NEAR-FIELD MICROSCOPY AND SPECTROSCOPY.

See MICROSCOPY AND SPECTROSCOPY, NEAR-FIELD.

NEONATAL MONITORING

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INTRODUCTION

The care of premature and newborn infants is quite different from other areas of clinical medicine. The infant represents a special patient with special problems not found in other patients. For this reason a subspecialty of pediatrics dealing with these patients has been established. Neonatology is concerned with newly born infants including those prematurely delivered and those delivered at term. The field generally covers infants through the first month of normal newborn life, and so for prematurely born infants this can be several additional months.

Neonatology includes special hospital care for infants who require it. In the case of the prematures, this involves specialized life-support systems, as well as special considerations for nutrition, thermal control, fluid and electrolyte therapy, pulmonary support, and elimination of products of metabolism. While the full-term infant generally only requires routine well-baby care, there are special cases that require intensive hospital care as well. These include treatment of infants of diabetic mothers, some infants delivered by cesarean section, infants with hemolytic diseases, infants who encounter respiratory distress, and other less common problems. Special hospital care is also necessary for infants requiring surgery. These infants are generally born with severe congenital anomalies that would be life threatening if not immediately repaired. These include anomalies of the gastrointestinal system, urinary tract, cardiovascular system, and nervous system. Pediatric surgery has developed to the point where many of these problems can be corrected, and the infant can grow and lead a normal life following the surgery.

The neonatal intensive care unit is a special nursery in major tertiary care hospitals that is devoted to the care of premature or other infants who require critical care. This unit is similar to its adult counterpart in that each patient is surrounded by equipment necessary for life support, diagnosis, and therapy. Often, as indicated in Fig. 1, the patient appears to be insignificant in the large array of equipment, but, of course, this is not the case. Nursing

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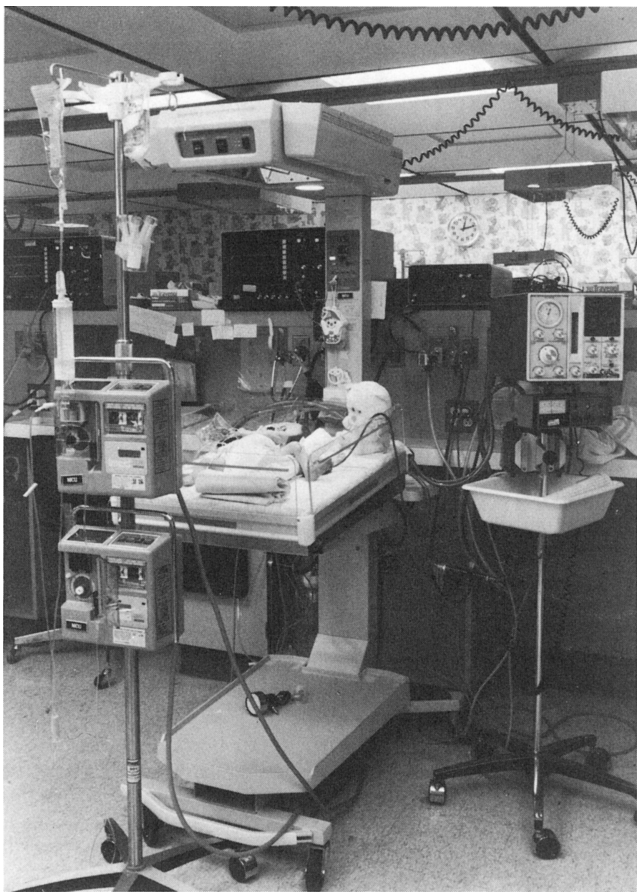

Figure 1. Typical infant station in a neonatal intensive care unit showing infant warmer, infusion pumps, ventilator, transcutaneous oxygen instrument, cardiopulmonary monitor, bilirubin lights, and other miscellaneous apparatus.

functions in the neonatal intensive care unit are very important. The patient/nurse ratio is small, and the nursing staff must be familiar with the equipment as well as special procedures and precautions in caring for these special patients.

Electronic monitoring of the infant plays an important role in neonatal intensive care. Not only does it allow the clinical caregivers to follow vital signs, such as pulse rate, temperature, blood pressure, and respiration rate, but other critical variables in the care of these special patients can be followed as well. These include blood gas tensions, acid–base balance, bilirubin, and glucose concentrations. Monitoring is especially important in fluid therapy for it can provide precise data for fluid control of these very small patients. Electronic monitoring, however, goes beyond just monitoring the patient and its physiologic functions. A good neonatal intensive care unit also monitors the functioning of life-support systems. These include incubators for maintaining an appropriate thermal environment, ventilators for providing respiratory support, and phototherapy units for the control of bilirubin.

Although electronic monitoring devices for just about all of the areas mentioned in the previous paragraph are used in adult intensive care medicine, their application in neonatology often represents a unique aspect of the technology. The infant should not be viewed as a miniature adult, but rather he/she is a unique physiologic entity. Although similar variables are measured to those measured in adults, they often must be measured in different ways. Frequently, sensors unique for infants must be applied because the sensors used for adults when interfaced to the infant might provide errors or change the variable being measured by their very presence. Size is an important aspect here. If one considers a sensor to be used on an infant and compares it to a sensor for the same variable on an adult, in most cases although the sensor for the infant is smaller than that for the adult, the ratio of sizes of the two sensors is quite different from the ratio of sizes of the different patients. Although sensors for use on infants are reduced in size, they are still quite large when compared to the size of the subject. This is especially true for premature infants and can result in the sensors actually interfering with the care of the patient.

There are also special problems related to the measurement of physiologic variables in infants resulting from the special physiology of newborns and especially premature newborns. One first must realize that a newborn has come to live in a new environment quite different from the uterus. In the case of premature infants, they are not ready for this major change in their lives, and special considerations need to be made to minimize the transitional trauma. In the case of the premature, some of the body systems are immature and not ready for life outside of the uterus. Two notable examples of this are the control of temperature and control of respiration. Both are obviously unnecessary in the uterus, but become crucial in extrauterine life. Instrumentation to assist these control systems or to detect when they are not functioning properly is essential in the care of many premature infants.

One also must realize in applying instrumentation systems for premature infants that the patient in many cases is much more fragile than an adult patient. Fluid and electrolyte balance has already been indicated as an important aspect of neonatal monitoring and control. When one considers some of the very small premature infants that are cared for in neonatal intensive care units today, this can be better appreciated. Infants between 500 and 1,000 g can be successfully cared for and nurtured until they are old enough and grow enough to go home with their parents. These very small babies, however, can easily run into problems if they receive either too much or too little fluid. Since feeding of these very small infants can be done by intravenous hyperalimentation, the possibility of a fluid overload is always present since it takes a certain amount of fluid to transport the nutritional requirements of the infant. Another example of the fragility of these very small patients is the simple problem of attaching devices to the infant's skin. In some infants, the skin is very sensitive and can easily become irritated by the attachment procedure or substance.

This article, looks more closely at electronic monitoring systems for neonatal intensive care and emphasize those aspects of these monitoring systems that differ from similar monitors for adult patients. The reader is encouraged to supplement information contained in the following paragraphs with other articles from this encyclopedia

dealing with the sensors and instrumentation for similar monitoring in adults.

CARDIAC MONITORING

Cardiac monitoring involves the continuous assessment of heart function by electronic measurement of the electrocardiogram and determination of heart rate and rhythm from it by means of electronic signal processing. As such, cardiac monitors for neonatal use are very similar to those for use with adults. There are, however, two major differences. The sensors used with both types of monitors are biopotential electrodes, and in the case of infants the interface between the electrodes and the patients has more stringent requirements than in the adult case. Second, cardiac monitors designed for use with infants frequently are incorporated into cardiorespiratory monitors that include instrumentation for determining breathing rate and apnea as well as cardiac function.

The primary use of cardiac monitors for infants is in determining heart rate. These electronic devices are designed to indicate conditions of bradycardia (low heart rate) and tachycardia (high heart rate) by determining the heart rate from the electrocardiogram. In the case of infants with heart diseases, cardiac monitors are used to detect various arrhythmias as well.

Cardiac monitors for use with infants are organized similarly to their adult counterparts (see MONITORING, HEMODYNAMIC). There are some minor differences due to the fact that infant heart rates are higher than those of adults, and the Q–S interval of the infant electrocardiogram is less than it is in the adult. Thus, heart rate alarm circuits need to be able to respond to higher rates in the infant case than in the adult case. For example, it is not at all unusual to set the bradycardia alarm level at a rate of 90 or 100 beats·min^{-1} for an infant, which is well above the resting heart rate of a normal adult. Filtering circuits in the monitor for infants must be different from those of adult monitors for optimal noise reduction due to the different configuration of the neonatal electrocardiogram. Generally, bandpass filters used for isolating the QRS complex will have a higher center frequency than in the adult case.

Two types of cardiotachometer circuits can be used in cardiac monitors (1). The averaging cardiotachometer determines the mean number of heartbeats per predetermined interval to establish the heart rate. The mean R–R interval over a number, of heartbeats can also be used in average heart rate determination. In such systems the heart rate is calculated by averaging over from as few as three to as many as fifteen or more heartbeats. An instantaneous or beat-to-beat cardiotachometer determines the heart rate for each measured R–R interval. This type of cardiotachometer must be used when one is interested in beat-to-beat variability of the heart rate.

Biopotential electrodes for use with cardiac monitors for infants are usually scaled down versions of skin surface electrodes used for adult cardiac monitoring. As pointed out earlier, the scale factor does not correspond to the body size ratio between the neonate and an adult, and the smallest commercially available skin surface electrodes for neonates only approaches about one-fourth the size of those used in adults. For this reason, electrodes used with neonatal cardiac monitors and their method of attachment can cover a large portion of the neonatal thorax. This is especially true with the small premature infant and can interfere with direct observation of chest wall movements, an important diagnostic method. In addition to size, shape and flexibility of the electrode are important for biopotential electrodes in neonates. Stiff, flat electrode surfaces will not conform well to the curved, compliant surface of the infant. This means that optimal electrical contact is not always possible and it, therefore, becomes more difficult to hold electrodes in place. This problem is further complicated by the fact that the neonatal skin can be sensitive to the electrode adhesive. It is not at all unusual to find skin irritation and ulceration as a result of placement of biopotential electrodes on the infant. Such skin lesions are usually the result of the adhesive and the electrode attachment system, although the electrode itself can in some cases be the problem as well.

Since electrodes are relatively large on the small infant, an additional problem develops. The materials used in many electrode systems are X-ray opaque; hence, it is necessary to remove the electrodes when X rays are taken so that shadows do not appear in the resulting radiograph. Some biopotential electrodes especially developed for neonates have minimized this problem by utilizing special electrode structures that are translucent or transparent to X rays (2). These electrodes are based upon thin films of metals, usually silver, deposited upon polymer films or strips or various fabric materials. These films are sufficiently thin to allow X rays to penetrate with little absorption, and the plastic or polymer substrate is also X-ray transparent. Such electrodes have the advantage of increased flexibility, which helps them to remain in place for longer periods of time. In intensive care units, however, it is a good idea to change electrodes every 48 h to minimize the risk of infection.

Electrode lead wires and patient cables present special problems for cardiac monitors used with infants. Lead wires should be flexible so as not to apply forces to the electrodes that could cause them to become loose, but this increased flexibility makes it easier for them to become ensnarled with themselves and the infant. The potential for strangulation on older, active infants is always present. The connectors between the lead wires and the patient cable also present special problems. They must be capable of maintaining their connection with an active infant and provide a means of connection that will be unique for these components. The possibility of inadvertently connecting the lead wires, and hence the infant, to the power line must be eliminated (3).

RESPIRATORY MONITORING

Respiratory monitoring is the most frequently applied form of electronic monitoring in neonatology. In its most common application, it is used to identify periods of apnea and to set off an alarm when these periods exceed a predetermined limit. There are direct and indirect methods of

sensing alveolar ventilation and breathing effort. The direct methods are those in which the sensor is coupled to the airway and measures the movement or other properties of the air transported into and out of the lungs. In the indirect methods, the sensor looks at variables related to air movement, but not at the air movement itself. Indirect methods involve no contact with the airway or the air being moved into or away from the lungs. Usually, indirect methods are noninvasive and can be mounted on or near the body surface. Some of the most frequently applied methods are described in the following paragraphs.

