

Apnea monitoring by means of thoracic impedance pneumography



**Association for the Advancement
of Medical Instrumentation**

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TIR4 Apnea Monitoring by Thoracic Impedance Pneumography

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Apnea Monitoring by Means of Thoracic Impedance Pneumography

Approved February 1989

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FOREWORD

The AAMI Apnea Monitoring Committee, which developed and authorized the distribution of this technical information report, has the following members:

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The committee had the following additional member at the time this technical information report was balloted:

Rey Gorsuch, Healthdyne

Comments on this report are invited and should be sent to AAMI, 3330 Washington Boulevard, Suite 400, Arlington, VA 22201-4598.

RATIONALE FOR THE TECHNICAL INFORMATION REPORT

This technical information report (TIR) addresses one of the apnea detection methods most commonly used in hospitals and home markets. At present, a great deal of information is available on impedance pneumography, and the purpose of this document is to summarize this information. Because impedance pneumography is an indirect measurement, it does not detect all forms of apnea, but it has proven to be a practical and effective apnea detection method for a large patient population.

When the committee was formed, there was substantial interest in generating a TIR on impedance pneumography for apnea detection. There are many other methods of apnea detection, but because of the large numbers of installed impedance-pneumography-based apnea monitors, it was felt that this measurement technology should be addressed first. The committee also felt that limiting the scope of the document to transthoracic impedance pneumography would allow consensus on the issues to be more easily achieved. It is not the intent of this TIR to exclude other apnea detection methods, and the committee hopes that they can be added to the document at a later time.

This TIR should provide information that would be useful in developing a voluntary standard for impedance pneumography as a detection method for apnea. The information was collected from a broad range of clinical and technical resources. Special clinical information was derived from the American Academy of Pediatrics' 1978 and 1985 reports on apnea and the report on the National Institutes of Health consensus conference, "Infantile Apnea and Home Monitoring," September 29 and 30 and October 1, 1987. Technical information was gathered from manufacturers, clinical engineers, and researchers in the field.

APNEA MONITORING BY MEANS OF THORACIC IMPEDANCE PNEUMOGRAPHY

1. Introduction

1.1 Overview. This report addresses the current state of the art in the design and clinical application of apnea monitoring by transthoracic electrical impedance. The impedance technique is only one of several methods of detecting apnea in infants, but currently it is by far the most frequently used. (Over 95% of the home apnea monitors now on the U.S. market use this technique for measuring respiration.) Therefore, the authors of this report chose to concentrate mainly on this particular technique. Impedance monitoring of respiratory effort is also used to follow the course of patients being weaned from ventilatory support and during postanesthetic recovery periods. However, this application is beyond the scope of this report.

Apnea monitoring by transthoracic electrical impedance is principally indicated for use in the management of three populations of infants:

- (1) Hospitalized premature infants outgrowing developmental problems with respiratory frequency control
- (2) Full-term infants, hospitalized or at home, who have had a significant, unexplained respiratory arrest, and preterm infants who are ready for discharge but are manifesting persistent apnea
- (3) Apparently healthy infants born into a family in which a previous infant died with a pathologic

assessment of sudden infant death syndrome (SIDS) or was found to have a significant apnea problem after birth (Ariagno 1984)

In 1972, Steinscheider reported that two of five infants noted to have apnea lasting for more than 20 seconds later died of SIDS episodes, and he was the first to suggest the use of respiration monitors to manage apnea at home. In a report of follow-up and evaluation of infants presenting apnea at several weeks of age, 4 of 84 infants died despite the use of a monitor of thoracic impedance alone (Kelly et al. 1978). All four of these infants were being actively monitored at the time of death. Other reports (for example, Yount and Lewman 1987) suggest that parental noncompliance is a more common cause of death.

Although a number of groups have documented the association of persistent apnea with later death, an extensive series of observations from five large obstetrical services in England showed no association of prolonged central apnea (of greater than 20 seconds' duration) and profound bradycardia (less than 50 beats per minute [BPM]) with death in either full-term or preterm infants (Southall et al. 1982, 1983). In a more extensive and blinded review of the same data, prolonged mixed apnea (of greater than 15 seconds' duration), coupled with bradycardia (of 20% of the previous rate) and periodic breathing (lasting longer than 5 minutes), was found to be associated with later SIDS risk in preterm infants (Yount et al. 1988). The same team found that, for 22 full-term infants who later died of SIDS, there was no association with any of these patterns (unpublished data).

In 1978, after a vigorous debate, the American Academy of Pediatrics (AAP) recommended use of monitoring equipment in managing prolonged apnea. The definition given for apnea was "cessation of breathing for 20 seconds or longer, or a briefer episode associated with bradycardia, cyanosis, or pallor" (American Academy of Pediatrics 1978). The original AAP statement was later modified to clarify some of the clinical and medical-legal issues as well as the limitations of equipment (American Academy of Pediatrics 1985). These issues were also explored at a National Institutes of Health consensus development conference (National Institutes of Health 1987).

