Monitoring Gas Exchange: Clinical Effectiveness and Cost Considerations

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Introduction

The main purposes of an intensive care unit (ICU) are to provide active therapy to very ill patients (treatment) and to watch for and prevent infrequent but important adverse events (monitoring). Continuous monitoring allows titration of therapy and identifies undesirable trends. The information that monitors provide permits timely intervention that can improve clinical outcome. ICUs emerged out of the operating and recovery rooms, where expertly trained clinicians (anesthesiologists and nurses) watch patients and administer powerful drugs to maintain unconsciousness and physiologic homeostasis. Various forms of therapy are used in ICUs to maintain physiologic stability in the face of organ system failure. In this setting, monitoring helps caregivers to maintain patients' physiologic stability and to quickly identify when therapy needs adjusting. The second goal of monitoring is the detection of undesirable trends in patient status so that appropriate interventions can be applied and a bad outcome avoided.

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One of the common meanings of "to monitor" is "to observe closely," and a monitor can be defined as an advisor, informant, or counselor. Monitors are not active devices; they do not provide patient care; they can only advise or inform those who do provide care. In evaluating the effect of monitors on patient care, it is important to remember this fact. Monitoring is only the first step in initiation of action. The person using the monitor is the essential ingredient in quality patient care. Errors in using monitors can occur because of inadequate education, inexperience, or inattention. These errors can result in an undesirable patient outcome despite adequate monitor function.

Figure 1 illustrates the process of action in an ICU. The output from a monitor suggests that further testing is needed to confirm a specific diagnosis. After these results are acquired, a diagnosis is established and an action may be taken. For example, when a ventilator monitor indicates that a low exhaled minute volume is present (monitor output), the therapist checks the circuit (additional test), and finds a partial disconnection at the endotracheal tube (diagnosis). The therapist reconnects the circuit to the patient (action), and now the exhaled minute volume monitor shows a normal value (monitor output). If the therapist had not noticed (or heard) the monitor, had not found the disconnection, or had not reconnected the patient, harm might have resulted. In evaluating the impact or value of a particular monitor, it is important to recognize the additional steps necessary to affect patient outcome—a monitoring device is no better than the person using it.

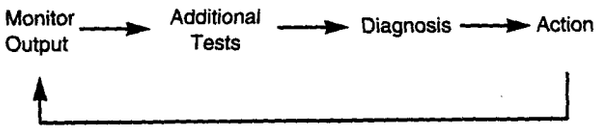

Fig. 1. Flow of information and decision making in the ICU.

General Issues Related to Monitoring

Alarms as Monitors

Sometimes in life-threatening situations, the additional diagnostic or confirmatory tests are bypassed, and action is taken without a firm diagnosis (Fig. 2). When a particular event is believed to be immediately associated with a bad outcome, action should be empiric without delaying to more firmly establish the cause. Alarms are a special feature of monitoring related to such situations. When the output variable being monitored is outside what is considered the safe range, a visual or auditory alarm is issued by the device. Once again, no change in patient care is effected by the monitoring device; the decision to act must be made by the caregiver. Caregivers often have control over the limits that trigger the monitor alarm. Given this total system, it is not reasonable to expect monitors, of themselves, to impact patient care in a positive way. Any time a monitor is evaluated for its impact on patient care, this complicated action scheme must be taken into account. Because invasive monitors always involve direct patient risks, they can easily be shown to increase morbidity. It is more difficult (if not impossible) to show that they improve patient outcome because the caregiver using the device has the major impact on outcome.

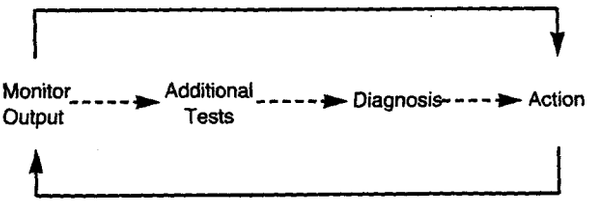

Fig. 2. When a critical value is observed, action may bypass further evaluation.

Often several monitors are used, reflecting different but related aspects of patient physiology. An experienced, watchful clinician can often respond appropriately to a critical situation without use of complicated monitors. This further confuses the objective analysis of the impact of specific monitors on patient care.

The action model shown in Figure 1 is applicable to all forms of medical diagnostic testing. The results of the first test trigger the next to confirm (or refute) a diagnosis. This sequential approach to diagnosis requires that tests be selected that are appropriate to the patient's disease process. ICU monitors should be selected for patient appropriateness as well. Patients on mechanical ventilation receiving neuromuscular blocking agents require monitoring that is different from that required by patients

breathing spontaneously without supplemental oxygen.

'Routine' Monitoring

The application of a standard battery of tests to a population of patients in an attempt to find subclinical disease is called screening. The use of screening tests may cause diagnostic problems. When screening is used indiscriminately, the likelihood of finding an abnormal result is high because of random error in the test methods or because of normal patient-population variation. The additional testing required to identify these normal 'abnormal' results increases the cost of care and may offer little or no benefit. Screening tests should be applied only when a reasonable likelihood of finding true abnormality exists. The cost-benefit of screening depends on the characteristics of the population under study. This concern has been incorporated into cost-benefit analyses of medical diagnostic tests (eg, mammography in women and prostate examination in men) with good clinical results and cost savings. It has not yet been applied to ICU monitoring but undoubtedly should be.

