Chapter 5

PHYSIOLOGICAL MONITORING

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INTRODUCTION

Physiological monitoring of combat casualties is often compared unfavorably with monitoring as it is done in civilian trauma situations. However, those who make this comparison are usually not cognizant of the significant differences between the management of trauma in civilian versus military settings. Especially important are the severe constraints that logistics place on the availability of monitoring equipment and the vulnerability of sophisticated monitors to the rough-and-tumble environment of combat zone hospitals. Another important difference is the number of casualties needing care: mass casualties are all too common in wartime.

The type of monitoring for anesthesia and surgery in the field depends on the echelon of care (the casualty flow through the echelons of care is illustrated on page xv in the opening pages of this book). The spectrum extends from the austerity of the battalion aid station (first echelon) and the medical company (second echelon) through the intermediate capability of mobile army surgical and combat support hospitals (third echelon) to the complexity found in general hospitals and in medical centers in the continental United States (fourth echelon).

Another factor determining the sophistication or even the possibility of monitoring will be the number of casualties requiring care. Obviously, the number of casualties is beyond the control of an individual medical unit. In a mass casualty situation, the overriding goal will be to use the available monitoring resources to do the greatest good for the largest number of casualties. The goal of monitoring then becomes one of deciding who needs monitoring and which monitoring devices to use. The standards of care seen in medical centers, or even in small community hospitals, in the continental United States may have to be altered to conform to the reality of the battlefield. Although the standards applied on the battlefield may be unfamiliar to those trained in a modern medical facility equipped with the latest technical devices, this does not mean that medical care in the field is inadequate.

Military trauma anesthesiologists must resist the tendency to become dependent on sophisticated devices such as monitors. Extremes of temperature; delays; and damage to equipment due to transport, dust, or other environmental conditions may all require innovative approaches to monitoring the combat casualty. Flexibility in using more basic (low-tech) monitors is also desirable. The U.S. Army Medical Department should ensure that anesthesia care providers play a role in helping logisticians decide which equipment should be available in field hospitals.

This chapter is divided into two sections. The first deals with the type of monitoring likely to be found in medical treatment facilities from the first through the fourth echelons; the second section deals with the monitors used to evaluate the various body systems. Wherever possible, the principles of monitoring are related to the practical aspects of field anesthesia care.

MONITORS IN THE ECHELONS OF CARE

The monitors that military anesthesia providers can expect to find vary with the level of care from austere through intermediate to complex (Table 5-1). Each unit will, no doubt, modify the list of equipment supplied. Specifically, individual military trauma anesthesiologists will likely go to considerable lengths to obtain (from their colleagues) monitoring equipment not officially included in their units' Table of Organization and Equipment.

First and Second Echelons

Austere conditions prevail at unit- and division-level medical facilities of the first and second echelons as well as forward surgical teams deployed below corps. Although only the most basic devices for monitoring casualties will be found at these levels of care, initial surgery to make the casualty transportable may be necessary. Ideal circumstances would allow monitoring of pulse, ventilation, oxygenation, and blood pressure during monitored anesthesia care or general or regional anesthesia. However, in austere battlefield conditions, general anesthesia will be provided in emergent situations only, and will most likely be provided via the drawover system and not the portable anesthesia machine. Most monitoring will be for procedures carried out with local or possibly some form of regional anesthesia.

Monitoring at the first and second echelons may consist of recording only vital signs (blood pressure, respirations, and heart rate) and the physical examination. The monitoring equipment available, which needs to be sturdy and transportable, may be

TABLE 5-1

RECOMMENDED EQUIPMENT AVAILABILITY AND MONITORS REQUIRED

Equipment Available	Physiological Parameter	Monitor Required
Austere (First and second echelons)	Hemodynamics	Manual blood pressure cuff Precordial stethoscope
	Temperature	Thermometer
Intermediate (Third echelon)	Hemodynamics	Blood pressure Precordial stethoscope Electrocardiograph
	Temperature	Thermometer
	Urinary output	Foley catheter Specific gravity Sodium concentration
	Respiration	Pulse oximeter
	Blood components	Laboratory analyses (hematocrit, electrolytes, blood urea nitrogen, creatinine, prothrombin time/partial thromboplastin time, whole-blood clotting time, activated clotting time)
	Other	Nerve stimulator Oxygen analyzer Capnography
Complex (Fourth echelon and higher)	Hemodynamics	Blood pressure Precordial stethoscope Electrocardiograph A-line Central venous pressure Pulmonary artery catheter
	Temperature	Thermometer
	Urinary output	Foley catheter Specific gravity Sodium concentration
	Respiration, airway pressure, lung compliance	Pulse oximeter Ventilator pressure gauges
	Blood components	Laboratory analyses (hematocrit, electrolytes, blood urea nitrogen, creatinine, prothrombin time/partial thromboplastin time, whole-blood clotting time, activated clotting time)
	Other	Nerve stimulator Oxygen analyzer Capnography, Doppler

limited to a manual blood pressure cuff and a stethoscope. Whether pulse oximetry can be used will most likely be determined by the availability of electricity to run or charge the equipment. Pulse oximetry would be highly valuable at first- and second-level medical treatment facilities.

If there is a threat that the enemy will use chemical or biological agents, both the providers of care and the casualties are in full mission-oriented protective posture (MOPP) gear. Obviously, any monitoring, other than possibly a cursory mental-status examination, may have to wait until the casualty has been decontaminated. Ambient noise may limit the use of the stethoscope to just determining the presence of heart sounds.

