# Noninvasive blood gas monitoring: a review for use in the adult critical care unit

**Technology Subcommittee of the Working Group on Critical Care, Ontario Ministry of Health**

**Objective:** To evaluate the accuracy, reliability, clinical effectiveness and economic impact of bedside pulse oximetry and capnometry as used routinely in the adult critical care environment.
**Data sources:** The key words "oximetry," "carbon dioxide/analysis" and "evaluation studies" were used to search MEDLINE for all relevant articles published from January 1985 to January 1991.
**Study selection:** Articles were included for review if they were original research studies designed to clinically evaluate pulse oximetry or capnometry, or both, were published in English and described a critically ill adult population. Eleven articles met these criteria; seven evaluated pulse oximetry, three evaluated capnometry and one evaluated both.
**Data extraction:** The data were evaluated by means of five validity criteria: study setting and subjects, diagnostic accuracy, reliability, clinical effectiveness and economic impact.
**Results:** No study satisfied all our criteria. Most of the studies were designed to evaluate diagnostic accuracy only, and clinically relevant information was lacking. The accuracy of pulse oximetry was clinically acceptable in five of the eight studies. However, in two of them physiologic extremes, skin pigmentation and an arterial saturation of less than 90% resulted in unacceptable error. The diagnostic accuracy of capnometry was unacceptable.
**Conclusions:** Pulse oximetry may expedite accurate and continuous monitoring of oxygenation at the bedside of the critically ill adult patient. Nevertheless, there are clinical limitations, and caution is needed before oximeters are accepted for routine use. The routine bedside use of capnometry should be discouraged.

**Objectif :** Évaluer la précision, la fiabilité, l'efficacité clinique et l'incidence économique de l'oxymétrie de pouls et de la capnimétrie au chevet du patient dans la mesure où on les utilise couramment dans le cadre des soins intensifs aux adultes.
**Sources de données :** Les mots clés «oxymétrie», «gaz carbonique/analyse» et «études d'évaluation» ont fait l'objet d'une recherche dans MEDLINE de tous les articles pertinents publiés de janvier 1985 à janvier 1991.

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**Sélection d'études** : Les articles ont été retenus s'il s'agissait de recherches originales conçues pour évaluer cliniquement l'oxymétrie de pouls, la capnimétrie ou les deux, s'ils étaient publiés en anglais et décrivaient une population adulte gravement malade. Onze articles ont répondu à ces critères; sept évaluaient l'oxymétrie de pouls, trois évaluaient la capnimétrie et un évaluait les deux techniques.
**Extraction de données** : Les données ont été évaluées au moyen de cinq critères de validité : le contexte et les sujets à l'étude, la précision diagnostique, la fiabilité, l'efficacité clinique et l'incidence économique.
**Résultats** : Aucune étude n'a répondu à tous nos critères. La plupart des études sont conçues pour évaluer la précision diagnostique seulement, et les informations cliniquement pertinentes faisaient défaut. La précision de l'oxymétrie de pouls était cliniquement acceptable dans cinq études sur huit. Dans deux études, des extrêmes physiologiques, une pigmentation de la peau et une saturation artérielle inférieure à 90 % ont causé une erreur inacceptable. La précision diagnostique de la capnimétrie était inacceptable.
**Conclusions** : L'oxymétrie de pouls peut hâter une surveillance précise et continue de l'oxygénation au chevet d'un patient adulte gravement malade. Néanmoins, il y a des limites cliniques, et on doit faire preuve de prudence avant d'accepter l'utilisation courante des oxymètres. L'emploi courant de la capnimétrie au chevet du patient devrait être découragé.

Confirming the adequacy of oxygenation and ventilation is an integral part of monitoring the progress of critically ill patients. Although arterial blood gas (ABG) analysis has been the gold standard for the early detection of arterial hypoxemia and hypercarbia it is invasive, gives information only intermittently, and frequently imposes a substantial delay between sampling and the availability of results. Accurate, reliable and continuous methods of monitoring oxygenation and ventilation at the bedside should eventually replace ABG analysis. Pulse oximeters and capnometers are examples of recent noninvasive blood gas monitors (NBGMs), but they have clinical limitations and require close scrutiny before they are widely accepted in the routine bedside care of critically ill adult patients.