Monitoring in the ICU incurs a similar likelihood of finding false-abnormal results. These 'abnormals' must be worked up, wasting time and costing additional resources. This is a cost of routine monitoring. The value (benefit) and likelihood of finding a true-abnormal must be weighed against the cost of a false-abnormal finding. This concern is especially valid when one considers the alarm functions of monitors. Frequent false alarms divert the caregiver from more productive tasks and, with repeated occurrences, cause caregivers to become desensitized—to 'tune out' the sound. A true emergency may go unnoticed due to such desensitization. Evaluations of routine monitoring must include an assessment of the likelihood of a true-positive versus a false-positive alarm. The cost of monitoring includes the additional time, energy, and costs of the additional tests incurred by this problem as well as the risks incurred by frequent false alarms.

Why Monitor?

Monitors may be employed for more than a single purpose. Besides aiding the caregiver in making active interventions, monitors reduce caregivers' anxiety by confirming that the functions being monitored are within certain limits. This allows attention to be directed to other areas or to other patients. Monitors are extensions of the caregiver's senses, allowing more than one variable to be 'watched' at the same time. Table 1 lists some of the many purposes of monitors.

Table 1. Purposes of Monitoring in Intensive Care Unit Patients

Reduce uncertainty.
Reduce caregiver anxiety.
Reduce medicolegal risk.
Reduce unnecessary treatments.
Allow attention to be focused elsewhere.
Identify the need for additional therapy.
Identify undesirable trends and modify them.
Identify need for additional diagnostic studies.
Avoid lethal outcome.
Initiate action without diagnosis.
Monitor extremes.
Monitor alarm functions.
Guide ongoing therapy.
Titrate therapy.
Discontinue therapy as soon as appropriate.
Direct the use of intermittent diagnostic studies.
Confirm suspected diagnosis.
Identify false-positive findings.
Reduce number of additional intermittent tests.

The reduction in uncertainty provided by monitoring has affected medical malpractice. The widespread use of respiratory gas monitoring (pulse oximetry and capnography during surgery and anesthesia) has resulted in fewer lawsuits for poor outcome allegedly caused by inadequate ventilation and hypoxemia. Lower malpractice insurance rates have been awarded to those anesthesiologists who routinely use these forms of monitoring.[1,2] Many believe it is unlikely that the number (or kind) of adverse outcomes from anesthesia has changed greatly due to the use of monitors,[3,4] but their application is a strong defense against the claim that the cause of an adverse outcome is undetected hypoxemia.[5,6] Anesthesiologists believe that monitoring with pulse oximetry is useful even though no study has shown that improved patient outcome is attributable to its use.[7,8] The clinical detection of hypoxemia manifested as cyanosis is difficult and inexact, espe-

cially in anesthetized patients. Because irreversible harm from hypoxia occurs rapidly and laboratory evaluation of arterial oxygenation is invasive, delayed, and expensive, oximetry, with its many faults, has been accepted by clinicians who work in the operating room environment as an advance for detection of hypoxia.[9] The appropriateness of monitoring via pulse oximetry in the ICU has not been established.

Monitoring Affects Cost of Care

Monitoring for the purposes listed in Table 1 could improve the quality and reduce the cost of ICU patient care. Titration of expensive drugs to minimum effective levels and discontinuation of unnecessary treatments as soon as possible generate obvious cost savings. Avoiding organ system complications such as renal failure by minimizing toxic drug effects can save money if a prolonged hospitalization is prevented.

Some monitoring may result in increased costs. Besides the cost of the monitor itself, monitoring may lead to further testing to confirm specific diagnoses, and these additional tests add costs.

Invasive monitoring imposes additional risk to patients. The cost incurred by providing treatment for complications of invasive monitoring must be included in any assessment of the costs of such monitoring. The risks of invasive monitoring are related to the nature of the invasion and the user's technical skills and clinical experience.[10]

The choice of monitors depends on patient and clinical factors. Monitors can provide intermittent or continuous (or semicontinuous) measurements. The rate of change of the variable measured and the clinical importance of the change determines the appropriate frequency of monitoring. For the purpose of this paper, only continuous or semicontinuous monitoring is discussed. Intermittent measurements made simultaneously with blood gas analysis should be considered a type of diagnostic testing and, for the purposes of this discussion, are not monitoring. This distinction is necessary because events that adversely affect gas exchange with their consequent negative outcomes, transpire in seconds or minutes. Therefore, gas exchange monitoring for the purpose of preventing these events must be continuous.

The ideal monitor should have the characteristics listed in Table 2. Although listed first, accuracy per se is not as important as an accurate reflection of the monitored variable's changes and trends. Precision refers to the scatter around a true value. Accuracy and precision are easy to measure in controlled experiments but are less important in the clinical realm than other characteristics such as durability. Ease of use is extremely important; equipment that is complicated to set up or requires prolonged warmup time may not be used frequently or properly. Because ease of use is difficult to quantitate and because it is even harder to compare this characteristic among products, the fact that the device is actually used clinically by caregivers is evidence of that particular monitor's usefulness. Invasiveness, cost, reliability, and noise produced are other important intrinsic qualities of the devices used to monitor patients. To my knowledge, no gas exchange monitor is yet available that incorporates all of the desired characteristics listed in Table 2.