Blood pressure may have to be taken by merely documenting the point at which the systolic pressure becomes palpable or the needle on the aneroid manometer begins to bounce. (Blood pressure can be measured by inflating a manual cuff and slowly letting the cuff deflate while watching for the needle on the manometer to begin to bounce; this corre-

lates with the point at which one can begin to feel the pulse.) This quick, accurate means of monitoring blood pressure may be the only method practicable. The bouncing needle on the sphygmomanometer also allows the observer to form an impression of the patient's heart rate. Heart rate can be counted by either listening with a stethoscope or by taking the pulse. Subtle signs, such as threadiness of pulse and crispness of heart sounds, may provide information about the casualty's volume status.

Third Echelon

The intermediate level of care includes mobile army surgical and combat support hospitals. This setting is more fixed than a medical company clearing station, but third-echelon hospitals must be somewhat mobile also. These hospitals are designed to perform resuscitative surgery. General anesthesia is available and, therefore, more elaborate monitoring equipment will be necessary. The equipment found at this level must be sturdy, able to withstand the multiple moves that may be required of a third-echelon hospital. Much of the equipment used in this setting may arrive by some expedient means (eg, being dropped by parachute from a cargo plane). For these reasons, it is unlikely that sensitive equipment such as mass spectroscopy or other highly sophisticated monitors will be seen at this level of care.

The portable anesthesia machine will probably not contain an automated ventilator with disconnection alarms. The only "monitor" for sensing disconnections of the anesthesia circuit will probably be the individual responsible for providing the manual ventilation. Equipment at this level should include electrocardiograph monitors, blood pressure cuffs, pulse oximetry, temperature-monitoring devices, and perhaps even some form of capnography. The anesthesia machines (Ohio Model 855A Field Anesthesia Machine, manufactured by Ohmeda, Inc., Madison, Wisc.) also should contain an oxygen analyzer.

Pulse oximetry provides such valuable information that it should also be included at this level. Although not standard equipment at this level, the pulse oximeter will often be added as supplementary equipment. The automated blood pressure cuff may or may not be present. It is unlikely that more than one or possibly two will be available—if present at all at this level of care. The manual blood pressure cuff will certainly find use at this level, whether in the operating room or in the recovery areas.

Devices to monitor the casualty's temperature should also be included at this level of care. Adhesive, disposable, skin-temperature monitors will be of little value at the third echelon. A more appropriate device is one able to measure axillary, oral, esophageal, or rectal temperatures. Monitoring of the skin temperature is unlikely to provide useful information in casualties who are either receiving large amounts of fluid or blood or are hypovolemic because of blood loss.

The ability to monitor end-tidal carbon dioxide ($ETCO_2$) can be very useful, not only for verifying endotracheal intubation but also for monitoring carbon dioxide levels in casualties with head trauma. Currently, these monitors are somewhat large and are unlikely to be added as supplementary equipment. With improved technology and as they become more compact, capnographs will no doubt be added even at the third echelon.

One additional method of providing anesthesia that allows significant monitoring of the casualty's respiratory status (including oxygen requirements) is the use of closed-circuit anesthesia. This method of providing anesthesia has many advantages:

- Changes in the patient's oxygen utilization are readily apparent.
- Oxygen waste is minimized (rather than flows of 3–5 L/min, flows of 250–350 mL/min or less are used).
- The use of a sophisticated vaporizer requiring calibration and high oxygen flows to provide accurate delivery of anesthetic agent is omitted; the potent anesthetic agent can be delivered by merely introducing a syringe containing a volatile anesthetic into the breathing circuit.
- The total amount of inhalational anesthetic agent used is decreased. This can be a most significant factor if supplies are short.

The disadvantages of the use of this method of providing anesthesia are few. It behooves providers of anesthesia, particularly those in the military, to become familiar with this technique. Although it may appear to be more time consuming (because recent graduates of anesthesia training programs lack familiarity with this technique), this technique may be safer and more appropriate than the conventional vaporizer technique when supplies of oxygen are short or when vaporizers are broken or uncalibrated. Extremes of ambient temperature (eg, in the desert) may also make the closed-circuit

anesthesia delivery technique more desirable (see Chapter 8, Closed-Circuit Anesthesia, for a more complete discussion of this subject).

Fourth Echelon and Higher

Complex levels of equipment are found at fourth and higher echelons of care, including hospital ships and hospitals along the chain of evacuation from the theater of operations. The sophistication of monitoring equipment is more like what anesthesia providers would expect to see at a civilian or military community hospital or small medical center. These are fixed facilities and would be unlikely to move, once set up (the obvious exception being the hospital ship). For this reason, more-elaborate monitoring is likely to be found. At fourth and higher echelons of care, automated blood pressure cuffs, pulse oximeters, automated ventilators with disconnection alarms, capnographs, and invasive hemodynamic monitoring devices (ie, arterial and central lines for measuring central venous and pulmonary artery pressure) will all be found.