We briefly describe NBGM technology and review relevant original research articles to make recommendations on the use of pulse oximetry and capnometry in adult critical care.

## Pulse oximetry

Pulse oximetry has taken clinical anesthesia, respirology and now critical care by storm over the past 5 years.[1,2] It has many of the characteristics of an ideal monitoring technique: portability, noninvasiveness (a cutaneous sensor is employed), ease of use (calibration is not required) and the capability for continuous on-line monitoring of arterial oxygen saturation ($Sa_{O_2}$).

The pulse oximeter is a spectrophotometric device that detects and calculates the differential absorption of light by oxygenated and reduced hemoglobin to produce a measurement called $Sp_{O_2}$, an estimate of $Sa_{O_2}$. A light source and a photodetector are contained within an ear or finger probe for easy application. Two wavelengths of monochromatic light — red (660 nm) and infrared (940 nm) — are used to gauge the presence of oxygenated and reduced hemoglobin in the arterial blood of the capillary bed being monitored. With each pulse beat the device interprets the ratio of the pulse-added red absorbance to the pulse-added infrared absorbance. The calculation requires previously determined calibration curves that relate transcutaneous light absorption to direct $Sa_{O_2}$.

To estimate saturation over a wide range of pulse volumes the pulse oximeter automatically increases its amplification as the pulse signal decreases. When perfusion in the capillary bed is too low to produce a pulse strong enough to allow an accurate reading, the instrument displays a "no $Sp_{O_2}$ value" message.

Although the oximeter measures arterial saturation, not arterial oxygen tension ($Pa_{O_2}$), the two are related through the oxyhemoglobin dissociation curve. On the steep portion of the S-shaped curve (below an $Sa_{O_2}$ of 90%) the saturation is more sensitive than is the $Pa_{O_2}$ in assessing oxygenation. In contrast, on the upper horizontal portion of the curve (above an $Sa_{O_2}$ of 90%) an error of a few percentage points could represent a large error in $Pa_{O_2}$. Therefore, oximetry is not a sensitive guide to changes in oxygenation when the $Pa_{O_2}$ is high.[1]

Noninvasive and continuous monitoring of the $Sa_{O_2}$ in adult critical care units may be particularly beneficial when a patient's arterial oxygenation is precarious and hemoglobin desaturation occurs rapidly. Restlessness, agitation, confusion, cyanosis, hypotension and tachycardia are all delayed manifestations of hypoxemia and may be missed or inappropriately managed. Pulse oximetry can warn of a decrease in $Pa_{O_2}$ before clinical signs indicate the

need for ABG analysis. Hence, pulse oximetry may be useful in the management of patients with pulmonary edema or pneumonia who are undergoing ventilation, endotracheal intubation or suction, bronchoscopy, position changes, transport or weaning from mechanical ventilation.

Pulse oximetry has become a part of the regular monitoring of most, if not all, patients undergoing general anesthesia,[3] especially children, and it is expected that the same enthusiasm will extend to the adult critical care unit if it has not already done so.[4] Hospital committees will have to decide whether pulse oximetry at each bedside in these units should become standard. They will be concerned with the accuracy of the new device and its cost ($3700 to $6500 per unit).[5]

## Capnometry

A capnometer is a device that measures carbon dioxide ($CO_2$) concentrations in respired gases.[6,7] An infrared light beam with a narrow wavelength of light (4.3 $\mu$m) is projected through a gas sample and the intensity of the transmitted light measured, the light absorbed being dependent on the concentration of $CO_2$ molecules in the sample.