Table 2. Characteristics of the Ideal Monitor

Accurate	Noninvasive
Precise	Inexpensive
Reliable	Safe
Easy to use	Compact
Easy to repair	Quiet
Meaningful	Indestructible
Continuous	Portable

Cost Analysis of Monitoring

Complete cost accounting of monitoring is difficult because the value of associated variables, such as additional diagnostic tests required and the benefits accrued due to prevention of costly complications, cannot be fully known. However, the following basic approach can be used in considering this problem.[11-13] Direct costs of monitoring include

- capital—the cost of the equipment, service, and replacement,
- labor—the cost of personnel to run and maintain the equipment, the education needed to maintain proficiency in its use, and

- materials—the reagents and disposable components needed for each patient use.

To these must be added the indirect costs:

- additional testing costs needed to respond to a monitor output,
- treatment costs added by monitoring including costs of complications from monitoring devices, and
- treatments related to correcting the identified abnormalities.

Cost savings may also occur and should be considered in the cost analysis of a particular monitor, including

- cost of tests replaced by the monitor output,
- savings from decreased hospital stay, and
- savings realized by the prevention of more costly treatments and complications.

Potential savings are difficult to estimate, but should be subtracted from the total cost when a complete cost analysis of monitoring is performed (Table 3).

Table 3. Components of a Cost Analysis

Direct Costs
Capital
Labor
Materials
Indirect Costs and Savings
Tests added
Tests avoided
Treatment costs added
Treatment costs avoided
Caregiver Impact
Apparatus attention (saving if others do it)
Apparatus attention (cost if it adds work)
Additional tasks (phone calls, time to perform additional tests)
Tasks reduced
Outcome Benefits
Increase in quality of life
Decrease in morbidity
Improved safety
Other patients may receive more attention
Side Effects, Risks

Monitors can affect caregiver efficiency in activities other than laboratory testing. If the device is user-friendly, needs little attention, and provides important and useful information accurately, time and energy for other important tasks are made available and may be counted as a cost reduction. If the device requires frequent attention, provides poor quality or redundant information, or necessitates additional time-consuming confirmatory testing, the caregiver may be distracted from the more important task of treating the patient. Patient risk and potential benefit from monitoring are difficult to quantitate and evaluate.

Table 4. Monitors of Gas Delivery and Exchange

Oxygenation
Bulk O_2 tank analysis, fill level
Piped-oxygen pressure monitor (alarm)
Ventilator blender pressure alarm
Inspired O_2 analyzer
Intermittent ABG
Transcutaneous O_2 monitor
Pulse oximeter
Continuous ABG
S_{vO_2} monitor
Shunt measurement
Exhaled gas analysis ($\dot{V}_{O_2}$)
Tissue oxygen electrode
Ventilation
Airway pressure
Inhaled, exhaled, and minute volumes
Gas flow
Compliance
Work of breathing
Exhaled gas analysis
End-tidal CO_2
Intermittent ABG
Transcutaneous CO_2
Continuous ABG

Many components of the gas supply and/or ventilator system that can affect gas exchange can be monitored. Some of these are listed in Table 4. With the cost analysis framework in mind, this paper is limited to continuous and semicontinuous monitoring of respiratory gas exchange. Only a quasi-comparative analysis is possible because many of the cost-benefit details of monitoring have not been determined.

Gas Exchange Monitoring—Oxygen

The flow of oxygen from the bulk source to the mitochondrion is illustrated in Figure 3. When mitochondrial oxygen depletion occurs it may be due to a failure at any of these steps. Possible mechanisms for failure at these points and representative types of monitoring for some of these steps are listed in Table 5. Some monitors are specific and diagnostic because they reflect only one isolated aspect of the process. For example, if the bulk oxygen system is exhausted, the empty-tank alarm indicates precisely what is wrong. The line-pressure monitor also detects this problem but several other failures could also cause low line pressure. If an upstream failure (eg, piped gas failure) continues for several minutes, the downstream monitor (eg, oximetry or continuous blood gas analysis) reflects the patient's response to this failure but is not diagnostic of the specific problem. Rapid and precise location of the problem is more likely when several different monitors are employed at different critical steps.

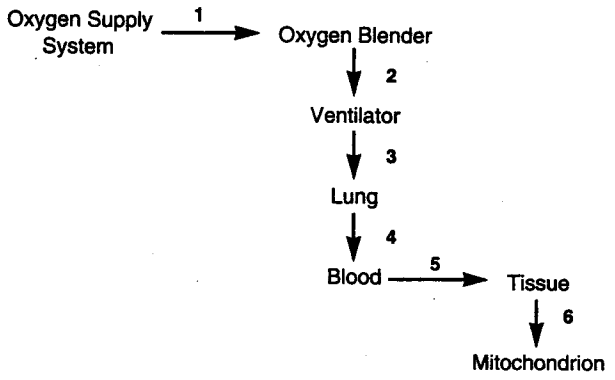

Fig. 3. The flow of oxygen from the supply system to the mitcochondrion.

Currently, there are four continuous blood oxygen monitoring systems available: pulse oximeters, transcutaneous oxygen monitors, continuous mixed-venous oxygen saturation monitors (Swan-Ganz catheters), and continuous indwelling arterial oxygen sensors. Each can be used to titrate therapy and detect oxygenation failure from upstream or down-