The use of these invasive monitoring devices will, of necessity, depend on not only the individual patient's clinical situation but also on the number of casualties requiring treatment. The great majority of casualties will already have received resuscitative surgery at mobile surgical or combat support hospitals; monitoring will be employed either in difficult emergency cases requiring reoperative surgery or, as is more common, in elective reconstructive operations. An inordinate amount of time cannot be spent placing invasive monitors in all casualties; nor is sophisticated monitoring necessary in most operations (eg, delayed primary closure of soft-tissue wounds or reestablishment of gastrointestinal continuity). The intensity of monitoring will have to be tailored to the needs of the casualty. This philosophy, which is inherent in military triage, is likely to be unfamiliar to most civilian personnel, who are accustomed to providing all the care that *can* be done, not just what *must* be done.

SYSTEMIC MONITORING

Anesthesia care providers will be faced with difficult decisions regarding which monitors are practical and necessary at the various echelons of care. The decision regarding what monitoring devices to have available should be based on the level of care to be provided, the expected needs of the casualties, the durability of the equipment, and the storage capability and mobility of the equipment.

Hemostasis and Coagulation

The first step in monitoring for hemostasis is the evaluation of blood loss. This can be done by directly measuring the volume of blood in the suction containers that were used to draw blood from the operative field. Weighing, or estimating the weight of, used surgical sponges is another method of accounting for surgical blood loss. Besides monitoring for vascular integrity, monitoring of the coagulation system is also necessary.

Determining platelet count and function can easily be done at both the intermediate and complex levels of care. A platelet count of 50,000 to 75,000 normal, functioning platelets may be inadequate for intraoperative hemostasis. The Ivy bleeding time test is used to measure platelet function. The test is performed by making a standard, 9-mm–long incision on the volar surface of the forearm while an inflated blood pressure cuff on that arm is maintained at 40 mm Hg. The elapsed time required for bleeding to stop is known as the bleeding time. Normal bleeding times vary between 5 and 8 minutes.[1]

Several methods are available for monitoring coagulation as well as for monitoring the coagulation status of casualties who have received therapeutic anticoagulation drugs. These methods include (1) heparin level measurements; (2) protamine titration; (3) activated clotting times; and (4) other tests such as prothrombin time, thrombin time, fibrinogen levels, and fibrin split product levels.

Heparin, a mucopolysaccharide, acts by stimulating the enzymatic activity of antithrombin III, which inactivates the serine proteases in the coagulation scheme (factors II, VII, IX, and X). Approximately one individual in 2,000 has a physical condition (eg, liver disease, pregnancy, debilitating illness) that depresses the antithrombin III level; therefore, that individual may not respond to heparin. Serum levels of antithrombin III can be depressed by a variety of conditions; such deficiency may be responsible for as many as 2% of clinical cases of venous thrombosis.[2]

Devices used to estimate heparin level include the automated protamine titration system and fluorometric analysis. The automated protamine titration method (Hepcon, manufactured by HemoTec, Inc., Englewood, Colo.) uses protamine titration to

estimate heparin levels. Advantages of this method include (1) the rapidity of obtaining results, (2) the ease of use, and (3) the reliability of the results. The disadvantages are (1) the cartridges expire in a short time (60 d) and (2) the reagents require refrigeration.

The Hemochron system (manufactured by Technidyne Corp, Edison, N.J.)—a simple, reliable, automated activated clotting time test—was introduced during the mid-1970s; (unfortunately, however, it is not available in field hospitals). A normal baseline activated clotting time is 110 to 130 seconds. A low baseline should alert the anesthesia provider to a hypercoagulable state. Activated clotting times between 300 and 600 seconds are acceptable for cardiopulmonary bypass to be initiated. There is a linear relationship between the activated clotting time and the milligram per kilogram heparin dose for any given patient.[3] Determining the adequacy of protamine reversal is one area in which heparin-level tests may be more useful. Although plotting the heparin dose against the activated clotting time can be used to determine the protamine-reversal dose, the difficulty arises when the clotting time remains elevated after the protamine has been given. The reasons for this can be (1) continued excess heparin or (2) a derangement of the coagulation system. The usual clinical response is to give an additional dose of protamine. If the activated clotting time remains the same or is elevated further, then a coagulopathy should be suspected.

Physiological monitoring of the hematological system in the first echelon of care will be very basic. Accuracy in the evaluation of the nonmechanical bleeding can be obtained with a whole-blood clotting time. Decreased clotting factors should be suspected if whole blood does not clot within 15 minutes. Measurements of prothrombin, partial prothrombin, and bleeding time should be available at the third or fourth echelons. The ability to measure activated clotting time intraoperatively would also be useful. This approach should be considered when logisticians are determining which monitoring devices to include for each unit that provides complex care.

Cardiovascular System

Physical examination will remain a mainstay in the evaluation of the casualty's cardiovascular system. Assessment should include mental status examination, presence of nausea or vomiting, capillary refill, vital signs, coolness of extremities, and so forth. Other, more-direct monitors of the cardiovascular system include methods to monitor blood pressure and central venous pressure, and monitors of the heart for rhythm and ischemia.

Blood Pressure

Noninvasive Monitoring. Depending on the equipment available, blood pressure can be monitored by several noninvasive methods:

- Doppler technique,
- oscillations of an aneroid manometer during deflation of a manual cuff,
- return of tactile pulses during deflation of a manual cuff,
- auscultatory method using Korotkoff's sounds, and
- automated blood pressure devices.

Of these, the first three monitor only systolic pressures; the others, in addition, monitor diastolic and mean pressures.

The simplest way to detect systolic blood pressure is to palpate the pulse while an occluding cuff is deflating. A modification of this technique involves watching for oscillations of the aneroid manometer during deflation of the occluding cuff.