- 1.2 The Apnea Monitoring System. An understanding of the techniques of infant apnea monitoring is important in determining the most appropriate monitor to use on a patient and in using it in the best possible way. In considering the technical aspects of an apnea monitor system, one should be concerned with the method by which breathing effort, ventilation, or apnea is sensed and the method by which this information is processed to determine whether apnea of greater than a preset duration is present. It is also important to know the potential errors associated with the monitoring system so that the conditions that produce such errors can be avoided.

An apnea monitor can be considered a general biomedical electronic instrumentation system. Such a system consists of three major parts ([Figure 1](#)). The *sensor* serves as the interface between the electronic circuits and the biologic system. It converts the biologic variable being measured into an electronic signal that can be processed to obtain the desired information. This processing is carried out by the signal processor, which modifies the raw signal from the sensor so that the desired data can be derived, displayed, and recorded. An important function of the signal processor is to determine whether the lungs are being ventilated and, if not, to determine how long there has been no ventilation. The display and recording part of the system represents another type of biologic interface, one that provides information from the instrument to the people responsible for the care of the patient. In apnea monitors used in the home, this interface provides the alarm; in monitors capable of recording pneumograms or providing hard copy, this part of the instrument includes the memory and recording apparatus as well.

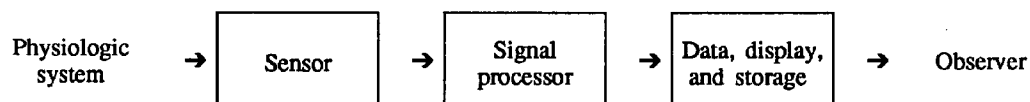


Figure 1. Block diagram of a general medical electronic instrument. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987)

- 1.3 Methods of Sensing Ventilation. Alveolar ventilation and breathing effort can be sensed either directly or indirectly. In direct methods, the sensor is coupled to the airway and measures the movement or other properties of air transported into and out of the lungs. In indirect methods, the sensor monitors variables relevant to air movement but not air movement itself. Indirect methods involve no contact with the airway or with the air being moved into or away from the lungs. Indirect sensors are usually noninvasive and can be mounted on or near the body surface.

There are many more indirect sensors of ventilation than direct ones. These devices can be attached to the subject more easily than direct sensors and are less likely to interfere with breathing patterns. The transthoracic electrical impedance method is used in most commercially available apnea monitors for both hospital and home use. In this method, the ac electrical impedance across the chest varies with respiratory effort. The measurement of these small variations is the basis for the majority of infant apnea monitors in use today, both at home and in the hospital (Baker and Geddes 1970; Nyboer 1970; Olsson et al. 1970; Pacela 1966).

Each method of sensing respiration-related variables has advantages and disadvantages in terms of reliability, invasiveness, relative cost, and other factors. [Table 1](#) highlights the relative merits of the various methods; it is not designed to be detailed or quantitative, but rather to help put the various methods in proper perspective.

- 1.4 Understanding Transthoracic Electrical Impedance. The chest contains various materials, ranging from bone to air. Each of these materials has different electrical properties and is located in a different portion of the chest. A schematic cross-section of the chest in [Figure 2](#) indicates the relative size of the major components of the chest and their approximate relationship to each other. The materials of the chest vary in electrical resistivity (the amount of electrical resistance between opposite faces of a cube of that material), which is an important determinant of electrical impedance in the body.

[Table 2](#) ranks chest materials in ascending order of electrical resistivity. Two of the major components of the chest, blood and air, are at opposite ends of the scale. Furthermore, the volume of each of these materials varies with time over the cardiac and breathing cycles. Blood has relatively low resistivity, which varies over the cardiac cycle owing to changing blood volumes in the heart and in the vascular compartment. Air, on the other hand, has high electrical resistivity and hence impedance, and it undergoes wide volume changes in the lungs during normal breathing. Thus, the impedance of the lungs will increase as they fill with air.

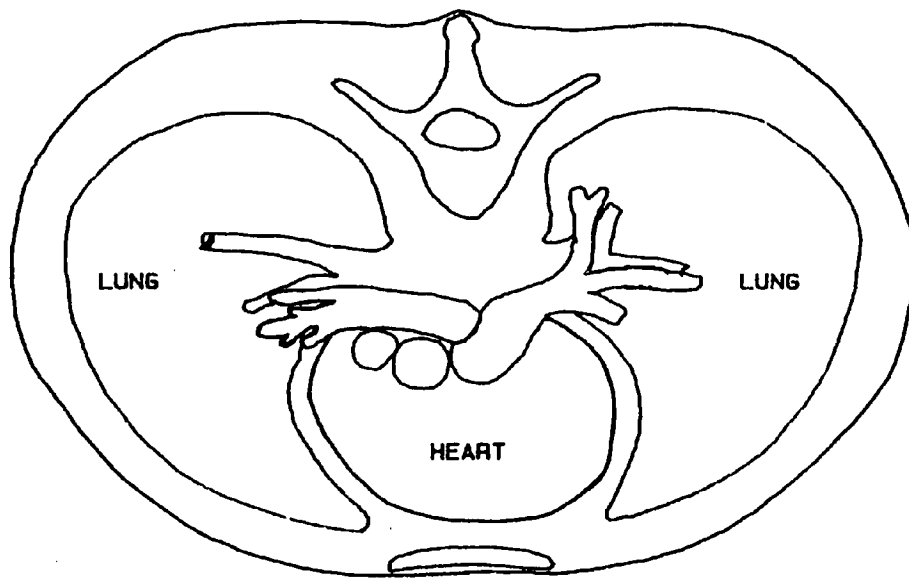


Figure 2. Cross-section of an infant's thorax showing anatomic structures and tissues and their relative sizes and positions. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987)