Table 5. Oxygenation Failure: Possible Mechanisms and Monitors

Location of Failure	Possible Causes of Failure	Possible Monitors of Delivery Step
Supply system	Empty tank	Tank gauge
	Damage to pipelines	Line pressure gauge
	Demand system overload	System flow gauge
Blender	Malfunction	Oxygen sensor, gas analysis
	Improper O_2 setting	Oxygen sensor, gas analysis
	Improper gas	Pin index system, gas ganalysis
Ventilator	Incorrect O_2 setting	Oxygen sensor, gas analysis
	Mixing valve malfunction	Oxygen sensor, gas analysis
Circuit	Disconnection	Low pressure alarm
		Low minute ventilation alarm
		Apnea alarm
Endotracheal tube	Extubation	Low pressure alarm, Apnea alarm
	Cuff leak	Low minute ventilation, end-tidal CO_2
	Endobronchial intubation	High pressure alarm, compliance monitor
	Occluded tube	High pressure alarm, compliance monitor
Lung	Hypoventilation	Low minute ventilation, end-tidal CO_2
	Shunt effect	Pulse oximetry, continuous ABG's
	Bronchospasm	High pressure alarm, compliance monitor
Arterial blood	Decreased cardiac output	End-tidal CO_2, $S_{\bar{v}O_2}$ monitoring
	Hemoglobinopathy (ie, COHb)	Hemoglobin spectroscopy (intermittent)
	Hypoxemia	Pulse oximetry
Tissue	Poor perfusion	Transcutaneous O_2 monitor
	Hypoxemia	Pulse oximetry
	Uptake failure (ie, cyanide)	$S_{\bar{v}O_2}$ monitoring, tissue oxygen monitors, magnetic resonance imaging

stream delivery failures. Each of these has its own characteristics, optimal uses, risks, and problems. These issues and the cost-benefit of each of these are analyzed in detail later in this paper.

Pulse Oximetry

Although no published or agreed-upon standard exists (outside of the operating theater), pulse oximetry monitoring is widely practiced in patients receiving mechanical ventilation in ICUs.[14-18] Pulse oximetry is based on the differential absorption of light by oxygenated and reduced hemoglobin (Hb) in blood, and the changes in absorbance coincident with arterial pulsation. The accuracy of these devices has been extensively evaluated.[15-17] Pulse oximeters have an acceptable accuracy in critically ill patients as long as arterial oxygen saturation exceeds 75%.[16] At lower values, differences between CO-oximeter and pulse oximetry saturations (S_{aO_2} and S_{pO_2}, respectively) may exceed 10%.[17] Oximetry inaccuracies have been noted at $S_{pO_2} \leq 90\%$ in patients with heavy skin pigmentation.[18] As a result, critical S_{pO_2} values of 92% for White patients and 95% for Black patients have been suggested. Some dyes significantly alter the accuracy of pulse oximetry;[19] however, bilirubin does not appear to affect oximetry accuracy.[20,21] It is important to remember that the relationship between saturation and partial pressure is affected by many factors. S_{aO_2} is not identical to P_{aO_2} and, in fact, the relationship between the two is rarely linear. Another factor reducing accuracy of pulse oximeters is blood flow through the point of attachment (digit or ear).[22-30] Hypoperfusion may result from hypotension, hypothermia, congestive heart failure, or the administration of vasoconstrictive drugs. The presence of carboxyhemoglobin or methemoglobin may produce a falsely elevated S_{pO_2}.[23,24] Despite these limitations, pulse oximetry yields useful information, especially about trends in oxygenation. Its ability to function in the clinical environment and provide meaningful data has been tested. Its routine use has not been shown to improve patient outcome. Oximetry increases caregiver comfort (reduces uncertainty) and may reduce medicolegal risk (cost).

In a large prospective, randomized study reported by Moller and colleagues,[7,8] hypoxemia, hypoventilation, and endobronchial intubation were identified more frequently and quickly in patients continuously monitored with oximetry during the perioperative period. These monitored patients also remained longer in the recovery room, received more invasive blood gas determinations, and received more supplemental oxygen than those who were not monitored by pulse oximetry. The incidence of myocardial ischemia (identified on ECG) was significantly less in the group with pulse oximetry monitoring. However, ultimate outcome variables (mortality and cardiovascular morbidity) did not differ significantly between the groups. In this study, the failure rate of oximetry was significant. This was especially important in the high-risk-patient group in which 7% of patients were not successfully monitored for a significant period of time. Despite failure of the study to show improved outcome, the anesthesiologists in the study said they would use oximetry routinely in their practice.

The routine use of pulse oximetry on all patients in the ICU is probably not clinically useful or cost-effective due to normal variations of S_{pO_2} in stable patients that is interpreted as an abnormal test requiring confirmation by arterial blood gas (ABG) analysis. However, use of this technology in high-risk patients, such as those on high levels of ventilatory support, and especially those receiving neuromuscular blocking agents, is justified and probably cost-effective. Unfortunately, these are the patients in whom the monitor is likely to fail to provide an adequate signal.[25] Due to its noninvasive character, direct patient risk from oximetry is almost nil in adults and children. (Burn injuries and pressure necrosis have been reported in neonates.[26,27]) The device works immediately, requires little attention, and is reasonably durable. For these reasons, this is a popular monitor among caregivers. Devices that provide a plethysmographic pulse tracing or indicator to help distinguish electrical interference from a true signal and thereby improve interpretation are preferred over those producing only a numerical output.[14,28]

Transcutaneous Oxygen Monitoring

Transcutaneous oxygen tension (P_{tcO_2}) is measured with heated electrochemical sensors. The amount of current transmitted between a platinum or gold cathode and a silver anode is directly pro-

portional to the P_{O_2} at the cathode surface.[29] The sensor is usually applied to the trunk in critically ill patients because limb perfusion varies considerably. In adult patients, the sensor should be applied to the skin and heated to 44° C for at least 20 minutes before the validity of the measurement can be assessed. The heated sensor encourages vasodilation and improves the agreement between arterial blood and transcutaneous oxygen tensions. Heating the skin reduces the influence of local perfusion on the measurement. However, the heating process cannot remove the influence of tissue edema or skin thickness on the measurements. Technical difficulties with transcutaneous sensors include