Once, the most common technique for indirect manual measurement of blood pressure employed by anesthesia care providers in hospitals in the continental United States was the auscultatory method of using Korotkoff's sounds.[4] A stethoscope or an automatic blood pressure–monitoring device placed over an artery serves as a detector. Slightly more sophisticated detectors include a Doppler or other sound-amplifying device as a signal detector. By placing the ultrasonic Doppler device over the radial artery, the anesthesia provider detects blood flow by listening for the characteristic "swishing" sounds. The Doppler method utilizes a 10-Hz ultrasonic device coupled to a transducer/receiver assembly. This device detects the difference in frequency between transmitted and reflected sound in response to deflation of an occluding cuff. The Doppler signal is detected when blood flow causes movement of the arterial wall during systole. There is good correlation between measurement of systolic blood pressure via Doppler and direct arterial monitoring.[5] Ultrasonic gel (if available) will provide a helpful medium for transmitting sound. The blood pressure cuff on the patient's arm is inflated as above. As the cuff is slowly deflated, the point at which sounds are again heard correspond to the systolic pressure. The Doppler device may be useful

Fig. 5-1. This patient monitor, the PROPAC 104 (portable anesthesia circuit, manufactured by Protocol Systems, Inc., Beaverton, Ore.), has ports for noninvasive measurement of arterial blood pressure, electrical activity of the heart, and temperature, and has two additional pressure ports.

and should be considered as supplementary equipment for the intermediate and complex levels of care.

The automated oscillometric method for measuring blood pressure has become the most common method used by anesthesia care providers for noninvasive blood pressure monitoring. Its advantages over the techniques discussed above are its greater accuracy and ability to measure mean blood pressure. The devices manufactured currently employ an electric pump to generate the pressure required to inflate the occluding cuff. A microprocessor controls the cuff inflations and deflations. A solenoid valve allows incremental deflation of the cuff. The cuff also acts as the signal sensor that responds to oscillations in the limb. A pressure-sensing function is performed by a pressure transducer, and digital readout of the systolic, diastolic, and mean blood pressure is provided. Under ideal circumstances, the accuracy of these units compared with direct arterial measurements is usually within 10 mm Hg.[6] Problems in obtaining measurements occur when the patient moves, when there is substantial beat-to-beat variability in the blood pressure (eg, atrial fibrillation), and with very slow heart rates. Originally, automated oscillometric units were somewhat bulky and required electricity to operate. Newer units have backlit liquid crystal displays. In addition to their ability to monitor blood pressure noninvasively, many units currently manufactured are also capable of monitoring pulse oximetry and the heart's electrocardiographic status, and have transduced pressure-monitoring capability (Figure 5-1). These new units can run on alternating or direct current. They are compact, weighing just a few pounds, and are currently used in tertiary-care centers as transport monitors. In the future, we are likely to find these units at third, fourth, and higher echelons of combat casualty care.

Invasive Monitoring. The medical officer's ability to evaluate a casualty's arterial waveform is a major advantage of direct monitoring of arterial blood pressure in the trauma setting. The arterial waveform allows a qualitative assessment of the patient's blood volume status to be made. The area beneath the arterial waveform is affected by myocardial performance, systemic vascular resistance, and circulatory volume status. The more common sites of arterial cannulation are listed in Exhibit 5-1. Most studies reporting the complications of direct arterial cannulation involve the radial artery. Complications include decreased circulation, infection, vasospasm, thrombosis, embolism, aneurysm formation, and hematomas.

The necessity of performing an Allen's test before cannulation of the radial artery has been questioned.[7] The incidence of thrombosis of the radial artery relates to the size of the catheter used. One study[8] found a 34% incidence of thrombosis when a 18-gauge catheter was used, compared to an 8% prevalence when a 20-gauge catheter was used. The incidence of catheter thrombosis also increases with the duration of cannulation. The safety of brachial-

EXHIBIT 5-1

SITES OF ARTERIAL CANNULATION

End Arteries
- Brachial
- Femoral

Other Arteries
- Radial*
- Ulnar*
- Dorsalis pedis
- Axillary

* Cannulation of both arteries of the same arm is not recommended because of the risk of significant occlusion of blood flow to the hand.

and femoral-artery cannulations is established; they serve as other sites of direct arterial monitoring.[9,10]

The common way of measuring direct arterial pressure is to connect the indwelling arterial catheter to a transducer that converts hydrostatic pressure into movement of a thin diaphragm. Ultimately, this energy is converted into an electrical signal, which is amplified and converted to analog or digital signals or both. Digital readouts and analogue displays of waveforms can be viewed on small monitors. A useful invasive means of measuring mean blood pressure is to use a manometer connected to the arterial tubing (formerly connected to a transducer) (Figure 5-2). This method provides a means of monitoring the patient's mean blood pressure, which may be particularly useful during transport or when transducers become unavailable for whatever reason. This type of monitor has the disadvantages of only giving an analog display of the mean blood pressure. The arterial waveform cannot be viewed.

Central Venous and Pulmonary Artery Pressures. Central venous lines are used for several reasons, including perioperative administration and management of fluids in the critically ill patient, administration of vasoactive drugs, and obtaining blood samples. Central venous pressures can be monitored by using either pressure transducers or a water manometer.