Table 1
Relative Characteristics of Various Sensors of Breathing

	Noninvasive or Not Connected to Airway	Measures Quantitative Tidal Volume	Sensitive to Motion Artifact	Special Training Necessary for Use	Relative Costs	Sensitive to Cardiogenic Artifact	Senses Obstructive Apnea	Sensitive to Small Breaths
Pneumo- tachograph	-	+	-	+	\$\$\$	-	+	+
Spirometry	-	+	-	+	\$\$\$	-	+	+
CO ₂ sensor	+/-	-	-	-	\$	-	+	+
Nasal thermistor	+/-	-	+/-	-	\$	-	+	+
Sound sensor (air flow)	+	-	+	-	\$	-	+	+
Whole- body phlethys- mograph	+	+	-	+	\$\$\$	-	+	+
Contacting motion sensors	+	-	+	+/-	\$/\$\$	-	-	+/-
Noncon- tacting motion sensors	+	-	+	-	\$	-	-	-
Electromy- ography	+	-	+	+	\$	-	-	+/-
Breath sounds	+	-	+	-	\$	+	-	-/+
Intra- esophageal pressure	-	-	-	+	\$	-	-	+
Transthor- acic electrical impedance	+	-	+	-	\$	+	-	-

Note: This table presents only general concepts, and there may be specific examples of sensors that do not conform. + is Yes; - is No; +/- is Yes or No, depending on the sensor and its use. Adapted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda MD: NIH 1987.

Table 2
**Materials in the Chest Region Listed in Ascending Order
of Electrical Resistivity**

1. Blood
2. Muscle
3. Bone
4. Fat
5. Air

Note: Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987.

Impedance variations due to volume changes in blood or air could be measured by means of electrodes placed on the heart or lungs, respectively. The electrical impedance between a pair of electrodes is

determined by dividing the voltage difference between the two electrodes by the current that passes between them. When the electrodes are placed on the actual structure, as described above, relatively large changes in impedance would be seen as the volumes of the respective structures change. It is not possible, of course, to place electrodes directly on the structures that are to be measured, and thus it is not possible in practice to see the large impedance differences that result from direct connections.

- 1.5 Impedance Monitoring of Respiratory Effort. Transthoracic electrical impedance was first introduced as a clinical method of measuring respiratory effort in the 1960s, after research in Europe and the United States had demonstrated the convenience and ease of access of the method for monitoring infants.

Continuous recording of thoracic impedance signals as a means of documenting apnea frequency and the clinical state of research subjects was first employed by Pacela (1966) and Daily et al. (1969). The routine recording of thoracic impedance and of the electrocardiogram (ECG) as an assessment of the clinical status of intensive care patients has become common. Continuous recording of thoracic impedance was used to document the effect of methyl xanthine treatment and was first described as a "pneumogram" by Stein and Shannon (1975) in the United States.

Since that time, increasing use of the technique has produced valuable insights into infant behavior that would not have been possible without the development of the infant monitor coupled with a slow-speed tape recorder (Kelly et al. 1978, 1980; Kelly and Shannon 1981; Hunt et al. 1985). Other groups have found limitations in using thoracic impedance and have used additional or alternative transducers for greater diagnostic accuracy (Dransfield and Fox 1980; Beckerman et al. 1982; Southall et al. 1982; Richards et al. 1984; Yount 1986). The use of respiration alarm systems for adults has increased in recent years in an effort to follow the course of patients as they are being weaned from ventilatory support and recovering from anesthesia.

Thoracic impedance monitoring is currently the most frequently used means of assessing respiratory effort. Transthoracic impedance is easily measured in the vast majority of patients who are susceptible to apnea and who are observed with monitors containing apnea and low-respiratory-rate alarms. A major advantage is the ability to detect ECG activity with the same electrodes. The major disadvantages are the small signal size compared with the signal size of the large, variable-base impedance monitor and the large, variable amount of noise originating from both the physiologic sources and the electrode attachment.

2. Patient Transducers and Connections

- 2.1 Overview. The impedance technique requires the application of a small ac electrical signal (typically 100 microamperes or less) across a pair of electrodes placed transthoracically on the infant. The frequency of the alternating current is typically in the range of 20 to 100 kHz. The electrode-body impedance is typically 100 to 1,000 ohms, varying with electrode type, size, dryness, and placement; skin dryness or oiliness; and frequency used to drive the electrodes.

The actual change in body impedance due to respiration, typically 0.1 to 3 ohms, can vary with the depth of inspiration and expiration, body position, electrode position, and the electronic technique used to extract the change in impedance from the drive signal. Motion and pressure on the electrodes will generate artifact that can easily be an order of magnitude greater than the respiratory impedance changes, making reliable detection of the respiratory signal difficult. The electrode-skin interface connection and the cables represent major sources of the false alarms and safety problems encountered during long-term infant monitoring in the home.