Direct Methods

Various direct methods of sensing breathing effort and ventilation have been in use in the pulmonary physiology and pülmonary function laboratories for many years. These involve the measurement of volume, flow, and composition of inspired and expired gasses. Table 1 lists some of the principal methods that have been used for the direct measurement of respiration in infants and neonates. Most of these methods are not appropriate for clinical monitoring, since they involve direct connection to the infant airway through the use of a mask over the mouth and nose or an endotrachial canula. In other cases a sensor must be located at the nasal-oral area for signal detection. These methods are, however, useful in some cases for diagnostic studies carried out for periods from several hours to overnight in the hospital setting.

Many of the methods listed in Table 1 are described in detail in the article on pulmonary function testing, and therefore are not repeated here. Others, however, have special application to neonatal monitoring and will be mentioned.

Pneumotachography. Clinicians and researchers involved in neonatal and infant care agree for the most part that the best measurement of ventilation can be obtained using the pneumotachograph (4). Although this involves direct connection to the airway and can add some dead space due to the plumbing, it, with an appropriate electronic integrator, provides good volume and flow measurements that can be used as a standard against which other direct or indirect methods can be calibrated and evaluated. Identical instrumentation as used for adults can be applied in the infant case, but it must be recognized that dead space due to the instrumentation represents a more important problem with the infant than it does with the adult. Lower flows and volumes as well as faster respiration rates will be encountered with infants than with adults.

Table 1. Direct Methods of Sensing Breathing and Ventilation

Method	Primary Sensed Variable
Pneumotachograph	Flow volume
Anemometer	Flow velocity
Expired air temperature	Temperature
Air turbulence sounds	Sound
Spirometer	Volume

Capnography. Special carbon dioxide sensors have been developed for measuring air expired from the lungs, and these are used as the basis of a direct respiration monitor (5). Expired air has a higher percentage of carbon dioxide than inspired air, and this can be sensed by placing an open-ended tube at the nose or mouth so that it samples the air entering and leaving the airway. The sampled gas is transported along the tube to an instrument that contains a rapidly responding carbon dioxide sensor. This is generally a sensor that detects the increased absorption of infrared (IR) radiation by carbon dioxide-containing gas. Thus, when a sample of expired gas reaches the sensor, an increase in carbon dioxide content is indicated, while a decrease in carbon dioxide is seen in samples of air about to be inspired. There is a delay in response of this instrument due to the time it takes the gas to be transported through the tube to the sensor; thus, it is important to have rapid passage through this tube to minimize this delay. This can present some problems since the tube must be thin and flexible and, therefore, offers a relatively high resistance to the flow of gas. While it is generally not necessary to have a quantitative measure of carbon dioxide for respiration monitoring, the system can be refined to the point where it can measure the carbon dioxide content of the end tidal expired air, which is the gas that actually was in the alveoli (6).

Temperature Sensor. Similar sensing systems based upon temperature variations have also been used to monitor respiration (7). These generally can be divided into two types: one that measures temperature differences between inspired and expired air and one that measures the cooling of a heated probe as inspired or expired air is transported past it. In both cases, the temperature sensor of choice is a small, low mass, and therefore fast responding, thermistor. In the first mode of operation, the thermistor changes its resistance proportionally to the change in temperature of the air drawn over it. This can then be electronically detected and processed to determine respiration rate. It is also possible to heat the thermistor by an electrical current. Some of this heat will be dissipated convectively by the air passing over the sensor. As the flow of air over the thermistor increases, more heat will be drawn from the thermistor, and it will cool to a lower temperature. Changes in the thermistor's temperature can be determined by measuring its electrical resistance. Thus, an electrically heated thermistor will cool during both inspiration and expiration, and it will become warmer in the interval between these two phases when air is not passing over it. This type of anemometer gives a respiration pattern that appears to be twice the breathing rate, whereas the unheated thermistor gives a pattern that is the same as the breathing rate. An important consideration in using the nasal thermistor for ventilation measurement is its placement in the flowing air. For young infants, the sensor package can be taped to the nose or face so that the thermistor itself is near the center of one nostril. Another technique is to place a structure containing two thermistors under the nose so that each thermistor is under one nostril and expired air flows over both thermistors.

Nasal temperature sensors, such as thermistors, have been used for monitoring ventilation in research studies and for making physiologic recordings in the hospital and in the laboratory (8). Their advantage is that the electronic circuit for processing the signal is relatively simple and inexpensive compared with other techniques. The major problem of the method is the placement of the thermistor on the infant and maintaining it in place. Thermistors can also become covered with mucus or condensed water, which can greatly reduce their response time. Most investigators who use this technique prefer the temperature sensing rather than the flow-detecting mode. The devices can also be used with radiotelemetry systems to eliminate the wire between the thermistor on the subject's face and the remainder of the monitoring apparatus (9).

Although thermistors have a high sensitivity and can be realized in a form with very low mass, they are fragile when in this low mass form and are relatively expensive components. Low mass, high surface area resistance temperature sensors can also be fabricated using thin- and thick-film temperature sensitive resistors.(10) These can either be fabricated from metal films with relatively high temperature coefficients of resistance or more sensitive films of thermistor materials. Single use disposable sensors have been produced for use in infant and adult sleep studies as shown in Figure 2.

Sound Measurement. Air passing over the end of an open tube generates sound by producing local turbulence. A miniature microphone at the other end of the tube can detect this sound, and the level of sound detected is roughly proportional to the turbulence and, hence, the air flowing past the open end. Nasal air flow can thus be detected by placing the open end of the tube in the stream of inspired or expired air at the nose by taping the tube to the infant's face in much the same way as was done for the carbon dioxide sensor mentioned previously (11). As with the thermistor anemometer, this technique can detect changes for both inspired and expired air and will give a pattern that appears to indicate double the actual respiration rate. The method has been demonstrated to give efficacious monitoring results, but can suffer from sensitivity to extraneous sounds other than the air passing the open ended tube. This can lead to incorrect detection of breaths.

Indirect Sensors of Ventilation

There are a wide variety of indirect sensors of ventilation that can be applied to monitoring in infants. Table 2 lists some of the principal examples of these various types of sensors and sensing systems, and those with aspects unique to neonatal monitoring will be described in the following paragraphs. The main advantage of the indirect methods of sensing ventilation is that attachment to the subject is easier than for the direct measurements and less likely to interfere with breathing patterns. Of the methods described in Table 2 and this section, the transthoracic electrical impedance method is the one used in most presently available respiration-apnea monitors for both hospital and home use. This, therefore, will be described in greatest detail in a separate section.

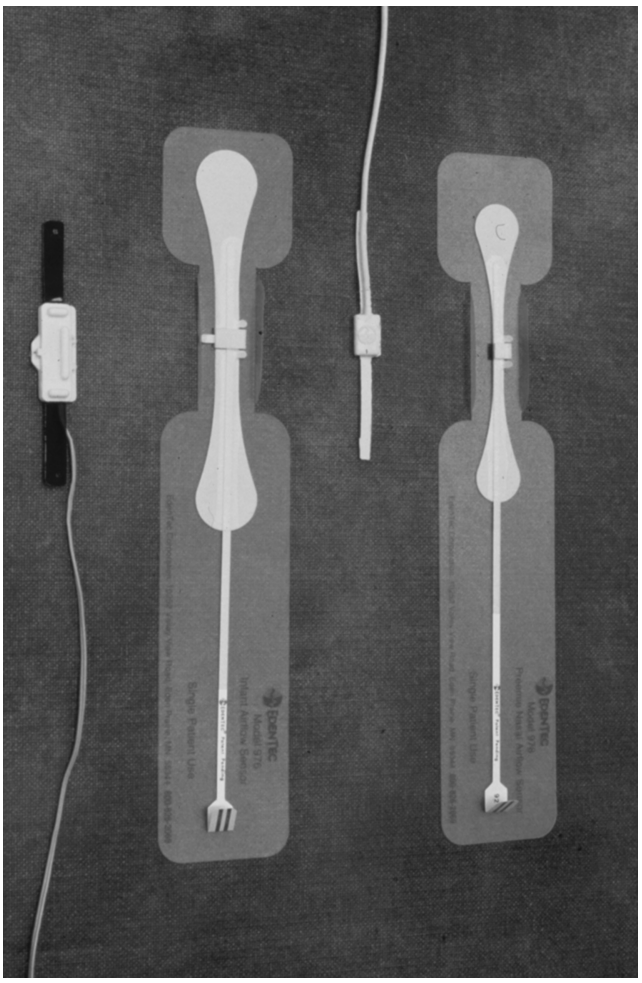

Figure 2. An example of commercially available thick-film nasal temperature sensors for measurement of breathing patterns. The small sensors on the illustration are conventional thermistor sensors.

The Whole-Body Plethysmograph. This method is used primarily in pulmonary function testing, and the reader is referred to the article on this subject for details on the method. Miniature whole-body plethysmographs have been designed for use with neonates and infants, but this

Table 2. Indirect Methods of Sensing Breathing and Ventilation

Transthoracic electrical impedance
Whole-body plethysmograph
Contacting motion sensors
Strain gage
Air-filled capsule or vest
Magnetometer
Inductance respirometry
Noncontacting motion sensors
Motion-sensing pad
Radiation reflection
Variable capacitance sensor
Electromyography
Breath sounds
Intraesophageal pressure

application is strictly for purposes of research or diagnostic studies. The technique is not appropriate for routine clinical monitoring.

Contacting Motion Sensors. Breathing effort involves the movement of different parts of the body for pulmonary ventilation to occur. Sensors can be placed upon and attached to an infant to measure this motion. These contacting motion sensors pick up movements of the chest and/or abdomen, and there are several different types of sensors that fall within this category. These are described in the following sections.

Strain Gage Displacement Sensors. Strain gages measure small displacements or strain in an electrical conductor by measuring changes in its electrical resistance. Most strain gages used for general measurements are made of thin metal foils or wires and are useful for measuring only very small displacements due to their very low mechanical compliance. A special type of strain gage consisting of a compliant, thin-walled, rubber capillary tube filled with mercury was developed by Whitney as a limb plethysmograph (12). This compliant device can be placed on the chest or abdomen of an infant such that breathing movements cause it to stretch and contract without offering significant mechanical constraint to the breathing efforts of the infant. By taping the ends of such a strain gage at different points on the chest or abdomen such that the gage is slightly stretched, the changes in electrical resistance of the gage can then be used to monitor infant breathing movements. Simple electronic resistance measurement circuitry can be used for processing the signal.

This technique is used primarily in research and in some rare cases for in-hospital monitoring and recording of infant respiration patterns. Its limitations are related to use of a toxic substance that could escape from the sensor and put the infant at risk. In addition, the mercury column frequently becomes interrupted after several days of use, thereby limiting the sensor's reliability for infant monitoring. Nevertheless, workers who use this sensor for monitoring purposes are enthusiastic about its reliability in picking up high quality respiration patterns.

Air-Filled Capsule or Vest. Breathing efforts of an infant can also be determined for chest or abdominal movements by a sensor consisting of an air-filled compliant tube, disk, or entire vest attached around an infant. The tube and disk can be taped to the infant's chest or abdomen in a fashion similar to the strain gage, and the structures will be stretched or compressed by the infant's breathing movements. This causes the pressure of the air within to increase or decrease as a result of volume changes, and this pressure variation can be measured by coupling the sensor to a sensitive pressure transducer through a fine-gage flexible tube. The advantage of this system is that the sensors on the infant are simple and inexpensive and thus can be considered disposable devices. Since only air is contained within the sensors, they are not toxic and are much more reliable than the mercury strain gages. They can be produced as inexpensive disposable sensors.

Displacement Magnetometers. The magnetic field from a permanent magnet or an electromagnet decreases as one gets farther from the magnet. By placing such a magnet on an infant's chest or abdomen with a detector located on the back of the subject or underneath the infant, differences in separation between the magnet and the detector can be sensed as the infant breathes (13). It is important that such a system be designed so that it will only respond to breathing movements and will be insensitive to other movements of the infant. Unfortunately, this is not always the case, and sensors of this type can respond to infant limb movement as well as movements between the infant and the pad upon which it is placed.