- the need to rotate sites every 2-4 hours to avoid skin burns,
- careful skin and electrode preparation, and
- lengthy calibration times.[30]

P_{tcO_2} values are generally lower than P_{aO_2} values. Some investigators believe that P_{tcO_2} more closely reflects tissue oxygen tension.[31,32] In normal subjects, the gradient between P_{aO_2} and P_{tcO_2} ($P_{tc} - P_{aO_2}$) is stable. However, in critically ill patients, $P_{tc} - P_{aO_2}$ is highly variable.[31,32] This is particularly true in patients with reduced cardiac index (CI).[33] Hasibeder et al[34] evaluated the influence of P_{aO_2}, mean arterial pressure (MAP), CI, oxygen dissociation curve, and Hb on P_{tcO_2} values. Significant linear correlations of P_{tcO_2} with P_{aO_2} and MAP were found, with *r* values of 0.6 and 0.42, respectively. However, only 40% of the variability in P_{tcO_2} could be explained by P_{aO_2} and MAP. They concluded that the hemodynamic, respiratory, and local influences affecting P_{tcO_2} measurements are poorly understood in critically ill patients.

Trending P_{tcO_2} values may be useful in the critically ill patient. Reductions in P_{tcO_2} values not associated with changes in P_{aO_2} imply reductions in local perfusion of skin tissue. P_{tcO_2}-P_{aO_2} ratios have been correlated with CI.[35] Hence, bedside trending of P_{tcO_2} may alert the clinician to hemodynamic alterations, even when P_{aO_2} is stable. P_{tcO_2} measurements have been used to rapidly titrate PEEP to an optimal level.[36] The effects of increasing PEEP on improving arterial oxygenation and decreasing cardiac output (C.O.) may be weighed by observations of changes in the P_{tcO_2} value.

This monitor is used less frequently in adults than in infants and children. The device is bulky, delicate, expensive, requires frequent maintenance, and takes a long time to warm up. There is a moderate degree of patient risk; burns have been reported. The need to change the sensor site every 2 or 3 hours and the difficulty interpreting the output value reduce caregiver interest in routinely using this monitor. Selective application of this technology (eg, weaning from mechanical ventilation) may be useful and cost-effective.

Mixed-Venous Oxygen Saturation Monitoring

Special pulmonary artery catheters (PACs) permit continuous display of mixed-venous oxygen saturation, $S_{\bar{v}O_2}$. Embedded in the wall of the catheter are fiberoptic filaments that transmit and detect light reflected from Hb. By comparing the reflectance at several wavelengths, computer analysis permits calculation and display of $S_{\bar{v}O_2}$.[37] Intermittent measurements of $S_{\bar{v}O_2}$ can be obtained from CO-oximeter analysis of blood aspirated from the PAC for calibration and comparison. Values for $S_{\bar{v}O_2}$ as determined by reflectance oximetry correlate well with CO-oximeter measurements, provided the catheter tip is not abutting a vessel wall or occluded by clot or debris.[38]

Mixed-venous oxygen saturation reflects the balance between oxygen consumption ($\dot{V}_{O_2}$) and delivery, and normally ranges from 70-75%.[39] $S_{\bar{v}O_2}$ is influenced by S_{aO_2}, CI, Hb, and oxygen consumption ($\dot{V}_{O_2}$). When interpreting $S_{\bar{v}O_2}$ changes, these variables should be considered.

Mixed-venous oxygen saturations below 65% suggest a poor reflectance signal, inadequate oxygen delivery, or excessive $\dot{V}_{O_2}$. Reduced oxygen delivery may result from reduced CI, S_{aO_2}, or Hb. Documentation of a falling $S_{\bar{v}O_2}$ mandates evaluation of each of these as potential causes. Therapy should then be directed at correcting the identified cause(s) of the change in $S_{\bar{v}O_2}$. Excessive $\dot{V}_{O_2}$ is known to accompany increased muscular activity (ie, shivering, seizures), fever, malignant hyperthermia,[40,41] and the sepsis syndrome.

Spuriously elevated venous oxygen saturation readings may be caused by persistent wedging of

the pulmonary artery catheter (thus measuring saturated pulmonary capillary blood), increased oxygen delivery, or reduced $\dot{V}_{O_2}$. Increased oxygen delivery may be seen in patients with peripheral shunts, sepsis, allergic reactions, or intracardiac shunts. Reductions in $\dot{V}_{O_2}$ and a rise in $S_{\bar{v}O_2}$ are seen when peripheral oxygen uptake is decreased due to toxins such as cyanide.[42] The interpretation of trends in $S_{\bar{v}O_2}$ requires additional testing. (The $S_{\bar{v}O_2}$ may be correlated with outcome, eg, patients with low $S_{\bar{v}O_2}$ after CPR and myocardial infarction do poorly.[43,44])

Cost-effective analyses of this device have been reported.[45-47] The additional cost of the catheter (above the usual PAC) is approximately $100. Savings may occur from a reduced number of ABG analyses. Venous blood gas analyses may be increased because calibration samples are needed daily. With the now frequent use of pulse oximetry, the savings attributable to $S_{\bar{v}O_2}$ monitoring is probably less than originally estimated. The use of these two monitors together provides rapid determination of which of the four variables (Hb, CI, S_{aO_2}, or $\dot{V}_{O_2}$) is responsible for a change in $S_{\bar{v}O_2}$. This form of monitoring is called dual-oximetry and can also be used continuously to reflect intrapulmonary venous admixture (shunt).[46] A reduced number of C.O. measurements may result. This saves the costs associated with supplies and caregiver time, and may result in weaning of the patient from hemodynamic and ventilatory support more rapidly.[47] The major value of this monitor seems to be that of an early warning system for imbalance of oxygen supply and demand.[48] It is not specific for a particular change; however, in controlled circumstances, it can be used as a surrogate measurement of changes in C.O., P_{aO_2}, or $\dot{V}_{O_2}$.