- 2.2 Electrode Considerations. An ideal infant monitoring electrode would be easy to attach, have a low profile, have low, stable ac and dc impedance, create no skin irritation, be low in cost, and utilize reliable, low-profile connectors and lead systems.

- 2.2.1 Electrode Attachment. Because home monitoring can last 8 to 10 months, it is imperative that a relatively

simple-to-apply electrode system be used.

The carbon rubber electrodes originally developed for transcutaneous electrical nerve stimulators (TENS devices) in the early 1970s have emerged as the most popular long-term electrodes for apnea monitoring. The carbon electrodes are placed on a fabric belt with a velcro-like attachment. The belt is then snugly tightened around the chest of the infant, with the lead wires from the electrodes usually connected so that they exit towards the infant's feet before the patient cable is attached.

Pregelised electrodes are usually used in the hospital; they are occasionally used in the home if the infant is on a short-term monitoring program or if adequate signal quality is difficult to obtain with carbon electrodes. Self-adhering electrodes, such as Karaya-base electrodes, are also used to a limited extent.

Dry, carbon-filled, elastomer electrodes have interfacial impedances that can be unstable when the electrodes are first applied. This instability can result in a wandering baseline on recordings of transthoracic impedance. Placing a drop or two of normal saline on the electrodes before they are placed on the skin makes the interface between the electrodes and the skin more stable, resulting in a more stable baseline. A study of carbon-filled elastomer electrodes applied to infants showed that the use of saline solution improved the quality of the recordings in 16 of 31 cases (Neuman 1985).

2.2.2 Electrode Profile. It is important that the electrode and the attachment lead have a relatively low profile, particularly for older infants who are very active and who roll over on their electrode systems. It is also important that the electrodes be flexible enough to conform to body contours and thus maintain good contact. It is desirable that electrodes used in hospitals not interfere with roentgenograms.

2.2.3 Electrode Placement. For practical purposes, electrodes must be placed on the skin surface. Most of the current passing between the electrodes remains in the chest wall and does not pass through the heart and lungs; consequently, the changes in the resistivity of these organs do not contribute as much as the chest wall to the overall variation in impedance between skin electrodes. [Figure 3](#) indicates the relative distribution of current through the chest wall when electrodes are placed on the mid-axillary lines. It can be seen that most of the current is conducted along the chest wall, so its impedance would dominate any measurement. Different monitor manufacturers recommend different electrode placements for optimum performance, but it is typically recommended that the two active electrodes be placed transthoracically. Some manufacturers do not require a third or reference electrode. For hospital use, the electrode position will usually be dictated by the lead configuration desired for diagnostic ECGs.

2.2.4 Impedance. Because the electrode system acts as both a stimulation electrode to measure the impedance change and a monitoring electrode to pick up the ECG signal for heart rate measurement, it is important to define the ac and dc impedance parameters. The American National Standard, *Pregelised ECG Disposable Electrodes* (Association for the Advancement of Medical Instrumentation 1984b), is a good reference guide for disposable electrodes; however, carbon electrodes have entirely different physical and electrical properties and a new set of standards must be developed for them.

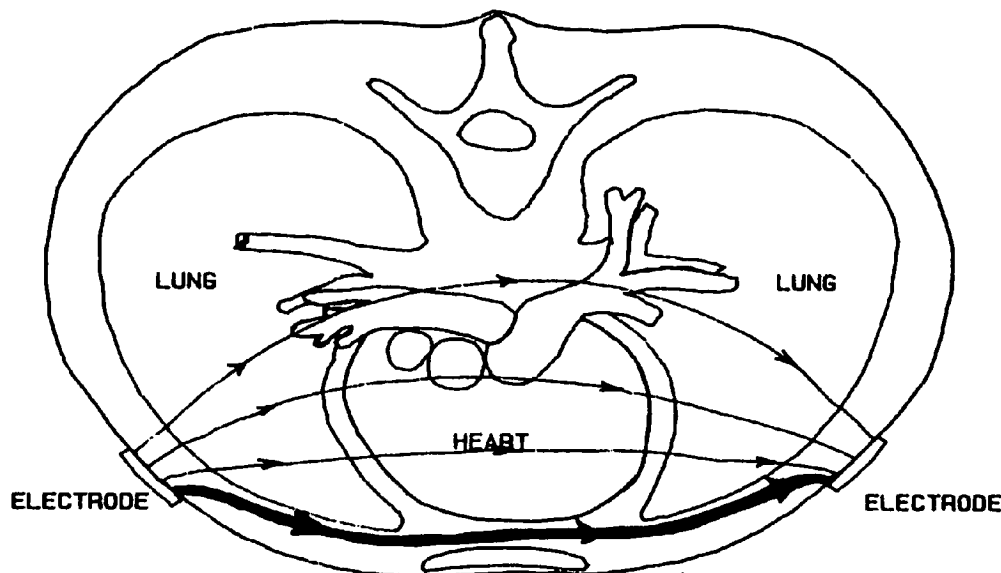


Figure 3. Cross-sectional view of the thorax showing approximate electrical current pathways and magnitude when a transthoracic impedance apnea monitor is used. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987)

2.2.5 Skin Irritation. Skin irritation can be a major problem during long-term monitoring. Because the electrodes are applied several times a day, skin delamination or irritation may occur if the electrode has a strong adhesive attachment or if a salt-base electrode gel is used. In addition, a very humid environment can make it difficult for some electrode systems to adhere properly, which causes many false alarms.