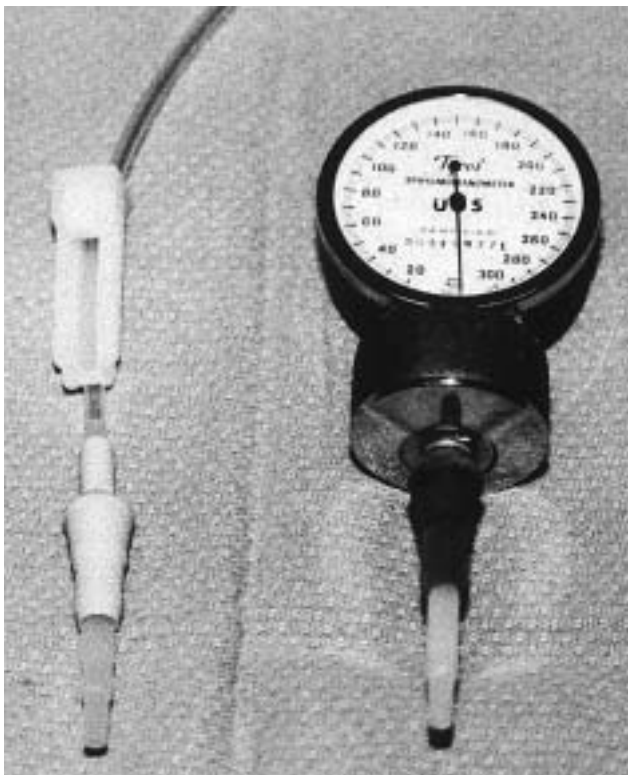

Fig. 5-2. A sphygmomanometer can be used as an ad hoc field blood pressure monitor, but only the mean pressure can be measured.

Normal central venous pressure is between 0 and 5 mm Hg or 0 and 7 cm H_2O. Although it is unlikely, it is possible that central venous pressure monitoring will be used at the third echelon of care. At this level, saline-filled manometers may be used because pressure transducers will be in short supply. The saline-filled manometers are measured in centimeters of water (1 mm Hg is equal to 1.36 cm H_2O). Measurements are made at the level of the right atrium (the midaxillary line). This is considered the zero point (the point at which the zero on the manometer is positioned). In fixed facilities, where more-complex monitoring is available, central venous pressure can be monitored using a pressure transducer. This allows both an analog display of the central venous waveform and a digital readout of the pressures. One advantage of having the waveform displayed is that the right ventricular wave pattern can be differentiated from the right atrial wave pattern. This would be particularly useful in verifying correct location of the catheter tip.

The four most accessible sites available for the insertion of central venous pressure–monitoring lines are the internal or external jugular, subclavian, antecubital, and femoral veins. The right internal jugular approach is the one most commonly used for central vein catheterization. This is because it (*a*) provides a straight path to the right atrium; (*b*) provides a clean site (the incidence of thrombophlebitis is low); and, perhaps most importantly, it (*c*) is easily accessible to the anesthesia provider during the operative procedure. The external jugular approach requires the use of a guide wire with a J-tip to allow it to be maneuvered into the central circulation.

Although the pulmonary artery catheter is used in medical centers in the continental United States, it has not yet been *hardened* (miniaturized and/or made sufficiently sturdy) for battlefield use; therefore, this device is seen only infrequently at third-echelon hospitals. Pulmonary artery catheters require that pressure transducers be used to confirm placement. The same approaches that are used for placement of a central venous pressure line can be used for pulmonary artery catheter placement. The insertion and management of this device require experience with its use.

The uses of pulmonary artery catheters include

the following:

- hemodynamic monitoring of both central venous pressure and pulmonary artery pressures;
- monitoring of cardiac output via the thermodilution technique;
- evaluation of changes in compliance of the left ventricle and, thus, evaluation of myocardial ischemia;
- measurement of mixed venous saturation;
- central infusion of cardiotonic drugs; and
- insertion of intravenous pacing wires through pacing ports added to the catheter.

The use of these catheters would most likely be restricted to the complex level of care provided by the evacuation hospital or specialized hospital ship.

Electrocardiography

The electrocardiograph is used for monitoring heart rhythm and ischemia. Hospitals throughout the United States use either three-lead or five-lead systems. The standard limb leads in general use monitor cardiac rhythm. Precordial leads are better for evaluation of ischemia. It is possible that only a three-lead system may be available in field hospitals. When using only three leads, the heart can still be evaluated for rhythm and ischemia: place the reference lead on the patient's left shoulder and the positive lead over the lateral precordial surface (V_5 position). By switching between lead I and lead II on the electrocardiograph, we can then view a limb lead and a modified precordial lead (modified V_5). The capability to monitor the electrical activity of the heart should be found at both the intermediate and complex levels of care.

Transesophageal Echocardiography

At present, evaluation of the cardiovascular system primarily involves hemodynamic monitoring. The introduction of transesophageal echocardiography has presented a new tool that provides useful information to the physician in highly sophisticated centers. The uses of transesophageal echocardiography include both monitoring for air embolism and monitoring of cardiac function.

Echocardiography uses sound waves emitted by sound transducers in a narrow beam. The sound waves travel through tissues and are reflected. The intensity of the reflected echoes is a function of the density of the reflecting tissue. Sound waves emitted by an esophageal transducer have to pass through only the esophageal wall and pericardium before reaching the heart. Thus, there is less likelihood of image distortion. Other advantages of transesophageal echocardiography include both the stability of the position of the transducer and the potential of continuous intraoperative recording.[11]

This monitor is very unlikely to be present during the operative care of the combat casualty. Currently, these monitors require excessive space and specialized training for their use. Although transesophageal echocardiography might provide useful information in specific instances, it remains a monitor that most likely will not be seen in hospitals that receive battlefield casualties.