Inductance Respirometry. The inductance of a loop of wire is proportional to the area enclosed by that loop. If a wire is incorporated in a compliant belt in a zigzag fashion so that the wire does not interfere with the stretching of the belt, such a belt can be wrapped around the chest or abdomen of an infant to form a loop. As the infant inhales or exhales the area enclosed by this loop will change, and so the inductance of the loop will also change. These changes can be measured by appropriate electronic circuits and used to indicate breathing efforts. Investigators have shown that the use of such a loop around the chest and the abdomen of an adult can, when appropriately calibrated, measure tidal volume as well as respiratory effort (14). Although the system is simple in concept, realizing it in practice can involve complicated and therefore costly electronic circuitry (15). Often as the subject moves to a new position, the calibration constant relating inductance and volume will change thereby making the instrument less quantitative, yet still allowing it to be suitable for qualitative measurements. Variations in tidal volume measurements using this technology have been reported by Brooks et al. (16) Since the instrument is sensitive to inductance changes in the wire loop, anything in the vicinity of the wire that affects its inductance also will affect the measurement. Thus, the instrument can also be sensitive to moving electrical conductors or other magnetic materials in the vicinity of the infant.

Noncontacting Motion Sensors. Sensors of infant breathing effort and pulmonary ventilation that detect breathing movements of the infant without direct patient contact fit in this category. These sensors can consist of devices that are placed under the infant or can sense movement of the infant by means of a remotely located sensor. A clinician, in effect, is an indirect motion sensor when he or she determines infant breathing patterns by watching movements of the chest and abdomen. Devices in this category have a special appeal for monitoring systems that are used outside of the hospital, such as instruments for use in the home. With many of the noncontacting sensors, the infant-sensor interface can be created by individuals who do not have specialized training. For example, the motion sensing pad discussed in the next paragraph is attached to the infant by simply placing the infant on top of it in a bassinet or crib.

Motion Sensing Pad. Movements of neonates and infants can be sensed by a flexible pad that responds to

compression by producing an electrical signal when the infant is placed on top of the pad. There are two different forms of this sensor that can be used for motion detection. The first utilizes a piezoelectric polymer film, polyvinylidene fluoride, that has its surfaces metalized to form electrical contacts. Depending on the piezoelectric properties of the film, an electrical signal is produced between the metalized layers when the polymer is either compressed or flexed. In the former case, the polymer film and its metalized electrode need only to be packaged in an appropriate pad structure to be used, while in the latter case the package must be a little more complex with the polymer film positioned between two corrugated, flexible layers so that compression of the structure causes the piezoelectric polymer to be flexed (17). The second form of the pad uses an electret material to generate the electrical signal. The actual pad structure in this case is similar to that for the piezoelectric material.

The sensitive portion of the motion sensing pad structure is usually smaller than the overall size of the infant and is located under the infant's thoracic and/or lumbar regions. Infant breathing efforts result in periodic compression of the pad as the center of mass of the infant shifts cephalad and caudad with respiratory motion. This generates a periodic electrical signal related to the breathing effort.

The major limitation of the motion sensing pad is its sensitivity to movements other than those related to respiratory efforts of the infant. Other body movements can be picked up by the sensor, and the device can even respond to movements that are not associated with the infant at all, such as an adult walking near or bumping the bassinet or crib, a heavy truck, train, or subway passing nearby, or even earthquakes.

Radiation Reflection. Electromagnetic radiation in the microwave range (radar) or ultrasonic radiation (sonar) can be reflected from the surface of an infant. If this surface is moving, as, for example, would be the chest or abdominal wall during breathing efforts, the reflected radiation will be shifted in frequency according to the Doppler effect. In some cases the reflected signal's amplitude will be shifted as well as a result of this motion. These changes can be detected and used to sense breathing efforts without actually contacting the infant. The problem with these methods is that the movement of any surface that reflects the radiation will be detected. Body movements of the infant that are unrelated to respiratory movements can be detected and mistakenly identified as breathing effort, and even in some cases movement of objects in the vicinity of the infant, such as a sheet of paper shifting due to air currents, will also be detected as infant respiration. Thus, this type of monitor has the possibility of indicating apparent breathing activity during periods of apnea if moving objects other than the infant are within the range of the radiation sensor. This technique of noncontacting detection of breathing is not considered to be reliable enough for routine clinical use, and a commercial device based on this principle has been withdrawn from the market.

Variable Capacitance Displacement Sensor. A parallel plate capacitor can be fabricated so that an infant is placed between the parallel conducting planes. For example, such a capacitor could be formed in an incubator by having the base upon which the mattress and infant are placed serving as one plate of the capacitor and having the second plate just inside the top of the incubator (18). To maintain good clinical practice, this second plate should consist of a transparent conductor, such as an indium tin oxide film, so that it does not interfere with a clinician's ability to observe the patient. Since a major component of the infant's tissue is water, and water has a relatively high dielectric constant compared to air, movements of the infant will produce changes in capacitance between plates that can be detected by an electronic circuit. Such changes can be the result of breathing movements by the infant, but they also can result from other infant movement or movement of some other materials in the vicinity of the conducting plates. Therefore, for this system to be effective, adequate electrical shielding of the capacitor is essential. Thus, this indirect motion sensor suffers from some of the same problems as other sensors in this classification: the lack of specificity for breathing movements.

Electromyography. Many different muscles are involved in breathing activity. The diaphragm is the principal muscle for pulmonary ventilation, but the accessory muscles of the chest wall including the intercostal muscles are also involved, Electromyographic activity of the diaphragm and intercostal muscles can be sensed from electrodes on the chest surface. By measuring these signals, one can determine if respiratory efforts are being made, although such measurements cannot be quantitative with regard to the extent of the effort or the volume of gas moved (19). Unfortunately, other muscles in the vicinity of the electrodes that are not involved in breathing also produce electromyographic signals. These signals can severely interfere with those associated with respiration, and this is especially true when the infant is moving. This represents a serious limitation of this method for clinical infant respiration monitoring.

Breath Sounds. Listening to chest sounds through a stethoscope is an important method of physical diagnosis for assessing breathing. The technique can be used for infant monitoring by placing a microphone over the chest or trachea at the base of the neck and processing the electrical signals from this sensor. In addition to the sounds associated with air transport and ventilation, the microphone will pick up other sounds in the body and the environment. Thus, for this type of monitoring to be efficacious, it must be done in a quiet environment. This puts a serious constraint on the practical use of this technique, and it has only been used in limited experimental protocols.

Intraesophageal Pressure. The pressure within the thorax decreases with inspiratory effort and increases with expiratory effort. These changes can be measured by placing a miniature pressure sensor in the thoracic portion of the esophagus or by placing a small balloon at this point and coupling the balloon to an external pressure

transducer through a small diameter flexible tube. While this method is invasive, it is not considered a direct method since there is no contact with the flowing air.

An important aspect of intraesophageal pressure measurement is that it represents a standard method that is accepted by physiologists as a measure of respiratory effort. Thus, by combining intraesophageal pressure measurement and the pneumotachograph, one is able to monitor both gas flow and breathing effort. Although both of these methods are generally too complicated for clinical monitoring, they can be used in conjunction with other monitoring methods described in this article as standards against which to assess the other devices.

Transthoracic Electrical Impedance. The electrical impedance across the chest undergoes small variations that are associated with respiratory effort. The measurement of these variations is the basis of the most frequently used infant respiration and apnea monitoring technique. The following section describes the basic principle of operation, the methods of signal processing, and sources of error for this technique.

RESPIRATION MONITORING BY TRANSTHORACIC ELECTRICAL IMPEDANCE

The chest contains many different materials ranging from bone to air. Each of these materials has its own electrical properties and of its own unique location in the thorax. One can roughly represent a cross section of the infant chest as shown in Fig. 3, where the major components consist of chest wall, lungs, heart, and major blood vessels. The various tissues contained in these structures range in electrical conductivity from blood, which is a relatively good conductor, to air, which is an insulator. Both of these materials in the thoracic cavity show a change in volume with time over the cardiac and breathing cycles. Blood varies in volume over the cardiac cycle due to changes in the amount of blood in the heart and the vascular compartments. Air undergoes wide volume changes in the lungs during normal breathing. Thus, the electrical impedance of the lungs and heart will change as the volume of air and blood in each, respectively, changes. If we want to measure the impedance variation due to these volume changes, this can be done by placing electrodes on the surface of each structure. If it were practical to do this, we would see large changes in impedance as the volumes of the respective structures change. Unfortunately, it is not possible to place electrodes on the structures that are to be measured and so these large impedance differences are not seen in practice.

Electrodes must be placed upon the surface of the skin for practical electrical impedance measurements on infants. Most of the current passing between the electrodes will travel through the chest wall and will not pass through the heart and lungs because of the low resistivity of the tissues in the chest wall. Thus, the changes in impedance of the heart and lungs will only represent a small proportion of the impedance measured between the electrodes. Fig. 3 schematically illustrates the relative distribution of the current through the chest when electrodes are placed on the midclavicular lines at the fourth intercostal space. It is seen that most of the current is conducted along the chest wall, so the chest wall impedance will dominate any measurement.

The actual impedance measured by the monitor consists of more than just the impedance between the electrodes on the chest surface. Since an ac electrical signal is needed to measure the impedance, this signal will affect the measurement as well. Generally, a signal in the frequency range from 20–100 kHz is used. At these frequencies, impedances associated with the electrode, the interface between the electrode and the body, and the lead wires contribute to the measured value along with the actual transthoracic impedance. This is illustrated schematically in Fig. 4. The actual impedances for each block are dependent upon the excitation frequency and the actual structures used, but for most clinical applications the net impedance seen by the monitoring circuit is nominally 500 Ω. Of this, the variation associated with respiration is generally no $>$ 2 Ω and frequently even less. The impedance

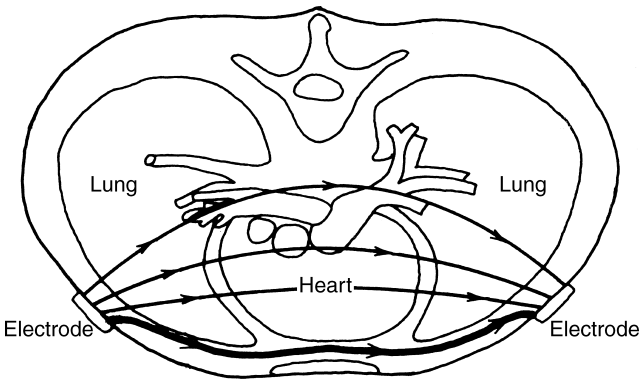

Figure 3. Cross-sectional view of the thorax of an infant showing the current distribution from electrodes placed on the chest wall and excited by a transthoracic impedance type of apnea monitor.

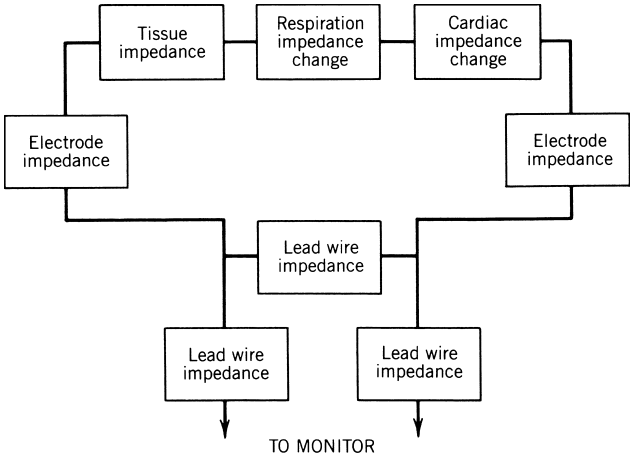

Figure 4. Block diagram of the various impedances seen at the terminals of a transthoracic electrical impedance apnea monitor looking along the lead wires to the patient.

