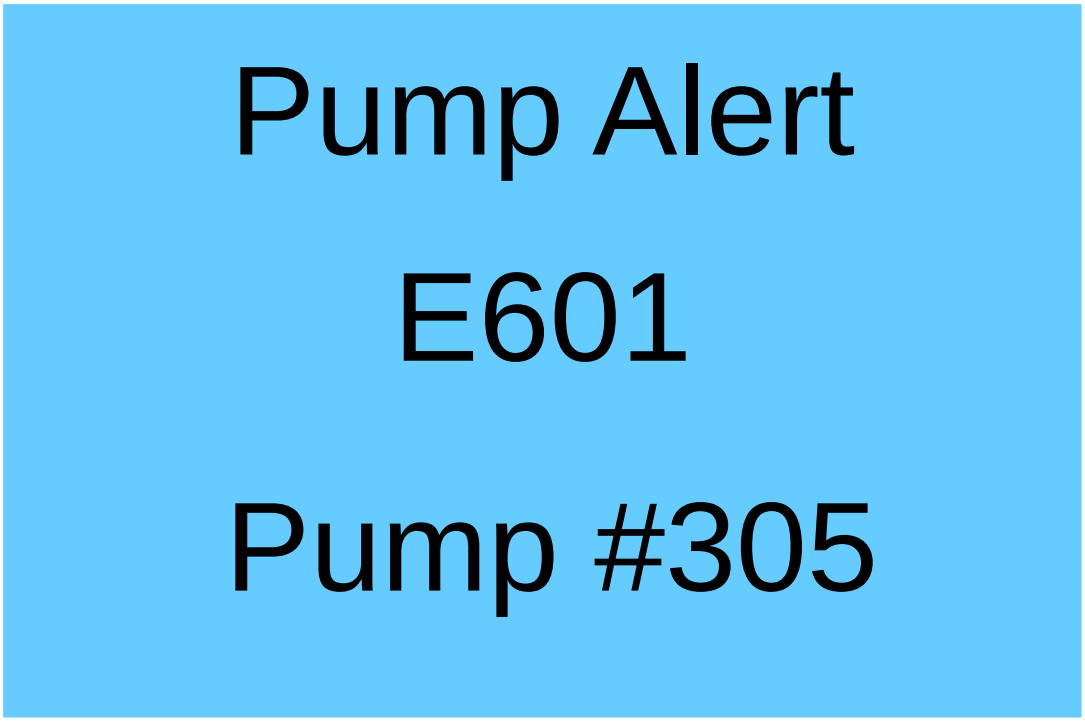


Figure 19.12 IV Pump Alert. This is for Pump #305 located in Room E601, but it is displayed on every computer screen in that particular ICU.