The carbon electrode with a small amount of water placed on it, without electrode gel, seems to cause the fewest skin reactions. Naturally self-adhering electrodes (that is, Karaya electrodes) and similar electrodes of synthetic material are also reported to work well during long-term monitoring.

2.2.6 Electrode Cost. The long-term cost of monitoring can be a major consideration. The electrode-cable system should be cost-effective, especially since many insurance programs do not cover accessories such as electrodes and the user is responsible for this cost.

The typical user cost of a carbon rubber electrode and pigtail cable can vary from 20 cents to 50 cents a day. Each pair will usually last at least two to three months. The typical cost of a disposable electrode and pigtail cable can vary from two to four times the cost of carbon rubber electrodes.

2.3 Connectors. The reliability of the electrode-cable attachment is important in reducing the number of false alarms due to disconnections. The electrode snap attachment used in the hospital environment is usually satisfactory for short-term monitoring when there is little or no infant movement, but it does not work well in the home environment of an active baby.

Carbon electrodes are usually attached with pin connectors, which are relatively low-profile, reliable, and inexpensive. The pin was developed in the early 1970s for TENS pain control devices, for which chronic pain patients had to wear electrodes over extended periods of time.

In 1985, the Food and Drug Administration (FDA) reported instances in which pigtail cables had been inadvertently plugged into ac power extension cords by apneic infants' siblings, with the result that several infants were electrocuted or burned. As pigtail cables are usually 24 to 36 in long, it is very important that the exposed connectors be designed so that they cannot be plugged into any power outlet. This is considered a mandatory requirement for most home monitoring programs.

Another potential hazard is that as infants become more active, they can wrap themselves up in the cables and strangle. A quick-disconnect cable might be a solution to this potential problem; however, if the cable

disconnects during normal use, it may cause too many false alarms and the lead would not be marketable. Careful routing of the lead wires down the infant's legs, under clothing, and exiting near the foot, together with safe and proper positioning of the patient cable, can reduce some of the problems associated with monitoring an active infant.

2.4 Methods of Signal Processing. The electrical signals from the apnea monitor sensor must be processed to recognize breathing activity, measure the respiration rate, and determine when apnea is present. The same general method of signal processing is used for all sensors, although different sensing systems require signal processors of differing complexity because of the nature of the individual signals.

A general block diagram of a transthoracic impedance type of apnea monitor is shown in Figure 4. The functions of the system can be categorized as impedance measurement, breath detection, artifact rejection, apnea identification, and alarms (Neuman 1984). Each of these functions can be carried out with varying degrees of complexity. The most recently designed infant apnea monitors employ sophisticated signal processing to get the most information out of a less-than-optimal signal.

The impedance measurement portion of the circuit contains a signal generator that produces the excitation signal applied to the electrodes. Frequently, this is a sinusoidal constant-current-amplitude source that produces a wave having a preset peak current. As this current is passed through the lead wire-electrode-body system (Figure 5), it encounters the total impedance of that system, and a voltage proportional to this impedance appears across the monitor input. Variations in this voltage reflect the variations in impedance from all sources, including ventilation. Therefore, it is important that the current source have a constant amplitude; if it does not, variations in current amplitude would also result in voltage variations, and it would not always be possible to distinguish whether these resulted from impedance variations or current source variations. Excitation signal frequency is also an important consideration in minimizing artifactual impedance variations.