Respiratory System

The respiratory system can be monitored by physical exam (presence or absence of labored breathing), stethoscopy, the casualty's color (presence or absence of cyanosis), pulse oximetry, arterial blood gases, and various sophisticated monitors such as capnography or mass spectrometry.

Pulse Oximetry

The pulse oximeter continuously measures the oxygen saturation of the arterial blood (Sa_{O_2}, which is expressed as a percentage). Of more importance, however, is the oxygen content of the arterial blood (Ca_{O_2}, which is expressed as grams of oxygen per 100 mL of blood), which is defined as Sa_{O_2} multiplied by the oxygen capacity (1.36 mL of oxygen per gram of hemoglobin [Hb]), multiplied by the concentration of Hb (grams per 100 mL of blood) divided by 100. The definition of Hb saturation (also called oxyhemoglobin, O_2Hb) does not include that fraction of Hb that may be either methemoglobin (MetHb) or carboxyhemoglobin (COHb). Therefore, the saturation percentage of Hb can be expressed as

$$\% \text{ saturation } (Sa_{O_2}) = (Ca_{O_2} \,/\, \text{total Hb content}) \bullet 100$$

where total Hg is equal to O_2Hb + Hb + COHb + MetHb. Under normal circumstances, this correction is of little importance. However, in the casualty who is suffering from smoke inhalation (with the associated potential for carbon monoxide poisoning, in which 10%–20% of the total Hg content may be in the form of COHb), use of the complete formula to estimate saturation becomes mandatory.

The oximeter estimates Sa_{O_2} by transilluminating

the ear or other appendage with light of two different wavelengths (one in the red range, the other in the infrared). The transmitted light is then measured with a photodetector. The pulsatile component of the transmitted light is related to the absorbances of the Sa_{O_2}. All pulse oximeters assume that the only pulsatile absorbance between the light source and the photodetector is due to arterial blood. The baseline absorbance represents the light that is absorbed by tissue, venous blood, or the capillary bed. Thus, the oximeter is able to differentiate Sa_{O_2} from venous or tissue saturation. The pulse oximeter further assumes that there are only two absorbing Hb types in the blood (ie, O_2Hb and Hb). If MetHb or COHb or both are present, they contribute to the pulse absorbance signal and, therefore, alter the Sa_{O_2}. Other limitations include any substance that absorbs light at the red and infrared pulse oximeter wavelengths used. Examples would be the use of methylene blue, indigo carmine, and indocyanine green dyes, which decrease the Sa_{O_2}. Colored nail polish also can adversely effect the measurement of Sa_{O_2}.

Pulse oximetry is an extremely useful noninvasive monitor of the respiratory system and has quickly become a standard of practice in operating rooms throughout the continental United States. Although it provides much information, however, pulse oximetry is not without pitfalls. Oxygen saturations greater than 90% indicate an arterial oxygen tension (Pa_{O_2}) greater than 60 torr. Patients who are given supplemental oxygen can have a significant shunt (causing decreases in Pa_{O_2}) before alterations in Sa_{O_2} are noted. For example, if a casualty with lung contusions were placed on supplemental O_2, his initial arterial blood gas could show a Pa_{O_2} of 300 torr. Oxygen saturation would show 100%. The casualty's condition could worsen such that the arterial blood gas might show a Pa_{O_2} of 100 torr and the Sa_{O_2} would still be 99% to 100%. Thus, a significant decrease in Pa_{O_2} might not be noted by the pulse oximeter. Another pitfall could occur in the casualty who has been exposed to cyanide. In this instance, Sa_{O_2} may remain high, despite the need for high concentrations of oxygen and treatment of cyanide toxicity.

The pulse oximeter may not be part of the standard equipment found at the second or third echelons of care, but it should be added as additional equipment. It should also be considered in the austere first-echelon setting when it is anticipated that anesthesia will be provided if electricity and space for equipment are available and maintenance can be provided.

Arterial Blood Gases

The ability to measure arterial blood gases serves as the standard in evaluating oxygenation. Modern measurement devices depend on selectively permeable membranes and the electrochemical activity of the gases present; besides measuring oxygen tension, modern electrodes also measure pH and pCO_2. The platinum electrode (Blood Gas System, manufactured by CIBA Corning Diagnostics, Medfield, Mass.) is used for measuring oxygen tension. The devices that monitor arterial blood gases are small, precise, and very sturdy. Arterial blood gas monitors will most likely be found at the more complex level of care (general hospitals); they may also be found at the intermediate level but certainly not in the austere setting.

Equipment able to continuously monitor oxygen tension is currently under development. The primary problem has been with miniaturization of the electrode. Another technology uses fiberoptic sensors, which can be miniaturized more easily. A continuous oxygen-tension monitor has recently been approved for clinical use, and this technology may soon be available for combat casualty care. At present, however, oxygen tension is measured only intermittently and only at the fourth echelon of medical care and higher.