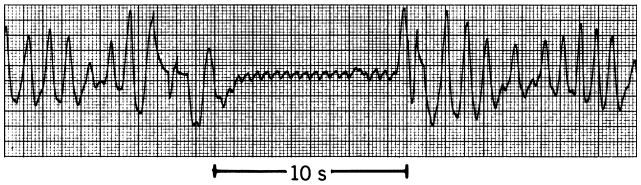

Figure 5. An example of cardiogenic artifact on infant respiration signals from a transthoracic impedance type of monitor illustrating cardiogenic artifact during apnea.

variation associated with the beating heart can be of the same magnitude, although it is generally a little less. Thus, it is seen that a fundamental problem in the indirect measurement of respiration by the transthoracic impedance method is the relatively small changes in impedance associated with the measurement.

To further complicate the situation, each of the nonthoracic impedance components of the circuit illustrated in Fig. 4 can vary in electrical impedance by at least as much if not more than the variation due to respiration. The impedance between the electrode and the infant's skin is strongly dependent on the electrode–skin interface. As electrodes move with respect to the skin, this impedance can vary by amounts much $> 2\ \Omega$. This is also strongly dependent on the type of electrode used and the method that electrically couples it to the skin.

Cardiogenic Artifact

The volume of the heart varies during the cardiac cycle, and so the contribution of the blood to the overall transthoracic impedance will change from systole to diastole. To a lesser extent the vascular component of the chest wall and lungs will also change in blood volume during the cardiac cycle, and this will have some influence on the transthoracic impedance as well, Cardiogenic artifact is illustrated in Fig. 5, which shows a recording of transthoracic impedance from an infant during breathing and during a period of apnea. The cardiogenic artifact is best seen during the apnea, where it appears as a smaller impedance variation occurring at the heart rate. This can be seen by comparing the impedance waveform with a simultaneously recorded electrocardiogram. One notes that the cardiogenic artifact is also present during the breathing activity and appears as a modulation of the respiration waveform.

In the example in Fig. 5 the cardiogenic artifact is relatively small compared to the impedance changes due to breathing, and it is possible to visually differentiate between breathing and apnea by observing this recording. This is not always the case when recording transthoracic impedance as Fig. 6 illustrates. Here one observes periods of breathing and apnea with much stronger cardiogenic artifact. It is difficult to determine what impedance variations are due to breathing and what are due to cardiovascular sources. It is only possible to identify periods of respiration and artifact when the recording is compared with a simultaneous recording of respiration from a recording of abdominal wall movement using a strain gage as shown in Fig. 6. Note that in the case of the impedance signal in this figure, the cardiogenic artifact has two components during each cardiac cycle.

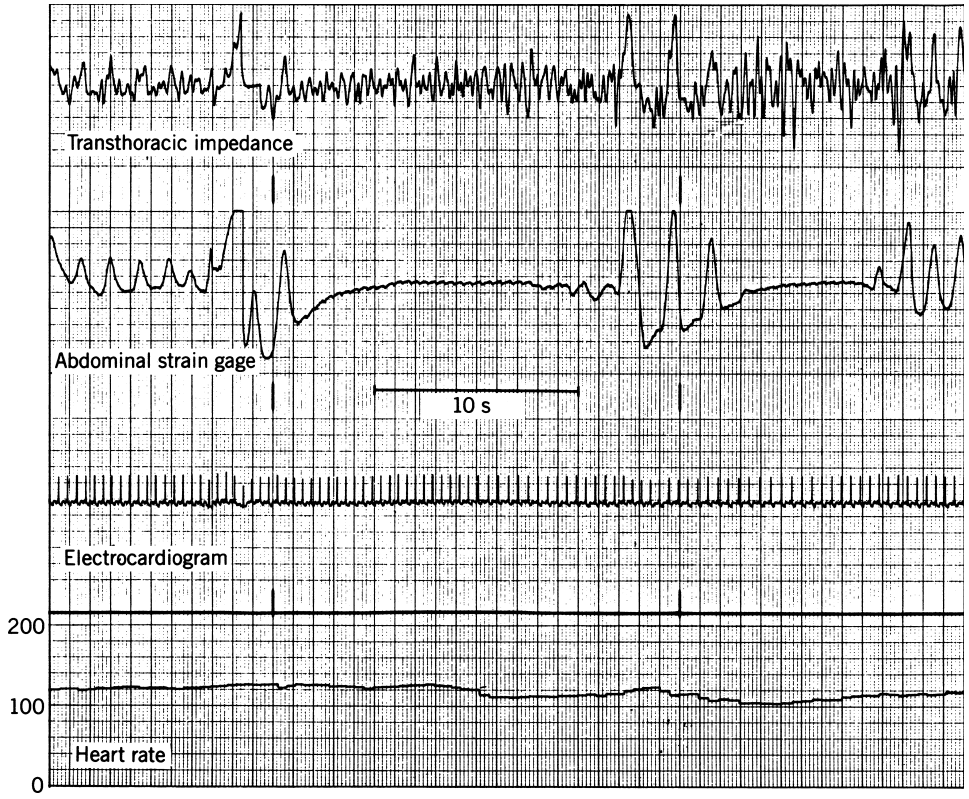

Figure 6. High amplitude cardiogenic artifact is shown on the transthoracic impedance tracing from this recording of multiple signals from a newborn infant. In this case, the transthoracic impedance changes correspond to the electrocardiogram shown on the third trace from the top. Simultaneous recordings from a nasal thermistor and an abdominal strain gage do not show these high frequency variations.

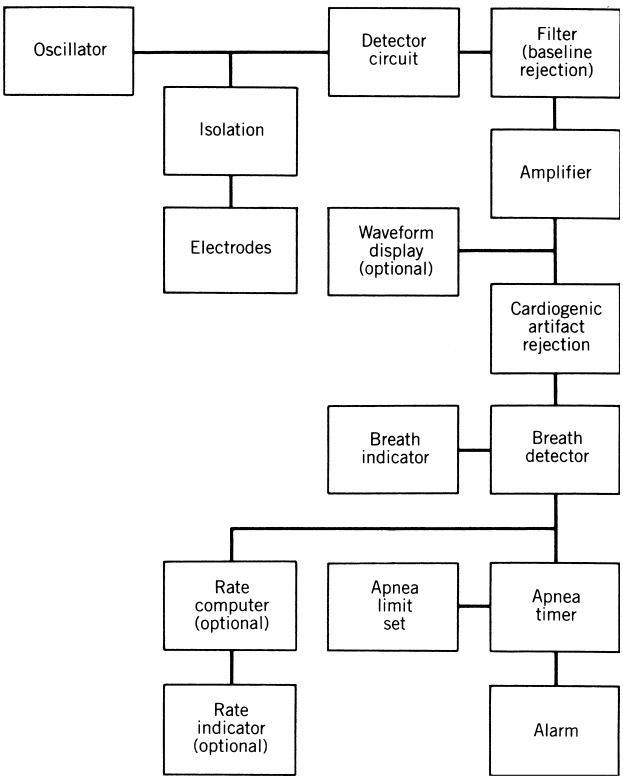

Figure 7. Functional block diagram of a transthoracic impedance infant apnea monitor.

Signal Processing

The electrical signals from the electrical impedance sensor, or any of the other respiration sensors, must be processed to recognize breathing activity and to determine when apnea is present. Different sensors require processors of differing complexity because of different signal characteristics, but the general method of signal processing is the same no matter what sensor is used. The signal processing associated with the electrical impedance method of apnea monitoring will be described in the following paragraphs, since it is one of the most complex as well as most highly developed monitoring systems.

A block diagram of the generalized sections of a transthoracic electrical impedance type of apnea monitor is shown in Fig. 7. The basic functions of the system can be broken down into impedance measurement, breath detection, artifact rejection, apnea identification, and alarm functions. Each of these can be carried out with varying degrees of complexity, and sophisticated signal processing techniques can be used to get the most information out of a less than optimal signal.

A signal generator in the impedance measurement portion of the system produces the excitation signal that is applied to the electrodes. This can either be a sinusoidal or a square wave, and frequently will have a high source impedance so that it behaves as though it was generated by a constant current amplitude source. Passing this current through the lead wire–electrode–body system causes a voltage amplitude proportional to its impedance to appear at the monitor input. Variations in this voltage reflect the variation in impedance. It is therefore important that the current amplitude of the excitation signal remain constant during a measurement. Excitation signal frequency is chosen to be in the range of 20–100 kHz so that electrode–body interface impedances are relatively low, thereby producing less artifact. Detection of individual breaths from a complex breathing signal represents a major task for the respiration monitor. While the design of electronic circuits to carry out such a function on a regular, noise-free, nearly constant amplitude respiration signal such as seen in Fig. 8a presents no problem; very often the respiration waveform is much more complicated and not so easily interpreted, as illustrated in Fig. 8b. Cardiogenic artifact also helps to complicate the signal detection problem since in some cases it can masquerade as a breath. Some of the basic methods of identifying breaths are listed in the following paragraphs. Often individual monitors will use more than one of these in various unique signal processing algorithms.

Fixed Threshold Detection. A breath can be indicated every time the respiration signal crosses a predetermined fixed threshold level. It is important to carefully choose this level so that nearly all breaths cross the threshold, but

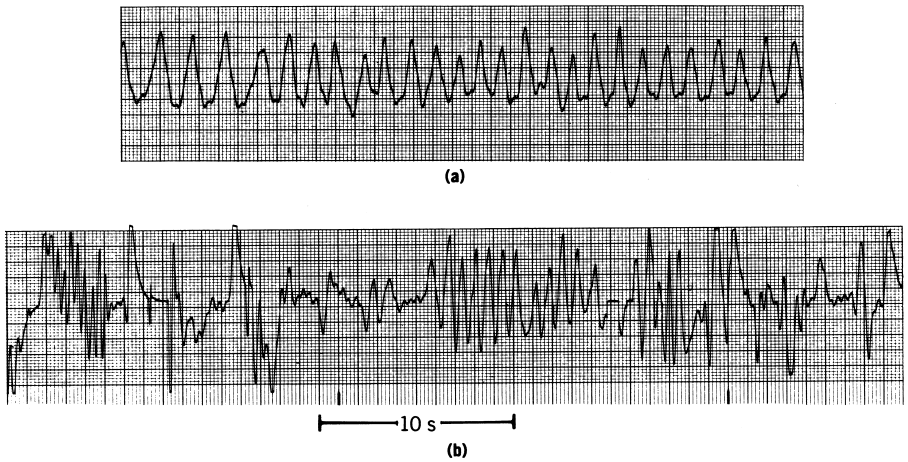

Figure 8. Typical infant respiration signals obtained from infant apnea monitors. (a) The top trace illustrates a relatively quiet signal that can be processed to determine respiration rate and apnea. (b) The bottom trace is a typical example of a noisy signal resulting from infant movement. In this case it would not be easy to determine respiration rate.

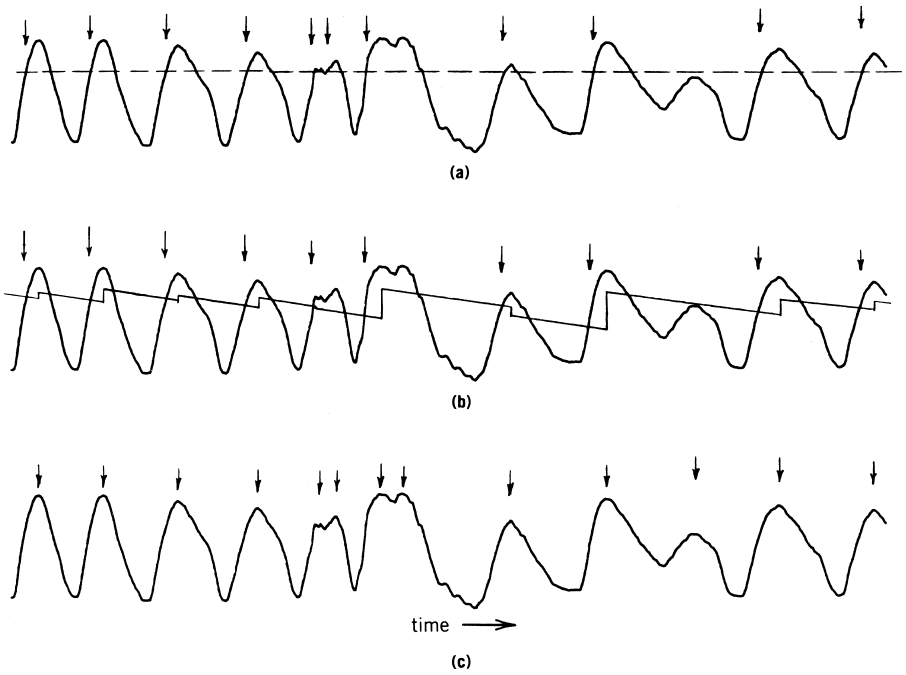

Figure 9. Three identical respiration signals in which different methods of detecting a breath are used. The arrows indicate when the apnea monitor would detect a breath for each method. (a) Fixed threshold detection, note missing breath when signal fails to cross a threshold. (b) Adaptive variable threshold detection, note that breaths can be missed with this method when the amplitude from one breath to the next is significantly different. (c) Peak detector, note that this method can result in double breath detection for signals with multiple peaks.

practically no noise or artifact does. Figure 9a illustrates the basic threshold breath indicator system in which a breath is indicated whenever the signal is greater than the threshold level.