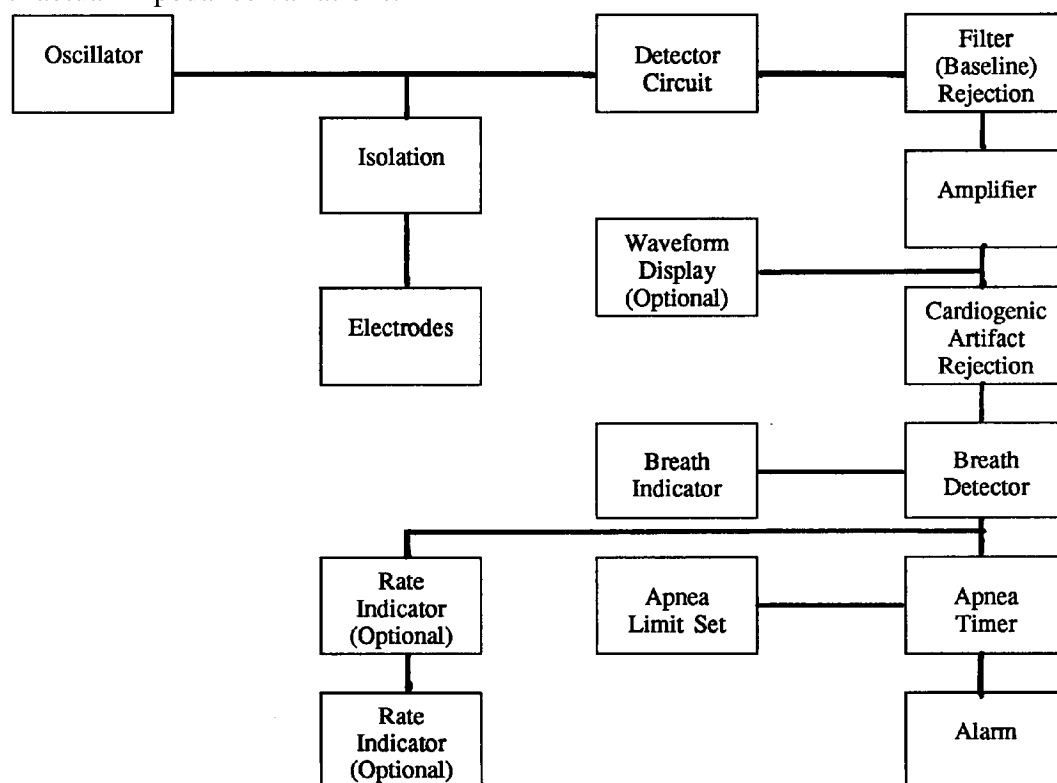


Figure 4 Functional block diagram of a transthoracic electrical impedance type of apnea monitor. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987)

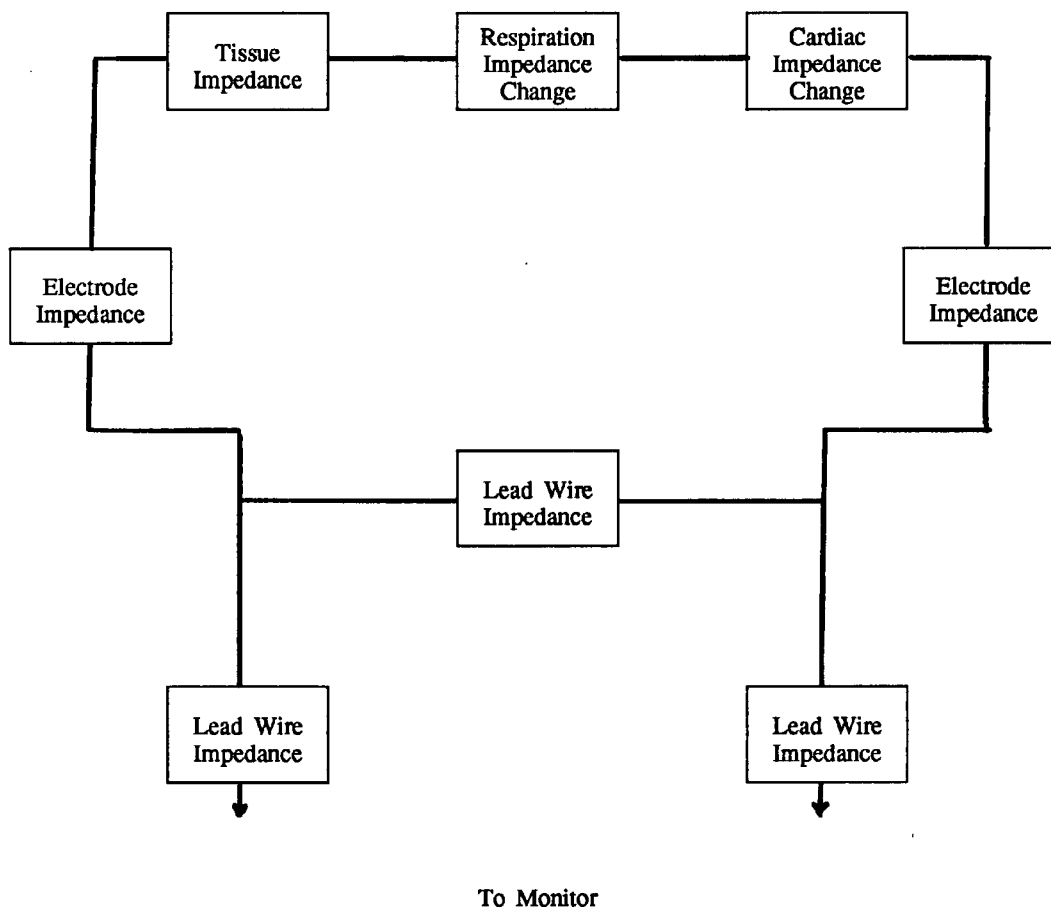


Figure 5 Block diagram showing the different components of the actual electrical impedance measured by a transthoracic electrical impedance apnea monitor. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987)

The quality of the respiration detection portion of the signal processor plays an important role in determining the overall efficacy of an apnea monitor. Detection of infant breathing is a simple matter when the impedance respiration waveform appears as a regular pattern, as shown in [Figure 6a](#). Unfortunately, the respiration waveform is not always this easy to interpret; frequently, patterns such as those in [Figure 6b](#) are seen and must be interpreted. Cardiogenic artifact also complicates the signal detection problem. It is important to note that, before a machine can be designed to detect a breath from the respiration signal, the designer must be able to look at patterns such as those seen in [Figure 6](#) and identify where the breaths occur.