Two types of capnometer are available that use different methods of gas sampling. Sidestream capnometers withdraw a continuous sample of gas through a capillary tube from the patient's airway to the monitor. A water trap removes particles of water before measurement takes place. A disadvantage is that the narrow lumen of the sampling tube may become obstructed with pulmonary secretions or condensate. Mainstream capnometers employ a special breathing-circuit cuvette that is placed directly in the airway. The cuvette houses an infrared light source and photodetector and is heated to prevent condensation. Because there is no sampling system this capnometer has a fast response. The major disadvantage is the size and weight of the cuvette in the patient's airway.

Capnography allows visual inspection of changes in $CO_2$ concentration by means of a waveform display or paper recording. The $CO_2$ waveform can be divided into segments that represent different phases of the respiratory cycle.[8] At the start of normal expiration gas is expelled from the anatomic dead space and therefore contains very low $CO_2$ concentrations. As more perfused alveoli empty, the increasing proportion of alveolar to dead space gas results in a greater concentration of exhaled $CO_2$. Next, the synchronous emptying of areas with different ventilation–perfusion ratios and $CO_2$ concentrations produces a nearly constant $CO_2$ concentration, called the alveolar plateau. The end-tidal $CO_2$ concentration ($P_{ET}CO_2$) closely approximates the mean alveolar concentration when the alveolar plateau is achieved. At this point the difference between the $P_{ET}CO_2$ and the arterial $CO_2$ tension ($PaCO_2$) is minimal, and the $P_{ET}CO_2$ reflects the $PaCO_2$. During healthy respiration the $P_{ET}CO_2$ is an underestimate of the $PaCO_2$ by less than 4 mm Hg, and a slightly positive $PaCO_2$–$P_{ET}CO_2$ gradient is therefore produced.[9] Finally, with inspiration the $CO_2$ concentration decreases rapidly to the baseline level, since there is no $CO_2$ in the inspired gas.

In the case of pulmonary parenchymal disease the $P_{ET}CO_2$ is the sum of the alveolar $CO_2$ tensions from areas of widely differing ventilation–perfusion ratios and emptying times. Increased positivity of the $PaCO_2$–$P_{ET}CO_2$ gradient occurs because of the continued ventilation of alveoli that are no longer perfused (i.e., there is an enlargement of the regions of the lung with high ventilation–perfusion ratios). Other conditions that might lead to increased positivity of the gradient are hypovolemia with decreased pulmonary artery pressure, excessive positive end-expiratory pressure with increased alveolar pressure, pulmonary vascular occlusive disease and venous air embolism.

Changes in $P_{ET}CO_2$ must be interpreted with extreme caution.[10] A sudden decrease may indicate ventilator disconnection, a leakage in the system, an obstructed endotracheal tube, sudden hypotension, sudden hyperventilation or a massive pulmonary embolus. A gradual decline could be a sign of hyperventilation, reduced pulmonary perfusion or decreased $CO_2$ production. A sudden increase in the $P_{ET}CO_2$ may result from an injection of sodium bicarbonate, a sudden release of a tourniquet or a sudden increase in cardiac output. A gradual increase could indicate a greater production of $CO_2$ or hypoventilation. Esophageal intubation would result in the total absence of a waveform. Therefore, although the analysis of respired gases is continuous it is greatly influenced by the differences in the ventilation–perfusion ratios in various regions of the lung, the total $CO_2$ production and the total alveolar ventilation. Unfortunately, in the critically ill patient these variables may not be stable; hence, monitoring the $P_{ET}CO_2$ may not provide a good warning of changes in the $PaCO_2$ or be a substitute for ABG sampling during adjustments of or weaning from mechanical ventilation.

## Methods

A search of MEDLINE with the key words "oximetry," "carbon dioxide/analysis" and "evaluation studies" was conducted for all articles published from January 1985 to January 1991. The resulting articles were included if they were original research studies designed to clinically evaluate pulse oximetry

or capnometry, or both, were published in English and described a critically ill adult population. The bibliographies of the retrieved articles were reviewed for missed studies.