Automatic Gain Control. The fixed threshold method of detection can be improved by preceding the threshold detector with an amplifier that has an automatic gain control. In this way the weaker signals are amplified more than the stronger ones so that all signals appearing at the fixed threshold detector circuit have roughly the same amplitude and will be detected. Although this method makes the fixed threshold detection scheme more reliable, there is also the possibility that noise or cardiogenic artifact will be amplified until it is strong enough to masquerade as a breath during periods of apnea thereby causing the monitor to fail to identify the apnea.

Adaptive Threshold Detection. A variable threshold level can be set by the monitor based upon a preprogrammed algorithm. One common example of this is to have the monitor determine the threshold level based upon the amplitude of the previous breath. This is illustrated in Fig. 9b, where the threshold is set at 80% of the peak amplitude of the previously detected breath. Since this threshold may still be too high if the previous breath had a large amplitude and subsequent breaths were of a relatively low amplitude, this threshold is not fixed, but rather it slowly decreases so that eventually a breath will be detected and the threshold level can be reset. The risk with this type of system is that the threshold will eventually get low enough to detect noise or cardiogenic artifact during an apnea resulting in a breath detected in error. Thus, the algorithm for this adaptive system must have minimum threshold levels that are still well above the noise or cardiogenic artifact level for it to work effectively.

Peak Detector. This circuit recognizes the maximum value of a signal over a short interval of time regardless of the overall amplitude of that signal. The way that a peak detector detects the breaths from a typical respiration waveform is illustrated in Fig. 9c. The basic peak detector can recognize more than one peak in a complex respiration wave. This can give errors if the monitor is used to determine respiration rate. Again, by adding complexity to the signal processing algorithm, this type of error can be greatly reduced.

Filtering. Frequency spectral analysis of infant respiration signals shows that most of the information is contained in the frequency band of 0–6 Hz, and in many cases the band is even narrower (20). Since artifactual signals can exist both within and outside of this frequency range, most apnea monitors filter the respiration signals so that only the frequencies containing information are processed. The type of filtering used depends on the particular monitor design, but any process of filtering can distort the waveforms and may itself introduce artifact. This is especially true when high pass filtering is used to remove the baseline. Thus, filtering can affect the performance of the breath detection method used in the instrument.

Although filtering is an important aspect of the breath detection circuitry, it can in some cases cause motion artifact to begin to look similar to a respiration signal and thus allow the detection circuit to recognize artifact as a breath. Often under the best conditions it is difficult to discriminate between artifact and true breathing signals, and the filtering only further complicates this problem. Nevertheless, without filtering breath detection would be much more difficult.

Pattern Recognition. Computer technology allows algorithms for recognizing various features of the respiration

waveform to be applied for breath detection in infant respiration monitors. Features, such as threshold crossing, peaks and valleys, slopes, amplitudes, width, and interval of a respiration wave can be readily detected. More sophisticated algorithms can be trained to recognize breaths that are similar in appearance to preprogrammed waveforms or based on the appearance of previous breaths for a particular patient. Another important aspect of computer recognition of patterns is that the computer can be programmed to ask various questions: Is the measured value physiologically possible? Does the waveform look more like artifact than information? Is the rate too fast? Does the signal correspond too closely to the cardiac cycle so that it might be cardiogenic artifact? Is there more than one peak per breath? All of these techniques of breath detection have advantages and disadvantages for infant monitoring. Each technique, however, imposes constraints on the signal that determine whether it will also detect artifact or miss some true breaths. Even the most sophisticated computer methods suffer from faults such as these and present limitations in breath detection.

Cardiogenic Artifact Rejection. Although cardiogenic artifact represents a major problem when breathing efforts are measured by the transthoracic electrical impedance method, this interference can be seen at times in the output of other indirect sensors of respiration as well. Usually, for these other sensors this artifact is small and does not pose any problem in breath or apnea recognition. Several methods have been used to reduce the problems associated with cardiogenic artifact in the transthoracic electrical impedance type of apnea monitor. Cardiogenic artifact occurs at the heart frequency and its harmonics, which can be different from the periodicity of the respiration signal. In infants the heart rate is usually higher than the respiration rate, although this is not always the case since infants can breath quite rapidly. If the respiration signal containing cardiogenic artifact is passed through a low pass filter having a cutoff frequency that is higher than the expected respiration rates but lower than the heart rates likely to be encountered, much of the cardiogenic artifact can be removed without seriously distorting the respiration signal. The problem with this approach is the selection of a cutoff frequency for the filter. It is generally not possible to find a frequency that is greater than the maximum respiration rate yet less than the minimum heart rate for small infants. Estimated values of such a frequency have to be changed according to the age of the infant, and since bradycardia can be associated with apnea, it is possible that the heart frequency will drop below the filter cutoff frequency during times of apnea, allowing cardiogenic artifact to get into the respiration channel just at the very time when it should be avoided.

The approach of using a filter, however, has merit if the above limitations can be taken into consideration in the design of the filtering system. Although there is no way that a filter can be useful when the heart rate is less than the respiration rate, the filter can help if its cutoff frequency is based upon the apparent respiration and heart rates of the infant. Such adaptive filtering techniques have been successfully used to minimize the effects of cardiogenic artifact.

Since most transthoracic electrical impedance apnea monitors also determine heart rate from the electrocardiogram, this cardiac signal can be used to help identify when a respiration signal consists primarily of cardiogenic artifact. The temporal relationship between the cardiogenic artifact and the electrocardiogram should be constant since both come from the same source. If the respiration signal consists only of cardiogenic artifact, as would be the case during a period of apnea, it is possible to identify the fixed temporal relationship between the signal and the electrocardiogram and therefore reject the signal from being accidentally detected as a breath. The only limitation with this technique is that in rare cases the infant can breath at the same rate as the heart is beating, and the monitor would indicate that an apnea had occurred when in fact it had not.

COMBINATION TRANSTHORACIC IMPEDANCE AND CARDIAC MONITORS

Most commercially available infant apnea monitors take advantage of the fact that the same sensor system, a set of biopotential electrodes, can be used for both transthoracic electrical impedance respiration monitoring and cardiac monitoring. Since the excitation signal for transthoracic impedance monitoring has a frequency of 20 kHz or greater and the highest frequency component of the infant electrocardiogram is < 200 Hz, the excitation signal can be applied to the same electrodes used for obtaining the electrocardiogram. By connecting a low pass filter between the electrodes and the heart rate monitor circuit, this excitation signal can be kept out of the cardiac monitor, and a bandpass filter in the respiration monitor centered at the excitation signal frequency will keep the electrocardiogram and biopotential motion artifact out of the transthoracic impedance monitor circuit.

The combination of respiration and heart rate monitoring in a single instrument helps to identify life-threatening events. If for some reason the respiration monitor fails to recognize prolonged apneas, bradycardia will often be associated with such episodes, and the heart rate monitor will recognize the reduced heart rate and set off an alarm.

MEASUREMENT OF BLOOD GASES

Blood gases refer to the oxygen and carbon dioxide transported by the blood. Acid–base balance is also included in discussions of blood gases since it is closely related to respiratory and metabolic status. Thus, measurements of blood gases are frequently combined with measurements of blood pH. There are invasive and noninvasive methods of measuring blood gases. Both can be used for hospital monitoring of critically ill infants. The principal methods that are used are described in this section.

Invasive Methods

Invasive blood-gas measurement techniques involve direct contact with the circulatory system so that blood samples can be drawn and measured in a laboratory analyzer or a

miniature sensor can be placed within the blood stream for continuous measurements. Some of these methods are described in the following paragraphs.

Intraarterial Catheter. The newly born infant has an advantage over other medical patients in that the vessels of the umbilical cord stump can accept a catheter for several hours after birth. Thus, it is possible to introduce a fine-gage, flexible, soft catheter into an umbilical artery of a cardiac or respiratory compromised infant and advance the tip into the aorta so that samples of central arterial blood can be obtained for analysis. Blood samples with a volume of only 50 μL can be analyzed for pH, P_{O_2}, and P_{CO_2} by means of specially designed miniaturized versions of standard analytical chemistry sensors of these variables. Such microblood analyzers are also used for analyzing fetal scalp blood samples. It is important in neonatal applications that only microblood analyzers be used since the total blood volume of very small infants is limited. Since an infant's blood gas status can be labile, it is often necessary to draw many blood samples during the clinical course of care, thus significant blood loss can occur unless very small samples are taken.

Microblood analyzers generally use the inverted glass electrode for pH measurement, a miniaturized Clark electrode for P_{O_2} measurement, and a miniaturized version of the Stowe–Severinghaus sensor for P_{CO_2}. The technology of microblood gas analyzers is well developed, and devices perform reliably in the intensive care situation. Instrumentation is frequently located within the neonatal intensive care unit itself, and respiratory therapists for collecting samples and carrying out the analyses as well as calibrating and maintaining the analyzers serve round the clock.

The major limitation of this sampling technique is that the sample only represents the blood gas status at the time it was taken. Thus, frequent samples must be taken during periods when variations can occur to track these variations, and even with microblood analyzers this can sometimes result in significant blood loss for very small infants. If the method for drawing the blood sample from the infant is stressful, such as a painful vascular puncture or heel stick, the blood gases of the sample will probably not reflect the quiescent status of the patient. As a matter of fact the very act of obtaining the blood sample may be of some risk to the infant since it can temporarily increase hypoxia (21).

The umbilical vessel canulation is not without problems itself. In placing the catheters, one must be careful not to damage the lining of the vessels or perforate a vascular wall resulting in severe bleeding or hemorrhage. Catheters must be made of materials that do not promote thrombosis formation. When catheters are not used for drawing blood, they must be filled with a physiological solution containing an anticoagulant such as Heparin so that blood that diffuses into the tip of the catheter does not clot. Any thrombi formed on the catheter wall or within its lumen can break off and cause embolisms further downstream. For arterial catheters this can be in the blood supply to the lower periphery of the infant, and it is possible to see under perfused feet in infants having an umbilical artery catheter. Catheters in the umbilical vein or peripheral veins can also produce emboli. In this case the clots are returned to the right side of the heart and can go on to produce pulmonary emboli.

Peripheral Blood Samples. Although it is frequently possible to introduce a catheter into an umbilical artery in a newly born infant, this is not always the case, or the need for blood gas monitoring may not arise until the infant is sufficiently old that the umbilical vasculature has permanently closed. In this case it is necessary to canulate a peripheral artery to obtain frequent arterial blood samples. On very small infants this is no minor task since these vessels are very small and difficult to canulate transcutaneously.

An alternative to drawing an arterial blood sample is to take a sample of capillary blood from the skin under conditions where the capillary blood flow has been significantly increased so that the capillary blood appears to be similar to peripheral arterial blood. This can be done, for example, in the heel by first warming an infant's lower leg and foot by wrapping it with warm, wet towels. A blood sample of sufficient size for a microblood analyzer can then be obtained by making a small skin incision with a lancet and collecting the blood sample in a capillary tube in a fashion similar to the technique for obtaining a fetal scalp blood sample (see FETAL MONITORING). Although this technique is not as reliable as sampling from an umbilical artery catheter, it can be used when only a single blood sample is desired and an umbilical catheter would be inappropriate or where it is not possible to place such a catheter. An important limitation of the technique is that the infant's heels can become quite bruised when frequent samples are required and suitable locations for additional samples might no longer be available. When frequent samples are required, it is generally better to attempt canulation of a peripheral artery.