- 2.5 **Preamplifiers.** A preamplifier, located close to the infant, might improve the measurement quality of low-level impedance and ECG signals. Neuman (1984) has reported on a hybrid microelectronic circuit that would provide high-level signals to the monitor. The major considerations for the preamplifier are cost, performance, and reliability.

Reimbursement for apnea monitoring is a major factor in determining which technological features are added to existing monitoring systems. If the preamplifier were to simplify the electronics required in the basic monitor, a better cost-benefit ratio could be achieved, making a market acceptance of the new product likely.

- 2.6 **Electronic Circuit.** The measurement of transthoracic electrical impedance involves more than placing electrodes on the chest surface. The electrodes must be connected to an electronic circuit that generates a signal used for impedance measurement. This circuit is most often ac in the frequency range of 20 to 100 kHz (Olsson et al. 1970). The circuit determines the voltage and current and calculates impedance, and it often provides a constant current amplitude so that the voltage will be directly proportional to the impedance

seen by the circuit. The impedance seen by the electronic circuit, however, represents more than just the transthoracic impedance (Kerns 1984). There are impedances associated with the electrode itself and the interface between the electrode and the body. Additional impedance is associated with the electrode lead wire and patient cable that connect the electronic instrument to the subject (Figure 5). The electrode and lead-wire impedances are in series with the transthoracic impedance, and the electrical impedance measured by the circuit represents the sum of all of these contributions. The actual impedances of each block in Figure 5 are dependent on the devices used. Generally, the total transthoracic impedance is approximately 500 ohms, with a variation due to respiration of no more than 2 ohms; thus, the respiration signal that is measured is less than 0.5% of the baseline.

To further complicate the situation, each of the other components in the system can vary in electrical impedance by at least the respiration variation. The impedance between the electrode and the infant's skin strongly depends on the electrode-skin interface. As electrodes move with respect to the skin surface, this impedance can vary by much more than 2 ohms.

The frequency of the ac signal used to determine the impedance also affects the impedance of each component in the circuit of Figure 5. As the frequency increases, the greater portion of the current is confined near the surface of a conductor, consequently, the sensitivity of the impedance method to changes in lung volume can decrease. On the other hand, higher frequency excitation reduces the effect of electrode-skin interfacial impedance. The changes in impedance associated with movement of the lead wires become more pronounced at higher frequencies. Therefore, most manufacturers have used excitation frequencies in the range of 20 to 100 kHz, a frequency range in which the results are optimal.