Capnography

The analysis of end-tidal carbon dioxide ($ETco_2$) has only recently become commonplace in operating suites, but it has rapidly become a standard of practice in many community hospitals. This type of monitoring

- provides useful information regarding mechanical and gas-exchange functions of the patient's lungs,
- detects changes in the patient's metabolic and cardiovascular function, and
- helps identify malfunctions of breathing circuits that are used while patients are under anesthesia.

The systems most commonly available use infrared light absorption by carbon dioxide. The expired carbon dioxide absorbs light in proportion to its concentration. The sensors are placed in line with the expired gases, and a continuous waveform provides the capnograph. This type of in-line system for measuring $ETco_2$ is relatively fragile and the equipment is bulky. Capnography can also use a gas-

withdrawal system (ie, mass spectrometry) as a way of measuring $ETCO_2$; however, this requires very sophisticated instrumentation. The gas-withdrawal system to transport the gas to be measured to the measuring device causes a delay in measurement of the capnogram. Also, the moisture that develops within the gas-transport tubing often will obstruct the flow of the gases to the measuring device. $ETCO_2$-measuring devices are not likely to be seen except at the more complex levels of combat casualty care.

Pulmonary Function

Lung compliance (the change in volume for a given change in transpulmonary pressure) is another monitor for evaluating the respiratory system in patients who require intubation, but we should bear in mind that the word "lung" is something of a misnomer: what is actually measured is the total compliance of the pulmonary tissue and the chest wall. Furthermore, two different compliances—dynamic and static—can be measured, depending on whether air is in motion when the measurements are made. Most mechanical ventilators have a pressure gauge that can be used to determine airway pressure on a moment-by-moment basis and, therefore, can be used to measure dynamic compliance. Dynamic compliance (DC) for a patient on a ventilator is defined as tidal volume (TV) divided by the peak airway pressure (PAP) minus the pressure at end expiration (PEEP):

$$DC = TV / (PAP - PEEP)$$

Normal lung compliance is approximately 100 mL/cm H_2O. A compliance of 25 mL/cm H_2O) is significantly decreased. Decreased dynamic compliance (increased peak airway pressure) may mean an obstructed endotracheal tube, bronchospasm, or a pneumothorax. Static compliance (SC) is calculated:

$$SC = TV / (\text{plateau pressure} - PEEP)$$

where *plateau pressure* is the pressure during the period in which there is no airflow. This is commonly estimated during the period of inspiratory pause. Decreased static compliance may signify atelectasis or increased lung water. Static compliance is a useful monitor for casualties with adult respiratory distress syndrome (ARDS).

Renal System

Monitoring the renal system serves as a means of measuring not only renal function but also the casualty's intravascular volume status. Useful monitors include urinary output, sodium concentration, and specific gravity. The patient should be able to maintain a urinary output of at least 0.5 mL/kg/h. Urinary specific gravity and sodium concentration help the medical officer determine whether the kidneys are attempting to conserve water (an indicator of the casualty's volume status). In nonhypovolemic patients who are not taking diuretics, urinary sodium concentration should be higher than 20 mEq/L and specific gravity lower than 1.020.

Above the second echelon of care, Foley catheters will be the primary device for monitoring renal function. Laboratory methods capable of measuring blood urea nitrogen or creatinine or urinary sodium concentration are not likely to be found at other than fourth-echelon medical treatment facilities.

Nervous System

Monitoring the nervous system involves both physical examination and the use of sophisticated equipment. Due to equipment limitations of durability and size, anesthesia care providers currently have limited ability to monitor the nervous system.

Central Nervous System

Monitoring the central nervous system is discussed in detail in Chapter 16, Neurological Injuries. The equipment used in this monitoring is often highly sensitive, fragile, and bulky; it is found only at the highest echelons of care. However, as technology improves and miniaturization of equipment then becomes practicable, these monitors will likely be used in the field.

Intracranial Pressure. For the most part, monitoring of the central nervous system will consist of mental-status checks and the physical examination. Intracranial pressure can be monitored at the fourth echelon of care and higher: specialized equipment is required and the monitors are generally inserted by neurosurgeons. The normal value for intracranial pressure is less than 10 cm H_2O.

Devices for monitoring intracranial pressure can be classified according to (*a*) the anatomical location at which the device is placed and (*b*) the method by which intracranial pressure is measured. Anatomically, these monitors can be placed in the lumbar spine, cervical spine, posterior fossa, or supratentorial area of the cranium. The supratentorial area is the preferred location for placement of the

monitor, because insertion of a catheter into the subarachnoid space below the tentorium cerebri can cause a potentially fatal decrease in pressure there and subsequent herniation of the uncus of the temporal lobe or the cerebellar tonsils.

Devices in current use can be fluid-coupled (ie, the pressure-monitoring device is connected to a transducer by a column of fluid). The transducer should be at the level of the external auditory meatus while the intracranial pressure is being measured. Routine pressure tubing and transducers used for arterial and central venous pressure monitoring are *not* used to monitor intracranial pressure. The flow through the standard tubing (approximately 2 mL/h) could harm a patient with increased intracranial pressure. Flushing the monitor tubing would also be harmful. Care must be taken not to inject any fluid into this system. Newer devices now use fiberoptics instead of a fluid-coupled system to transmit pressure waves to the pressure-measuring device.