Arterial Oxygenation Monitoring by Indwelling Sensor

The newest monitor of oxygenation is based on indwelling electrochemical sensor technology. The fluorescent optode continuously measures arterial oxygen partial pressure (P_{oO_2}), pH, and carbon dioxide partial pressure (P_{oCO_2}) through a small filament inserted through an arterial catheter.[49] A miniaturized Clark electrode device to measure P_{aO_2} is in use in Europe.[50] Usual pressure-monitoring and blood-drawing activities are unaffected by the devices. The devices repeatedly measure the variables and update values continuously. There is a sensor lag time of about 2 minutes (for equilibration) with the optode system.[51] Accuracy of these devices is good over the clinical range of the measurement.[52]

Clinical performance of the optode device appears promising. In a case report by Greenblott and colleagues,[53] pulse oximetry, transcutaneous monitoring, and a three-component fiberoptic optode (Cardiovascular Devices Inc, Irvine CA) were used during one-lung anesthesia. The optode device functioned well and was more effective at predicting actual ABG values than the other devices. Pulse oximetry failed at several critical times during the procedure and was not useful at all when the P_{aO_2} exceeded 100 torr (as saturation remained 100%). Figure 4 summarizes the changes in oxygenation reflected by these monitors during the case. P_{oO_2} reflected wide changes and accurately predicted ABG values, P_{tcO_2} averaged the peaks and valleys, and S_{pO_2} failed to report useful values during critical events throughout the case. More experience is needed to assess the place of this new technology in clinical care.

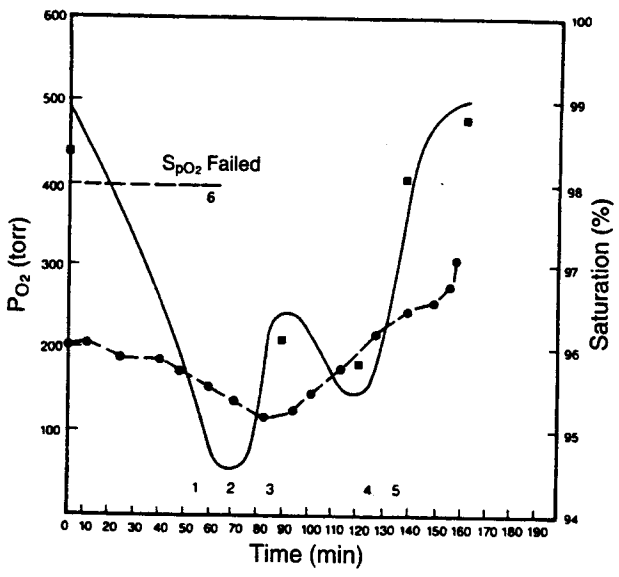

Fig. 4. A comparison of several monitors of oxygen during anesthesia for pulmonary resection. P_{aO_2} (ABG) = ■, P_{tcO_2} = ●–●–●, S_{pO_2} = – – –, P_{oO_2} = ——. (Reprinted from Reference 53, with permission.)

Optode devices are expensive, require considerable user attention, and are fragile. Their individual patient-use cost is high. However, they provide in-

able beyond several hours. Capnometry must be frequently correlated with ABG values to interpret changes, thus increasing cost. In our experience, mass spectrometers are large and delicate and may often require sophisticated service and frequent adjustments. They require external calibration with expensive standards. Use of capnometry during weaning trials, during optimization of ventilatory support with reduced intracranial compliance, and for ventilator disconnection detection in very critical patients (ie, patients receiving neuromuscular blocking agents) is helpful and may be cost-effective. CO_2 detection is the 'gold standard' for confirming tracheal intubation. However, I believe that continuous monitoring of P_{etCO_2} has yet to find its place in critical care.

Transcutaneous CO_2 Monitoring

Transcutaneous sensors, similar in design to those used to transcutaneously measure oxygen, are used to measure CO_2 (P_{tcCO_2}), and the technical concerns are similar for both. Often, the two sensors are combined within a single probe. As a result of skin heating, a local increase in local $\dot{V}_{CO_2}$ may occur, and values for P_{tcCO_2} often exceed P_{aCO_2}.[71] P_{tcCO_2} measurements remain linearly correlated with P_{aCO_2} values even in critically ill patients ($r = 0.76$) because they are less affected by changes in cardiac function and acid-base status than are P_{tcO_2} measurements.[34] This is partly because of the small arterial-to-venous P_{CO_2} difference normally present. Acute changes in CO_2 excretion are not reflected rapidly by transcutaneous monitors. Because of this delay, P_{tcCO_2} is a poor detector of circuit disconnection or apnea.