Internal Sensors. Blood gases can be continuously monitored from invasive sensors. Generally, these sensors are incorporated into umbilical artery catheters (22), but tissue measurements have also been demonstrated (23). The most frequently applied technique involves the incorporation of an amperometric oxygen sensor into a catheter system. This can be done either by incorporation of the sensor within the wall of the catheter, by using a double lumen catheter with the sensor in one lumen and the second lumen available for blood samples or infusion, or by using a conventional single lumen catheter with a sensor probe that can be introduced through the lumen so that the sensor projects beyond the distal tip of the catheter.

Oximetry, the measurement of hemoglobin oxygen saturation, can be carried out continuously by means of optical sensors coupled to intravascular catheters or probes. Optical fibers can be incorporated in the wall of a catheter or in an intraluminal probe and used to conduct light to the catheter's distal tip. The light illuminates the blood in the vicinity of the catheter tip, and an adjacent fiber or bundle of fibers collects the backscattered light and conducts it to a photo detector where its intensity is measured. By alternately illuminating the blood with light of two or more different wavelengths, one of which is close to

an isosbestic point, and measuring the backscattered light, it is possible to determine the hemoglobin oxygen saturation in the same way as done in laboratory instruments for *in vitro* samples.

Advantages and Disadvantages of Invasive Techniques. The methods described in the previous sections represent direct measurements in that the sensor that is used is in direct contact with the body fluid, usually blood, being measured. This direct contact improves the possibility of accurate measurements. When the sensor is not located in the blood itself but is used to measure samples of blood drawn from the patient, instruments can be frequently calibrated using laboratory standards. Sensors that are used within blood or other tissues have the requirement that they must be small enough to fit in the tissue with minimal damage, either as a part of a catheter or some other probe. The miniaturization process must not compromise accuracy or reproducibility. In cases where microelectronic technology can be used to miniaturize the structures, reproducibility can even be improved in the mass-produced miniature devices as compared to their piece-by-piece-produced larger counterparts. The continuous invasive sensors are also limited in where and when they can be applied. While the umbilical arteries are convenient conduits to the central arterial circulation, they are only patent for a few hours after birth in most newborn infants. Following this time it is very difficult to obtain arterial samples since other vessels must be used. The use of intravascular sensors, and those in tissue as well, also increases the risk of infection and mechanical damage. Care must be taken with intraarterial sensors to avoid serious hemorrhage due to system components becoming disconnected.

Noninvasive Methods

In noninvasive measurement of blood gases, there is no direct contact between the blood or other tissue being measured and the sensor. In this way there is usually less risk to the patient and the technique is easier to apply clinically. The major noninvasive methods used in neonatal monitoring are now described.

Transcutaneous Blood Gas Tension Measurement. One of the major advances in neonatal intensive care monitoring technology was the development of transcutaneous blood gas measurement instrumentation. This allowed the oxygen tension and later the carbon dioxide tension of infants at risk to be continuously monitored without invading the circulatory system (24). These methods make use of a heated sensor placed on the infant's skin that measures the partial pressures of oxygen or carbon dioxide of the blood circulating in the dermal capillary loops under the sensor. The heating of the skin to temperatures of 44 °C arterializes the capillary blood in a manner similar to that used for obtaining capillary blood samples with heel sticks. Although the heating of the blood increases the blood gas tensions in the capillary blood, oxygen consumption by the viable epidermis surrounding the capillaries and diffusional drops through the skin compensate for this increase resulting in good correlations between the transcutaneously measured blood gas tensions and those determined from arterial blood samples in neonates. Sensors can be left in place on neonates for up to four hours, but for longer periods of time it is recommended to move the sensor to a new location to avoid tissue damage due to the elevated temperature. Multiple sensors have been developed in which the heating element is switched between several sensors in the same package periodically so that the overall sensor can be left in place for longer periods of time without producing damage (25).

Although transcutaneous instrumentation can give good correlations between transcutaneous and central arterial blood gas measurements in neonates, it would be misleading to suggest that the transcutaneous instrument is measuring the same thing as is measured from arterial blood samples. Indeed in infants with unimpaired circulatory status, the transcutaneous blood gases and those in the central circulation are similar; however, when there is cardiovascular compromise, heating of the sensor can no longer completely arterialize the capillary blood, and there are significant differences between the transcutaneous and central measurements. Thus, when one makes both transcutaneous and central measurements, differences can be used as a means of identifying shock-related conditions (26).

Transcutaneous Mass Spectrometry. Another noninvasive method for measuring blood gas tensions involves the use of a transcutaneous mass spectrometer (27). A sensor similar to the transcutaneous blood gas sensor in that it contains a heater to arterialize the capillary blood under it is made of a gas-permeable membrane in contact with the skin. This is connected to the mass spectrometer instrument through a fine-bore flexible tube through which an inert carrier gas is circulated to bring the gases that diffuse from the skin into the sensor to the instrument. (For details of this instrument see MASS SPECTROMETERS IN MEDICAL MONITORING). At the present time, mass spectrometry instruments are far more expensive than instruments for electrochemically determining the transcutaneous blood gas tensions. The advantage of the mass spectrometer, however, is that it can simultaneously measure more than a single blood gas component. It can also measure other gases in the blood stream, such as anesthetic agents or special tracers.

Pulse Oximetry. The use of optical techniques to determine the hemoglobin oxygen saturation in blood is well known and is the basis for routine clinical laboratory instrumentation along with the fiber optic catheter oximeter described in the previous section on internal sensors. Oximeters have also been developed for measuring the oxygen saturation transcutaneously. Initial devices measured the continuous steady-state reflection of light of different wavelengths from the surface of the skin. Pigmentation of the skin, unfortunately, limited this technique to qualitative measurements unless the instrument was specifically calibrated to a particular individual at a particular site. Upon examining the backscattered optical signal from the skin, one can notice a small pulsatile

component at the heart rate. This is due to the changing blood volume in the capillary beds reflecting the light, and it can be seen for transmitted light as well. By looking at this pulsatile component of the transmitted or reflected light, it is possible to measure only the effect of each fresh bolus of blood entering the capillary bed at systole. This allows the principle of oximetry to be adapted to the transcutaneous measurement of arterial blood hemoglobin oxygen saturation (28). This technique is used for continuously monitoring tissues that can be transilluminated, such as the hand, foot, fingers, toes, ears, and nasal septum. These pulse oximeters have the added advantage that in most applications it is not necessary to arterialize the capillary blood by heating; thus, sensors can be left in place for longer periods of time without risk of tissue injury.

Pulse oximeters have rapidly achieved a major role in neonatal and adult intensive care medicine. It is important to point out that oximetry differs from oxygen tension measurement in that it tells how much oxygen is carried by the hemoglobin. To know total oxygen transport one needs to know the amount of hemoglobin in the blood as well as the profusion of the tissue in question. Thus, oximetry can with some additional data be quite useful in determining whether adequate amounts of oxygen are being supplied to vital tissues. There is one aspect of neonatal monitoring, however, where oximetry is of little assistance. The condition, known as retinopathy of prematurity, is found in premature infants and thought to be related to the newly formed capillaries in the retina, which are exposed to blood of elevated oxygen tension in infants who are receiving oxygen therapy. An important aspect of oxygen monitoring in premature infants is to determine if the arterial blood oxygen tension becomes elevated, so that the amount of oxygen that the infant breathes can be reduced to protect the eyes. If retinopathy of prematurity occurs as a result of elevated oxygen tensions, blindness can result. Thus, to truly protect the patient from this condition, one must measure oxygen tension not hemoglobin oxygen saturation.

Pulse oximeters in routine clinical use are primarily based on the the transmission mode of operation, although backscatter oximeters have also been developed (29,30). The clinical instruments, therefore, are limited in terms of where they can be attached to the subject. Generally, these positions are found on the periphery and are, unfortunately, the first to experience diminished circulation under shock or preshock conditions. Another limitation of currently available pulse oximeters is their great sensitivity to motion artifact. Signal processing algorithms have been developed to reduce the effect of motion on the pulse oximetry signal and to detect motion artifact and prevent it from being indicated as data (31). Nevertheless, since the oxygen saturation values presented represent averages over several heartbeats, movement can result in an apparent decrease in oxygen saturation that in fact has not occurred.

TEMPERATURE MONITORING

An important aspect of treating premature infants is to the maintenance of their thermal environment. A premature infant is not well adapted to extrauterine life, and its temperature control system is not fully developed since it normally would be in a temperature regulated environment in the uterus. Thus, an artificial environment must be provided to help the neonate control its body temperature. This environment is in the form of convective incubators and radiant warmers. Another reason for providing an elevated temperature environment for premature infants is that very often these infants suffer from problems of the respiratory system that limit the amount of oxygen that can be transported to the blood by the lungs. This oxygen is utilized in the metabolic processes of the infant, and among these are the generation of heat to maintain body temperature. By placing the infant in an environment at a temperature greater than normal room temperature, less energy needs to be expended for thermal regulation. A neutral thermal environment can be found where the temperature and relative humidity are such that the infant utilizes a minimum amount of energy to maintain its temperature, and oxygen and nutritional substrates that would normally go into heat generation can be utilized for metabolic processes related to growth and development. Thus, to maintain this environment, it is necessary to monitor both the temperature of the infant and that of the environment.

Temperature monitoring instrumentation in the nursery is relatively straightforward. The sensor is a thermistor that can be in one of two basic forms, an internal probe or a surface probe. The former consists of a semiflexible lead wire with a thermistor mounted at its distal tip. An electrically insulating polymer with good thermal conductivity covers the thermistor and is contiguous with the lead wire insulation. This probe can be placed rectally to give a neonatal core temperature measurement. The surface probe is a disk-shaped thermistor $\sim$ 6 mm in diameter with lead wires coming out in a radial direction. The sensitive surface of the probe is metallic and is in intimate contact with the thermistor, while the other surface of the probe is covered with a thermally insulating polymer so that the thermistor is well coupled to the infant surface it contacts through the metal but poorly coupled to the environmental air. The surface temperature measured is not necessarily the same as core temperature and is strongly dependent on the infant's environment. Often the surface mounted probe is placed over the liver since this organ is highly perfused and is close to the skin surface in small infants. To aid and maintain a good thermal contact between the surface probe and the infant skin, the lead wires, especially near the probe, should be highly flexible so that the wires do not tend to force the thermistor to come loose from the skin as the infant moves. As was mentioned for surface mounted biopotential electrodes, the skin of premature infants is sensitive to many factors, and strong adhesive can produce severe irritation. Weaker adhesives, however, can allow the thermistor to come off, and the use of flexible lead wires greatly reduces this tendency.