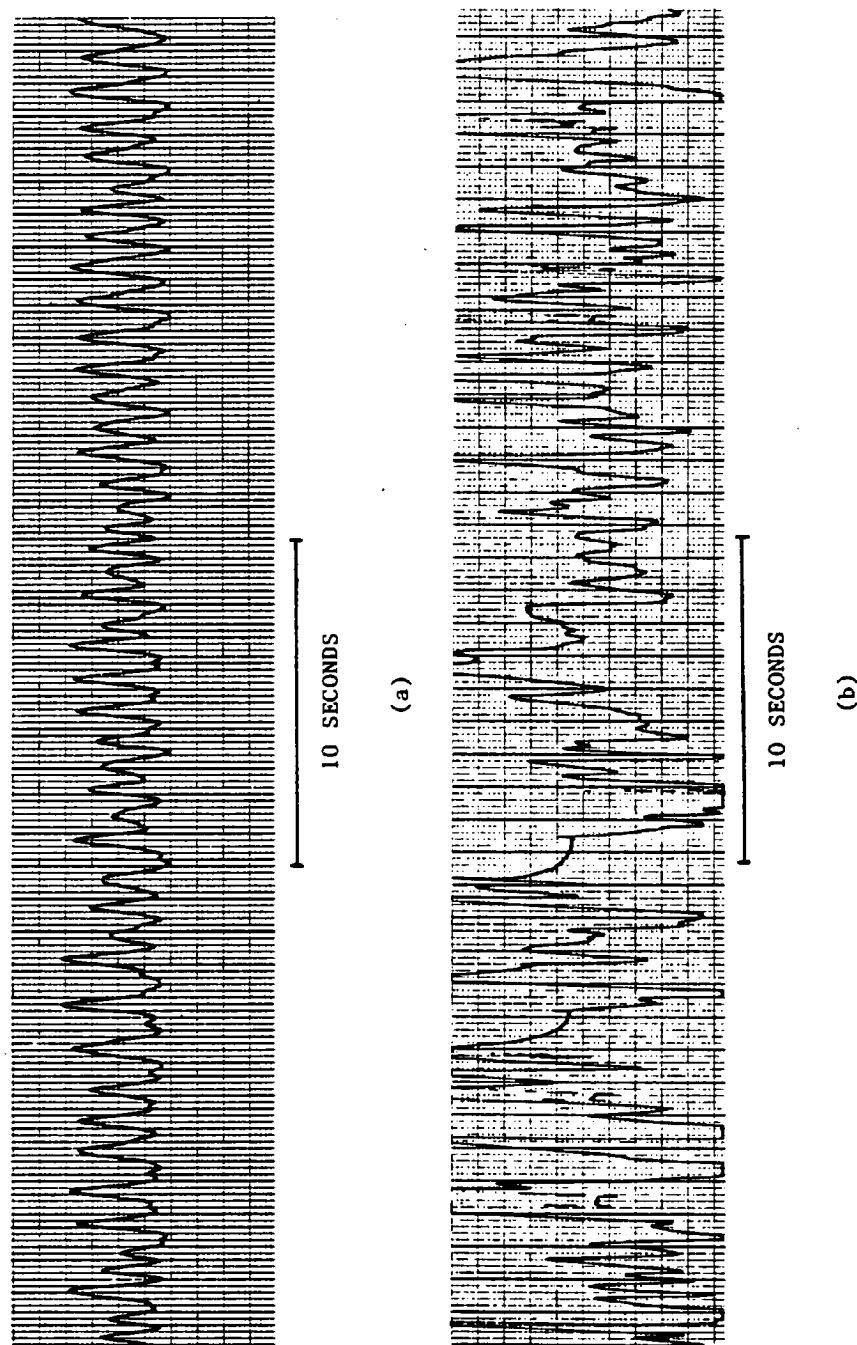


Figure 6. Two examples of transthoracic electrical impedance respiration signals in which (a) represents a regular signal during quiet sleep with little artifact and (b) shows a signal with sufficient artifact to make breath detection difficult. (Reprinted from: National Institutes of Health. Infantile apnea and home monitoring. Bethesda, MD: NIH; 1987.)

2.7 Telemetry. Many clinicians have suggested eliminating the lead-patient cable. The lead-cable-electrode system represents a major problem area for long-term infant monitoring. Telemetry would appear to answer many of the problems currently identified.

Unfortunately, a reliable telemetry system that will transmit both the impedance and heart rate signals does not exist in practical form. Several companies have developed alternative respiration measurement techniques and have coupled these systems to an FM telemetry transmitter to transmit alarm conditions to a bedside monitor. These new systems do not provide the respiration and heart rate information needed for a traditional 12- or 24-hour pneumogram.

Electronic technology is advancing rapidly. It is possible that, with custom-designed CMOS circuits, a multichannel transmitter system may be developed that is small enough to be placed on an infant and that can measure both respiration and heart rate and transmit the measurements to a bedside monitor.

The major considerations for the telemetry unit are cost, performance, and reliability. At present, use of telemetry would appear to add \$600 to \$1,000 to the monitor's cost. This probably translates into an additional \$100 per month in rental charges by the home care dealer. A telemetry system, if developed, would appear to offer significant advantages for monitoring infants over six months of age.

3. The State of the Art of Current Monitor Design

3.1 Overview. Most monitors are designed for either home or hospital use, with a few designated for use in either location. Designs are tailored for use on neonates or infants. Variations in user expertise, location and environment, and physiologic changes in the growing child require that manufacturers provide a series of monitors.

Monitors are available with various combinations of features to meet the needs of particular monitoring situations. One or more of the features listed in [Table 3](#) will be found in each monitoring system.

Additional features may include an alarm disabling function, tone or alarm loudness adjustment, adjustable brightness of display, remote alarm, connection to recorder or modem, battery operation, low-battery indication, telemetry, event memory, trending, and alarm reset.

Table 3
Performance Features of Commercially Available Apnea Monitors

<i>Apnea Detection</i>	<i>Breathing Rate</i>	<i>Heart Rate</i>
Apnea alarms	Event occurrence	Event occurrence
Alarm delay adjustment	Sensitivity adjustment	Sensitivity adjustment
Event counter	Alarm limits	Alarm limits
Cardiac artifact	Rate display	Rate display
detection/rejection	Waveform	Waveform
	Loose lead indicator	Loose lead indicator

Owing to the lack of user expertise, monitors for home use tend to have limited displays and a low number of adjustable parameters. The physician may preset the device to ensure proper monitoring of the patient, and there is often mechanical or electrical protection to prevent tampering with the control settings. Size, weight, and ease of transport are important if the monitor is to be used portably.

Hospital apnea monitors, especially those used in critical care areas, are usually integrated with systems that monitor other physiologic parameters. The system may stand alone or have a modular form. Maximum adjustability of parameters is usually provided. The system may be connected to a hospital information system for transfer of data to other areas of the hospital. It is important that hospital monitors provide stable displays in the presence of noise and voltage variations on the power lines.

3.2 Capabilities of Currently Available Impedance-Type Monitors. As noted previously, transthoracic impedance is by far the most frequently used method to detect apnea. The performance characteristics of the best impedance monitors currently available are described in [Table 4](#). These devices lack a few essential features in some situations. Thus, this technology, although useful in monitoring infants, at present is not optimal. Home monitors range from 190 to 360 cu in, and hospital monitors range from 360 to 3,300 cu in. Home monitors weigh 3 to 5 lbs, and hospital monitors weigh from 5 to 65 lbs. The cost of home monitors ranges from \$1,000 to \$3,000, and that of hospital monitors from \$2,500 to \$11,000. Size, weight, and cost are determined by the number of functions monitored, the number of adjustments and displays, the