As with P_{tcO_2} monitoring, difficulties with these devices include the time necessary for calibration and stabilization (less of a problem for P_{tcCO_2} than for P_{tcO_2}), the need to frequently change monitoring site, delicacy of the device, and the large size of the probe (particularly important for infants and children). I have found them to be expensive and finicky and to require a great deal of user attention. I believe that the clinical effectiveness of these devices in adults is minimal. In adults, selective use in some carefully controlled situations may be cost-effective because they reduce the need for other tests.

CO_2 Monitoring by Indwelling Sensor

Optode technology permits arterial CO_2 monitoring (P_{oCO_2}) in combination with pH and P_{oO_2} monitoring directly through an arterial catheter. As described earlier, this technology is accurate and precise and requires a short warmup period. It is, however, expensive and delicate. The use of this device may reduce the need for other ABG analyses. It has not yet been determined what types of patients benefit from monitoring with this device.

Clinical Efficacy, Clinical Effectiveness, and Cost-Effectiveness

Clinical efficacy is the ability of a device or treatment to achieve its ascribed goals under controlled circumstances.[72] Clinical efficacy of a monitor means that its output consistently correlates with the value of a physiologic entity and/or with other monitors whose accuracy is established and accepted. Clinical efficacy also means that the monitor contributes to a desirable patient outcome with a known disease process in prospective, controlled studies that have been performed in carefully selected clinical situations. Some monitors have been tested in this way and have demonstrated accuracy, predictability, and correlation with expected outcome.

Clinical effectiveness, on the other hand, is the ability of the device or treatment to achieve the same desired results during less rigorously controlled use,[73] and in general, this quality has not been demonstrated for any blood-gas monitoring device.

Clinical effectiveness should reflect (among other things) the balance between accuracy, ease of use, and production of meaningful information. A monitor will be used only

- if its use is mandated by policy, and/or
- it is felt to be 'worth the trouble' by the user (if given a choice).

A monitor or monitoring is cost-effective when, in addition to being clinically effective (or at least useful), it costs less or incurs less risk than other accepted monitors currently in use. New (or existing) technology should not be introduced unless it is

formation that is not available continuously from any other monitor. Currently, the sensors are used for only 72 hours or less. Once arterial correlation has been established, the use of the optode device should decrease the number of ABG analyses needed. None of the other oxygen monitors have this potential. The alleged improvements to patient care by this monitor remain to be shown.[54,55] Reliability, durability, and ease of use have yet to be demonstrated.

Gas Exchange Monitors—Carbon Dioxide

The other component of gas exchange is CO_2 elimination. CO_2 is the end product of oxygen metabolism. Approximately 70,000 mEq of CO_2 are excreted by the lungs each day. The steps in CO_2 elimination are illustrated in Figure 5. Major interference with CO_2 excretion occurs with decreased C.O. (delivery to the lungs), increased physiologic dead space (eg, pulmonary embolism, COPD), or ventilatory failure. CO_2 may be monitored continuously by capnography of exhaled gases, transcutaneous CO_2 monitoring, and continuous indwelling arterial CO_2 monitoring (P_{oCO_2}). Although the flow of CO_2 is through the venous blood to the lungs, changes in CO_2 delivery are usually reflected in arterial P_{aCO_2}, because the venous-to-arterial gradient for CO_2 is very small.

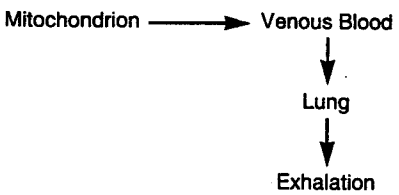

Fig. 5. The mass movement of carbon dioxide from the tissues to the room.

Capnometry & Capnography

The measurement of CO_2 concentrations in expired gases (end-tidal CO_2, P_{etCO_2}) is mandatory in operating rooms and is frequently used in ICUs. Bedside monitoring devices incorporate infrared light absorption, Raman light-spectrum scattering, or mass spectroscopy to estimate CO_2. The two types of capnometers are mainstream (the sensor is in-line with the breathing circuit) and sidestream (part of the exhaled gas is withdrawn from the patient circuit and delivered to the monitor). Mechanical problems with both types of sampling systems can result in over- and underestimation of the CO_2 fraction.[23]

Errors with mainstream sensors generally result from mucus or liquid obstruction of the light path. Sidestream units may provide erroneous data when mucus or moisture collects in the sampling tubing or when the tubing becomes kinked. When sampling rates are too high, room air may be entrained through the sampling catheter and dilute exhaled gas.[56]

Capnometry and capnography are useful for confirmation of tracheal vs esophageal intubation, identification of dislodgment of an endotracheal tube, and ventilator malfunction or disconnection.[57-60] Capnography can be used to estimate P_{aCO_2} in some situations. P_{aCO_2} is often equated to P_{etCO_2}. However, many factors affect P_{etCO_2} other than P_{aCO_2}. Increases in CO_2 production ($\dot{V}_{CO_2}$), increased pulmonary perfusion, and acute alveolar hypoventilation result in increased P_{etCO_2}, yet may not perceptibly change P_{aCO_2}.[61,62] The arterial-to-end-tidal gradient ($P_{aCO_2} - P_{etCO_2}$) varies under these and other circumstances and, therefore, the value of P_{etCO_2} in predicting the actual P_{aCO_2} is limited. Negative arterial-to-end-tidal gradients may be seen in 12% of normal subjects undergoing anesthesia who are ventilated with large tidal volumes at low frequencies.[63] Negative gradients are also seen in 50% of pregnant subjects,[64] 8% of patients following cardiac bypass surgery,[65] and 50% of infants.[66] Caution should be used when interpreting P_{etCO_2} as an estimate of P_{aCO_2}. Steady state conditions are necessary for this assumption to hold.