The intraventricular catheter is a simple device used for measuring intracranial pressure. It can be used both as a monitor and as part of a therapeutic regimen. The device is coupled directly to the cerebrospinal fluid and the transducer. In the event of increased intracranial pressure, fluid can be drawn off as needed. Iatrogenic infection can be introduced because this technique requires that the catheter be inserted through brain tissue; the incidence of such infection is estimated to be less than 6.3%.[12] Other devices used to monitor intracranial pressure include the subarachnoid bolt and epidural devices. These devices allow for monitoring without invading brain tissue.

Encephalography. The conventional, multichannel electroencephalograph is the standard against which all other types of monitors of the electrical activity of the brain are compared. The electroencephalograph and its electrodes are large and cumbersome. In addition, conditions within the operating room make it a hostile environment for electroencephalography (eg, electrocautery interference). The difficulty in using the conventional, multichannel electroencephalograph is largely overcome by monitoring a processed electroencephalogram (eg, the cerebral function monitor, which is a single-channel processed electroencephalogram). The use of the cerebral function monitor during carotid endarterectomy,[13] deliberate hypotension,[14] and cardiopulmonary bypass[15] is well documented. However, the inability to examine the behavior of different frequencies within the electroencephalograph is a major drawback. The Lifescan Monitor (manufactured by Neurometrics Inc., San Diego, Calif.) displays a processed electroencephalogram in which brain waves can be viewed as three-dimensional vertical spikes. The height of the spike represents the amplitude of the wave, its horizontal position represents its frequency, and time is represented on the Z axis. This device also can monitor sensory evoked potentials. The processed electroencephalogram is useful in monitoring cerebral ischemia and the effects of anesthetic drugs.[16–18]

There are many types of electroencephalographs that have differing processing techniques. Clinically, all the processing techniques show frequency changes when the raw electroencephalogram slows, and amplitude changes when it flattens. The difficulty lies in comparing two differing processing techniques. Qualitatively, the processed electroencephalogram may be quite useful. However, this monitor is unlikely to be seen at any echelon of care except in hospitals within the continental United States.

Sensory Evoked Potentials. The intraoperative use of sensory evoked potentials is labor intensive. Because many anesthesia care providers lack the time or skill to monitor and interpret sensory evoked potentials, their use has often been limited to large medical centers where neurologists or electrophysiologists are available. Some facilities have a specialized technician who assists in the technical aspects of the monitoring.

Sensory evoked potentials have been used in neurosurgery,[19,20] orthopedic spinal surgery,[21] and during positioning of the patient where brachial plexus injuries may occur.[22] Its usefulness as a monitor during care of combat casualties is doubtful, because even the most basic machines are so labor intensive and bulky. This monitor will most likely be found only at the larger medical centers in the continental United States.

Peripheral Nerve Stimulators

Peripheral nerve–stimulator devices allow muscle relaxation to be monitored while potent muscle relaxants are administered. They can also be useful when regional anesthesia is performed using a nerve-stimulation technique (see Chapter 11, Neuromuscular Blocking Agents, Figure 11-2). Those who select the nerve stimulator that will be used at the third and fourth echelons of care should take this dual use into consideration. A nerve stimulator with the ability to adjust the amount of output in milliamps (0–10.0 mA and 0–100 mA) will be more versatile. The ability to identify nerve structures by

direct stimulation of nerves or muscles or both during the surgical procedure would be an additional benefit to the surgeon.

Temperature

The ability to monitor temperature will no doubt be found at both the third and fourth echelons of care. Thermocoupled liquid crystal display devices that paste onto the skin will have little value in the field. Nondisposable devices that allow temperature monitoring at various sites will be most helpful. Monitoring core body temperature—via esophageal or rectal temperature probes—will provide the most useful information regarding the casualty's temperature.

COMPUTERS IN ANESTHESIA

In anesthesia, computers can be used as microprocessor-based drug and anesthesia delivery systems or as a means of patient-data management. Currently, there are no well-established systems in which physiological data are processed by computer and which subsequently permit the delivery of anesthesia drugs to be modified based on the data received by the microprocessor. More commonly, computers receive physiological data and record it on the anesthesia record. The ability to detect detrimental changes in the casualty's status and trigger the appropriate alarms are what separates simple data collection from computerized monitoring. Improvements in the technology of artificial intelligence will be required before useful microprocessor-based anesthesia drug delivery systems are seen either outside the research area or on the battlefield. The computers required for such elaborate tasks require processing in parallel with data received from monitors measuring cardiovascular, respiratory, and other physiological parameters. The enormous amount of data will then require processing so that appropriate responses (mimicking those of a human expert) will be made.

Computerized data recording is a much more manageable task. The objective is to make record keeping easy and complete: to free the anesthesia provider to monitor the casualty, not to institute time-consuming tasks. Accurate, detailed records of data from various physiological monitors can be stored and printed. The medical officer's ability to distinguish between artifact and real data, and a user-friendly computer program's processing of human input are essential to the practicability of any computerized record system.

SUMMARY

Monitoring of the combat casualty can be both adequate and austere. Levels of care practiced in fixed medical facilities such as combat support or general hospitals differ from those practiced closer to the battlefield. Strategies for obtaining data from various physiological systems for use in management of the medical care of the combat casualty need to be decided in advance, as do the types of monitors that can be expected at each echelon of care.

As technological advances make sophisticated equipment smaller, simpler, and sturdier for transport, the kinds of monitoring devices that are available at each echelon will undoubtedly change, making more-sophisticated monitoring available closer to the battlefront. The pulse oximeter is one example; capnography will most likely follow.

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