The remainder of the instrumentation in temperature monitoring devices is straightforward. An electronic circuit senses the resistance of the thermistor and converts this to a display of its temperature. In some cases alarm circuits are incorporated in the monitors to indicate when the

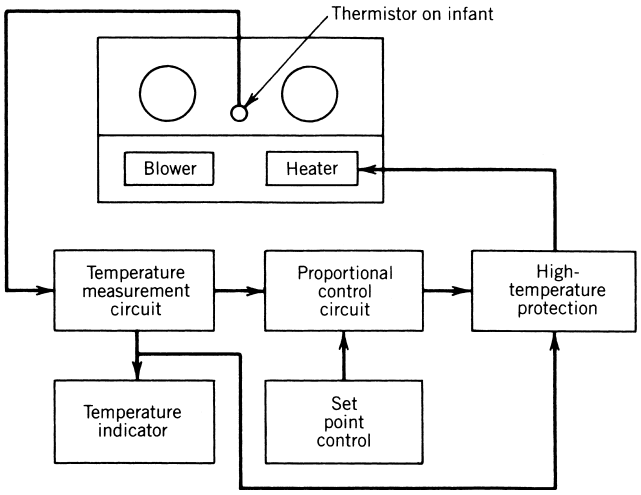

Figure 10. A servo-temperature control system for incubator temperature directed toward maintaining infants at a preset temperature.

temperature lies outside of a preset range. Temperature instruments are used not only for indicating infant surface and core temperatures, but also for the control of incubator or radiant warmer temperature. Although convective incubators have internal control systems to maintain the air temperature at a preset point, the purpose of the incubator is not as an air temperature controller. Instead the incubator is used to maintain the infant's body temperature at a certain point and to minimize thermal losses from the infant. For this reason some incubators have servo systems that control incubator temperature based on infant temperature rather than air temperature. A block diagram of such a system is illustrated in Fig. 10. Here a thermistor is the sensor and is positioned on the infant's skin or internally. If a radiant warmer is used, it is important that any surface mounted thermistor is not in the radiant field and thus directly heated by the warmer. Frequently thermistors are covered with an insulating disk that has a highly reflective outer surface of aluminum foil so that no direct radiant energy from the heater falls on the thermistor. An electronic circuit determines the thermistor resistance, and hence, its temperature, which is assumed to be equivalent to the infant's temperature. This drives a control circuit that provides proportional control to the heating element of the convective or radiant source. In some cases integrating and differential control is added to the system for optimal response. Additional safety circuits are included in the system to prevent it from overheating or underheating, both of which are undesirable for the infant. The final block of the system is the heater itself. The control system must take into account the time response of this element so as to provide optimal control. An indicator is frequently included in the system to show infant temperature and heater status.

PRESSURE MEASUREMENT

The measurement of the pressure in fluids is important in many aspects of medical care. This is especially true in neonatal monitoring, and instrumentation for the intermittent or continuous measurement of blood pressure is frequently used in the intensive care unit. There are also situations where the monitoring of intracranial pressure is important in the care of infants. Instrumentation for measuring these pressures is similar to other monitoring instrumentation described in this article in that measurements can be made by direct and indirect means. These are described in the following paragraphs.

Blood Pressure

The direct measurement of blood pressure consists of coupling the arterial or venous circulations to a pressure transducer that is connected to an electronic instrument for signal processing, display, and recording. The direct methods used are similar to those used in adult intensive care (see BLOOD PRESSURE MEASUREMENT). Generally, measurements are only made on the arterial circulation, and wherever possible an umbilical artery is used for access to this circulation. An umbilical artery catheter, such as described in the section on direct measurement of blood gases, is filled with a physiologic saline solution containing an anticoagulant. The proximal end of this catheter is connected to an external pressure sensor that is positioned in the incubator near the infant. This is usually a disposable semiconductor pressure sensor that is used only on a single infant and then discarded so that there is no risk of cross-contamination from one patient.

Indirect blood pressure monitoring in the neonate presents special problems not seen in the adult. It is generally not possible to measure an infant's blood pressure using a sphygmomanometer and the auscultation technique because Korotkoff sounds cannot be detected. Thus other, more complicated methods of indirectly measuring blood pressure must be used. If a sphygmomanometer cuff around a limb is still employed, it is important to use the correct size of cuff for the infant being studied. The width of the cuff should be from 45 to 70% of the limb circumference (32). Cuffs of several different sizes are, therefore, available for use with infants. These frequently are inexpensive disposable cuffs designed for use with a single infant.

Systolic and diastolic pressures can be sampled noninvasively using the oscillometric or the kinarteriography methods. Both techniques (see BLOOD PRESSURE MEASUREMENT) are based upon blood volume changes in the section of artery under or distal to the sphygmomanometer cuff. In the case of the oscillometric measurement, the actual volume changes are determined, while the kinarteriography method measures the radial velocity of pulsations in the arterial wall. In the former case pressure variations in the cuff itself are sensed, and signal processing allows mean arterial pressures as well as systolic and diastolic pressures to be determined.

The kinarteriographic technique utilizes an ultrasonic transducer under the cuff. Continuous wave ultrasound is beamed at the brachial artery, when the cuff is on an arm, and some ultrasonic energy is reflected from the arterial

wall. This is picked up by an adjacent ultrasonic transducer, and an electronic circuit determines the frequency differences between the transmitted and reflected waves. When the arterial wall is in motion, the reflected ultrasound is shifted in frequency thereby giving a frequency difference between the transmitted and reflected waves. Motion of the arterial wall is greatest when the cuff pressure is between systolic and diastolic pressures; and thus by measuring changes in the frequency shift of the reflected wave, it is possible to determine the systolic and diastolic pressures. Unlike the oscillometric technique, it is not possible to determine the mean arterial pressure with kinarteriography.

Monitoring of Intracranial Pressure

As was the case with blood pressure, intracranial pressure (the pressure of the cerebrospinal fluid and brain within the cranium) can be determined by direct and by indirect methods. The former involves the placement of a tube within the brain such that its distal tip communicates with the intraventricular fluid. The proximal end is connected to a low compliance pressure transducer. Although this technique is highly accurate, a significant risk of infection is associated with its application, and it is only used under extreme circumstances when no other technique is possible.

Noninvasive techniques of monitoring neonatal intracranial pressure are much safer than the direct technique but, unfortunately, are not as accurate. The newborn infant not only has special access available to the central circulation through the umbilical cord, but also has a means of accessing the intracranial contents through the anterior fontanel. This gap in the calvarium means that only soft tissue lies between the scalp surface and the dura mater. Thus, it is possible to assess intracranial pressure through this opening by various techniques.

A skillful clinician can palpate the anterior fontanel and determine to some extent whether the pressure is elevated or not (33). Another clinical method that can be used is to observe the curvature of the scalp over the fontanel as the position of the infant's head with respect to its chest is changed (34). The curvature should flatten when intracranial and atmospheric pressures are equivalent. These techniques are highly subjective and not suitable for neonatal patient monitoring; however, they can be the basis of sensors for more objective measurement.

Various forms of tonometric sensors have been developed for noninvasively measuring and monitoring intracranial pressure (35). These all consist of some sort of probe that is placed over the anterior fontanel in such a way that the curvature is flattened and formed into a plane normal to the surface of the probe itself. guard rings, calibrated springs, and other techniques have been used to achieve this applanation. Ideally once this is achieved the pressure on either side of the membrane consisting of the soft tissue between the dura and the scalp surface should be equal. Thus, by sensing the pressure on the probe side, one can determine the pressure on the other side of the dura. Unfortunately, such a situation only holds in practice when the membrane is thin with respect to the size of its planar portion. In the case of the soft tissue between the dura and the scalp, the membrane thickness can often be close to the size of the planar portion because of the limitations imposed by the opening of the fontanel. Thus, the technique has some definite limitations. The method of attachment of the probe to the infant and the structure of the probe itself are critical to the efficacy of the resulting measurements.

Many investigators have considered different approaches to making an appropriate probe for transfontanel intracranial pressure measurement. These range from strain-gage-based force sensors with guard rings to transducers that attempt to achieve applanation by means of a compliant membrane mounted upon a chamber in which air pressure can be varied. In the case of this latter technique, the position of the membrane is detected and a servo control system is used to adjust the pressure within the chamber so that the membrane presses the tissue of the fontanel into a flat surface. Such a device is shown is schematically is Fig. 11. The position of the membrane is established optically by means of a shutter attached to the membrane such that it varies the amount of light passing from a fiber optic connected to a light source to one connected to a light detector. A servo system controlling the air pressure within the structure adjusts it so that the diaphragm, and hence the tissue of the fontanel, is flat. At this point, the pressure of the air within the sensor should theoretically equal that of the tissue within the fontanel, which in turn should give the intracranial pressure.

Elevated intracranial pressure in infants can be the result of volume occupying lesions, excessive secretion of fluids within the epidural space, the brain tissue itself, or fluid in the ventricles of the brain. A frequent form of lesion is bleeding or hemorrhage within one of these volumes, a condition that is far too often seen in premature infants. Another form of elevated intracranial pressure results from hydrocephalus, a condition in which intraventricular fluid volume and pressure become elevated. By continuous monitoring or serial sampling of intracranial pressure, it

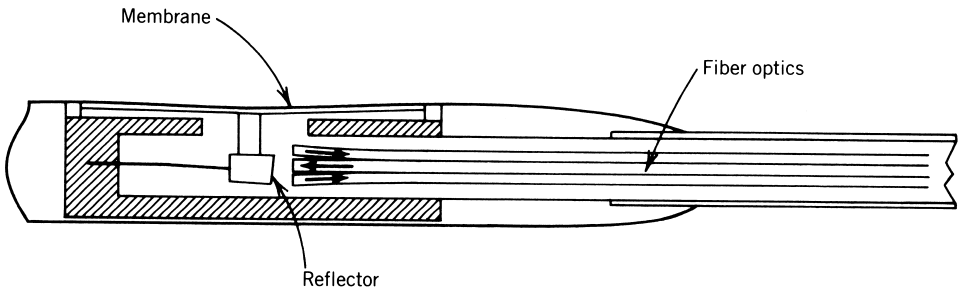

Figure 11. A pressure sensor used far intracranial pressure measurements in the newborn based upon measuring membrane deflection by means of fiber optics.

is possible to provide better control of therapy for these problems.

Monitoring of Intracranial Hemorrhage

As pointed out in the previous section, one cause of elevated intracranial pressure in the newborn is intracranial hemorrhage. It is important to be able to detect when this occurs so that therapeutic measures can be immediately taken to minimize irreversible damage. Although no technique is suitable for continuous monitoring of infants at risk of intracranial hemorrhage, several techniques can be used for surveillance and periodic sampling especially of infants showing possible signs and symptoms of intracranial bleeding.

Devices for the noninvasive measurement of intracranial pressure have been described in the previous section. In addition to these, intracranial hemorrhage can be identified by measurement of transcephalic electrical impedance (36). In this case, it is the baseline value of the impedance that is important. For this reason, a tetrapolar method of measurement must be used to minimize the effects of electrode and lead wire impedances. An alternating current at an excitation frequency of 20–100 kHz is passed between a frontal and occipital electrode placed on the infant's head. A second pair of electrodes are located near the excitation electrodes, but far enough to avoid voltage drops due to the spreading current at the excitation electrodes. The signal is picked up by these electrodes and detected by an electronic circuit to give a voltage proportional to the baseline impedance value. Since the specific impedance of blood is ~ 2.5 times greater than the specific impedance of the cerebral spinal fluid, one should see an elevated transcephalic impedance when the ventricles are filled with blood rather than cerebral spinal fluid. Similarly, if the ventricles have grown in volume because of excess cerebral spinal fluid as in hydrocephalus, the transcephalic impedance should be lower than expected.

In practice, one can only look for changes in transcephalic impedance in infants and not at absolute baseline values because of differences in geometry from one subject to the next. Typically, the technique requires one or more measurements to be taken during the first 24 h of life on each infant and using these measurements to obtain baseline intraventricular, hemorrhage-free data for that particular infant. Subsequent measurements through the infant's hospital course are compared to these initial measurements, and deviations are noted. Significant elevations in impedance have been associated with the occurrence of intraventricular hemorrhage. Studies have been carried out to show that this impedance shift correlates with intraventricular hemorrhage as found using other diagnostic techniques or, in the case of infants who expire, at autopsy (36). The principal advantage of this method is its relative simplicity and ease of measurement on infants in the intensive care unit.

Ultrasonic determination of intraventricular hemorrhage involves making a B scan of the infant's head and locating the ventricular system (37,38). If the ventricles are filled with cerebral spinal fluid alone, the fluid in the ventricles does not reflect ultrasound, and the ventricles appear clear on the image. If there is blood in the ventricular fluid, ultrasonic echoes are produced by the cellular components of the blood. This causes reflections to appear within the ventricle on the image and allows for a definite diagnosis of intracranial hemorrhage.

As with the transcephalic impedance method, the technique of making measurements on infants is straightforward and can be carried out in the neonatal intensive care unit. The equipment necessary for the measurement, however, is more costly than the impedance; but the results are far more specific to identifying intracranial hemorrhage, and thus this is the current method of choice.