Changes in P_{etCO_2} and the capnogram may be of clinical value. Abrupt reductions in P_{etCO_2} that occur when the ventilator circuit is intact and the endotracheal tube remains in the trachea can indicate pulmonary embolism.[67] P_{etCO_2} correlates well with measured C.O. during resuscitation and can be used to gauge the effectiveness of cardiac compressions.[68,69] The $P_{aCO_2} - P_{etCO_2}$ gradient also serves as an estimate of physiologic dead space and can be used as a guide to achieving "best-PEEP."[70]

Capnographs vary in cost depending on the method used to determine P_{etCO_2}. Disposable supplies are frequently expensive and may not be us-

- less costly and at least as effective as the current standard,
- more costly but more effective, and its added benefit is worth the added cost, or
- less effective and less costly but the benefit of the current standard is not worth the added cost.[74-76]

Most of the monitors described in this paper can be used in a cost-effective fashion. A comparison of relative costs and benefits is provided in Table 6.

Pulse oximetry is useful in high-risk patients because of its specificity for hypoxemia, low cost/patient, ease of use, and negligible patient risk. In certain clinical settings (diagnosing the absence of hypoxemia), this monitor can replace the need for intermittent ABG analysis. However, indiscriminate use of pulse oximetry may lead to an increase in intermittent ABG analysis. The cost-effectiveness of this monitor depends on careful patient selection.

$S_{\bar{v}O_2}$ monitoring has been shown to reduce the number of venous blood gas analyses and C.O. determinations required in critically ill patients on vasopressors.[53] However, this savings only accrues in patients who would have had these studies performed without the $S_{\bar{v}O_2}$ catheter. Generally, there are only a few such patients in the ICU—those who are most unstable and those requiring active therapy titration on a minute-to-minute basis.

Similar statements may be made about transcutaneous blood gas and end-tidal CO_2 monitoring. With careful patient selection, a reduction in ABG analyses and other tests used for monitoring may generate cost savings. If used indiscriminately, however, the cost of care may increase.

There are other techniques that may reduce the use of 'routine' blood analyses obtained for monitoring oxygenation and ventilation in stable patients. Simply removing the indwelling arterial catheter remarkably reduces the number of ABG analyses performed, with no demonstrable effect on quality of care.[77] Use of an algorithm to identify clinical indications and for education of ICU staff in application of these indications is also effective.[77,78]

Indwelling ABG devices may have a cost benefit. This is because they eliminate the need for additional ABG analysis except those infrequently required for calibration. Unlike the other monitors of gas exchange, these devices measure the actual physiology of interest instead of a surrogate or corollary. Changes in the monitor's output that call for patient intervention need not be confirmed by ABG analysis prior to caregiver response. Device malfunction rate, impingement on a vessel wall, drift in calibration, and delay in demonstrating changes have not been evaluated under less than controlled conditions. Thus, the clinical efficacy has been demonstrated but I believe that the clinical effectiveness is yet to be proved. Caregivers must have confidence in the monitor's output to abandon use of confirmatory ABG analysis when this device is used. The development of such confidence takes time, and cost savings with early or infrequent use are unlikely. In evaluating the output from the other monitors, confirmatory ABG analysis is usually mandated.

It remains to be seen whether any continuous monitor of gas exchange improves patient outcome.

Table 6. Comparison of Relative Costs and Benefits among the Available Continuous Gas Exchange Monitors

Device	Direct Costs			Indirect Costs Added Tests	Benefits Reduced Tests	Patient Risks	Clinical Utility
	Capital ($)	Labor	Materials ($)				
Pulse oximeter	5,000	Low	5-50	Moderate	High*	Low	High
Transcutaneous†	20,000	High	50-100	High	Low	Moderate	Low
Mixed venous saturation (PAC)	25,000	Low	150	High	Moderate	High*	Moderate
Continuous ABG†	30,000	Moderate	200	Low	High‡	Moderate	Moderate*
Capnography	15,000	High	50	Moderate	Moderate	Low	Moderate

*Presumed but not demonstrated.
†CO_2 and O_2 monitoring.
‡If Swan-Ganz catheter inserted for this purpose only.

I believe that the use of these technologies is now based on inadequate clinical evidence of benefit and operator uncertainty. The reason for employing these expensive devices is to better care for patients who are at high risk for mortality or morbidity and who are clinically unstable. The possibility of reducing other costs with use of these monitors should be considered. Cost-effective use requires considerable judgment in application.

In Conclusion

Monitors, of themselves, never improve patient outcome because they do not do anything. They provide information that must be interpreted. The decision to act (or not act) must be made by a person. The value of monitoring must be interpreted in light of this fact. Monitors do impose risks and cost money. The analysis of outcome of monitoring is likely to show that patient morbidity is directly related to the invasiveness of the monitor. Not all risks associated with monitors are due to mechanical factors. If a device's output conveys a false sense of security to caregivers when the patient is really in trouble, monitoring can add to patient morbidity and risk. If the caregiver pays too much heed to a monitor's output and fails to watch the patient directly, harm can result. Monitoring increases cost of care. The usefulness, effectiveness, and value of most monitors have not been convincingly demonstrated. The use of certain monitors may be considered a standard of care but may, in fact, be dictated by unsupported opinion based on theoretical models of pathophysiology. Often these patterns, supported only by anecdotal experiences of caregivers, are codified into recommendations, guidelines, and policies.

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