An additional method that can be used for detecting bleeding within the ventricles is the use of computerized tomography (CT) scans (39). While this technique is highly efficacious from the standpoint of identifying intracranial bleeding, it is undesirable because it exposes the developing nervous system to significant amounts of X radiation. It also is necessary to transfer infants to the radiology department where the scanning equipment is located to make the measurement. For severely ill, premature infants, this transfer can significantly compromise their care.

MONITORING BILIRUBIN

Bilirubin is a product of the biochemical degradation of the heme moiety that occurs in the hemoglobin molecule as well as other proteins. It is normally found as a result of red blood cell turnover, but it can be elevated in some hemolytic diseases. This form of bilirubin, known as unconjugated bilirubin, enters the circulation and then the skin and other tissues. When it is present in the skin in sufficient concentration, it causes a yellow coloration known as jaundice. It also enters nervous tissue where, if it reaches sufficient concentration, it can cause irreversible damage.

Increased serum bilirubin can occur either as the result of increased production or decreased clearance by the liver. The former situation can occur in normal and premature infants and is referred to as physiologic jaundice of the newborn. It is usually more severe in prematurely born infants and generally peaks about the third day of neonatal life. There are several modes of therapy that can be used to reduce serum bilirubin once elevated values are detected. The simplest way to detect jaundice in the neonate is to observe the infant's skin and sclera for yellow coloration. Quantitative assessment can be carried out by drawing a blood sample and extracting the cellular components from the serum. The absorption of light at a wavelength of 450 nm in such a serum sample is proportional to its bilirubin concentration. Photometric instrumentation for doing this is readily available in the clinical laboratory and some intensive care units (38). The problem with this method is the need for obtaining a blood sample and the time necessary to transport the sample to the laboratory and analyze it in the photometer. A method for the rapid assessment of serum bilirubin in all infants would represent an improvement over these techniques. Fortunately, a relatively simple optical instrument has been developed for assessing serum bilirubin in infants (40). It is illustrated schematically in Fig. 12 and consists of a xenon flash tube

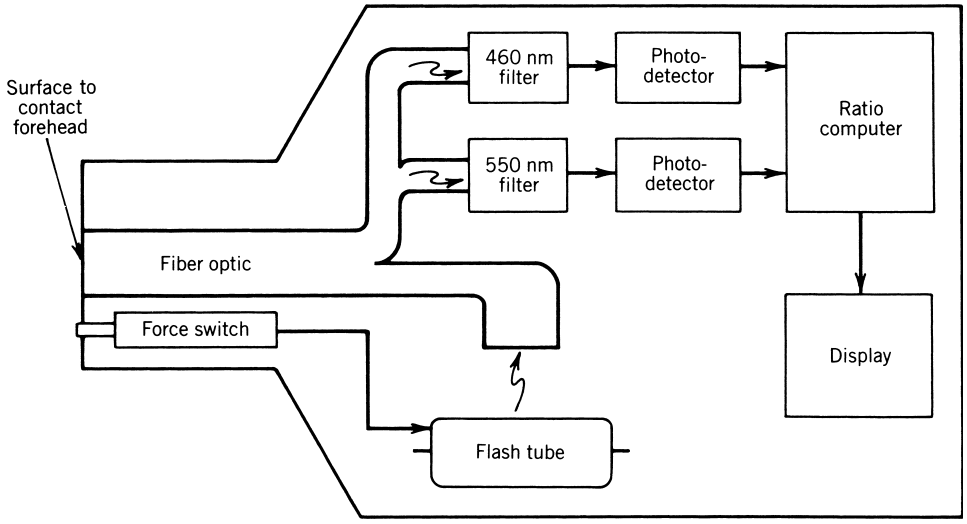

Figure 12. Schematic diagram of a transcutaneous bilirubin instrument.

light source and photometers with filters to measure the reflected light at 460 and 550 nm. A special feature of the instrument is a pressure switch on the portion of the probe that is pressed against the infant's forehead to make the measurement. This probe contains fiber optics that couple the xenon flash tube and the photometers to the skin surface. As the probe is pressed against the skin, the force squeezes the blood from the cutaneous capillaries. Once the force is great enough to sufficiently blanch the skin under the fiber optics so that the blood will not interfere with the measurement, a switch activates the flash tube and readings are taken from the photometers. An internal microprocessor analyzes the reflected light and compensates for any residual hemoglobin. It gives a number proportional to skin bilirubin on a digital display. The proportionality constant, however, differs for different types of neonatal skin; thus, proportionality constants have to be determined for infants of different age, race, and whether they have received phototherapy or not. This instrument involves a sampling technique and thus is only suitable for trend rather than continuous monitoring. Since changes in serum bilirubin are relatively slow, such a technique is entirely appropriate. The principal advantage of this instrument is that it can be readily applied to all infants in the nursery with little effort on the part of the clinical staff. Readings can be made quickly to identify those infants at risk of hyperbilirubinemia.

MONITORING LIFE SUPPORT SYSTEMS

Although one usually associates neonatal monitoring with the measurement of physiologic variables from the newborn or prematurely born infant, an aspect of neonatal monitoring that should not be overlooked is associated with monitoring the patient's environment. Various life support systems are important in neonatal intensive care, and electronic instrumentation for assessing and maintaining the function of these is also important. There should be alarm systems so that when the conditions of life support are inappropriate for neonatal care, care takers are alerted and the problem can be corrected before it causes any harm to the patient. There are many examples of life support system monitoring in the neonatal intensive care unit, and some of the major ones will be described in the following paragraphs.

Maintaining an appropriate thermal environment for the neonate is an important aspect of neonatal intensive care. Incubators and radiant warmers need to have internal temperature instrumentation to ensure that the environment is appropriate for the infant and so that the clinicians providing care can be aware of environmental conditions. Convection incubators frequently have temperature sensors for measuring the environmental air temperature and indicating it on the control panel of the device. These temperature sensors are often a part of the thermal control system in the incubator itself, and as indicated earlier the infant's own temperature can be used as a control signal for some incubators. Built into this incubator temperature monitoring function is an alarm function that can indicate when the incubator temperature becomes too high or too low; potentially life threatening conditions.

It is sometimes necessary to intubate the trachea of a patient and to use a ventilator to control breathing. A gas with elevated oxygen content is often used to help provide additional oxygen to infants who require it. There are many points in a support system such as this where monitoring devices can be useful to assess and in some cases control the function of the device. Where gases of elevated oxygen tension are given, instrumentation to measure the partial pressure of oxygen within the gas to indicate the oxygen fraction of inspired gas is desirable. Various types of oxygen sensors are, therefore, placed in the air circuit to either continuously or intermittently measure and display this quantity. The temperature and humidity of the inspired air are also important, and appropriate sensors and instrumentation for these variables can be included as a part of the respiratory support system. Continuous positive airway pressure is a mode of therapy used in infants requiring ventilatory support. It is necessary to measure and control the positive pressure in such systems to minimize the risk of pneumothorax and to ensure that the desired levels are maintained.

The use of arterial and venous catheters in infants for blood pressure and blood gas monitoring as well as fluid therapy and hyperalimentation represents a safety risk to the infant. Arterial catheters and associated plumbing can become disconnected and cause serious losses of blood that if not quickly checked can result in severe injury or death to the patient. Gas bubbles inadvertently infused along with intravenous fluids can, if sufficiently large, compromise the circulation by producing gas embolisms. Fluid therapy in very small infants must be precisely controlled so that excessive or insufficient amounts of fluid are not provided to the infant. Electronic instrumentation for controlling all of these variables and producing an alarm when dangerous conditions are encountered have been developed (41). Some of these, such as intravenous infusion pumps, are routinely used in neonatal intensive care units. Safety devices for over- or underpressures can be built into the pumps, as can sensors, to indicate when the fluid source has been depleted so that additional fluid can be attached to the pump.

Phototherapy is a technique of illuminating the baby with blue light in the wavelength range of 420–500 nm to oxidize bilirubin to compounds that can be eliminated from the body. Phototherapy units consisting of a group of 20 W fluorescent lamps 30–40 cm above the infant must be used cautiously because there are risks associated with this radiation. Therefore, it is important to determine the amount of radiant energy received by the infant in the 420–500 nm band so that minimal exposure times sufficient to oxidize the bilirubin can be given. Instrumentation consisting of a small probe containing a photosensor that can be held just above the neonate has been developed for this purpose. It is not necessary for this instrumentation to be used to continuously monitor the phototherapy units, but frequent testing of the therapy devices helps not only to determine the appropriate exposure times, but also to indicate when the fluorescent lights become ineffective and need to be changed.

DIAGNOSTIC RECORDINGS

The role of infant monitoring is to determine when events requiring therapeutic intervention occur so that optimal care can be provided. Hard copy recordings from electronic monitoring devices can also be useful in diagnosis of illness and identification of infants who may benefit from electronic monitoring over a longer period of time. Two types of diagnostic recordings are currently used in neonatology: polysomnograms and oxycardiorespirograms although both are still considered experimental and are not routinely used.

Polysomnography. Multiple channel, simultaneous, continuous recordings of biophysical variables related to the pulmonary and cardiovascular systems taken while the newborn or infant sleeps are known as polysomnograms (41–43). These recordings are often made overnight, and 8–12 h is a typical length. The actual variables that are monitored can vary from one study to the next as well as from one institution to the next. However, these usually include the electrocardiogram and/or heart rate. One or more measures of respiratory activity, such as transthoracic electrical impedance or abdominal strain gage; measures of infant activity and movement; measures of infant sleep state, such as eye movements and usually a few leads of the electroencephalogram; and measures of infant blood gas status are also recorded. The number of channels of data in polysomnograms is at least 3 and often is 12 or more. Recordings are made using computer data acquisition systems.

The primary application of polysomnography has been as a tool for research evaluating infant sleep patterns and related physiologic phenomena during sleep. Some investigators feel that polysomnographic recordings are useful in evaluating infants considered to be at risk to sudden infant death syndrome, but at present there is no conclusive evidence that this technique has any value in such screening. There may, however, be specific individual cases where such evaluations may contribute to overall patient assessment.

Oxycardiorespirogram. This technique is used for continuous computer monitoring of infants in the neonatal intensive care unit (44). Four or five physiologic variables are monitored and continuously recorded on a multichannel chart recorder (45). These are the electrocardiogram from which the beat-to-beat or instantaneous heart rate is determined; the respiration waveform or pattern as generally determined by transthoracic impedance monitoring; the respiration rate as determined from the respiration waveform; the oxygen status as determined from a pulse oximeter or transcutaneous blood gas sensors; and at times the relative local skin perfusion as determined by the thermal clearance method from the transcutaneous blood gas sensor.

The importance of the oxycardiorespirogram is that it brings these variables together on a single record, where they can be presented in an organized and systematic fashion. This makes it possible to observe and recognize characteristic patterns between the variables that may be overlooked when all of these quantities are not monitored and recorded together. The oxycardiorespirogram is able to look at variables related to various points along the oxygen transport pathway from the airway to the metabolizing tissue. Thus, it allows a more complete picture of infant cardiopulmonary function than could be obtained by monitoring just one or two of these variables. Typical oxycardiorespirogram patterns have been classified and organized to assist clinicians in providing neonatal intensive care (46).

SUMMARY

Infant monitoring along with adult monitoring under critical care situations involves many individual types of sensors and instruments. Depending on the application, many different types of output data will be produced. In addition, many different conditions for alarms to alert the clinical personnel can occur for each of the different instruments in use. Needless to say that although this provides better assessment of the infant as well as quantitative and

in some cases hard copy data, it also requires that this data be integrated to provide manageable information. By combining data from several different pieces of instrumentation, more specific conditions for alarms can be defined and variables can be more easily compared with one another. This can then lead into trend analysis of the data, and the computer certainly represents an important overall controller, analyzer and recorder of these functions. As technology continues to become more complex, it is important not to lose track of the primary goal of this technology, namely, to provide better neonatal and infant care so that critically ill neonates can look forward to a full, healthy, and normal life.

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See also BLOOD GAS MEASUREMENTS; INCUBATORS, INFANT; MONITORING, INTRACRANIAL PRESSURE; MONITORING, UMBILICAL ARTERY AND VEIN; TEMPERATURE MONITORING; VENTILATORY MONITORING.