To conclude that pulse oximetry and capnometry are ready for routine use requires rigorous evaluation of the tests' diagnostic accuracy (established in critical care units), their reliability (and thus their effect on health care providers), their clinical effectiveness and, because of the high cost, their economic impact.[11]

### *Study setting and subjects*

Most articles describe the accuracy of NBGMs under controlled conditions.[1,2] For example, most of the pulse oximetry studies involved healthy subjects with normal oxygen tensions or with laboratory-created, steady-state hypoxemia or hemodynamically stable anesthetized patients. At best these situations have only indirect clinical relevance to the critical care environment. A patient with adult respiratory distress syndrome due to sepsis is likely to require endotracheal intubation, mechanical ventilation with the application of positive end-expiratory pressure and high inspired oxygen concentrations, and vasoactive and sedating medications in order for adequate gas exchange to be maintained. An acceptable article should specify the clinical setting and the illness type and acuity. It is important to examine the performance of the NBGM in the clinical circumstances of its expected use.

### *Diagnostic accuracy*

The NBGM must provide information at the bedside that allows the clinician to accurately assess the presence or absence of hypoxemia or hypercarbia, or both. To establish this accuracy an independent comparison of the new method with a gold standard is necessary; for example, the arterial oxygen saturation as estimated by pulse oximetry ($Sp_{O_2}$) should be compared with the oxygen saturation of an ABG sample as determined by bench oximetry ($Sa_{O_2}$). Most of the studies that evaluated pulse oximetry did not adequately test for an agreement between these two measures. Often, a correlation coefficient with a $p$ value and a linear regression slope and intercept were the only data given. This information measures the association of the two values but not the agreement.

To measure agreement it is necessary to calculate the mean difference between the values obtained by the two methods (the bias) and the standard deviation (SD) of the differences (the precision).[12] The bias reveals whether there is a systematic overestimate or underestimate by the new method, and the precision quantifies the amount of random error or variability in the estimate. The range of values over which the estimate was made must also be identified. An acceptable article should document all these parameters.

### *Reliability*

If pulse oximetry and capnometry can provide accurate and reliable continuous monitoring the bedside clinician or nurse would be immensely reassured to know that the patient's state of oxygenation and ventilation was adequate or, for example, that the onset of agitation and tachycardia was not due to hypoxemia. On the other hand, if the frequency of a "no $Sp_{O_2}$" value is high, then confidence will be lost. An acceptable article should collect data about the reliability of the NBGM and thus about the reassurance it provides for the health care provider.

### *Clinical effectiveness*

Does the knowledge provided by the NBGM alter therapeutic decisions made by the clinician or nurse, and if so does the patient benefit? If a bedside NBGM is to result in appreciable changes in rates of illness and death, then the early warning information it provides must be followed by immediate correction of the blood gas abnormality. If the critically ill patient already has a radial arterial line for continuous blood pressure monitoring and blood sampling is he or she better off if pulse oximetry or capnometry is also performed? An acceptable study should be designed to confirm or refute the hypothesis that use of a bedside NBGM leads to improved, clinically relevant outcomes.

### *Economic impact*

What are the costs of this new diagnostic technology compared with the benefits? Rigorous scrutiny is required to investigate the economic impact on health care resources. For example, patients in an intensive care unit who undergo mechanical ventilation are at high risk for cardiopulmonary complications. The potential costs of the complications would depend on the duration of mechanical ventilatory support and the time spent by the patient in an "expensive" unit (2.3 times the cost of a ward bed[13]) and may be reduced through invasive and noninvasive monitoring technologies. A more obvious cost saving would be a reduced dependence on ABG determinations, since at present frequent sampling is performed to reassure the health care provider. Substituting the use of an NBGM for ABG measurements during reductions of supplemental oxygen or

during weaning from mechanical ventilation may decrease the number of ABG determinations needed.

## Results

### *Pulse oximetry*

The selection process yielded eight studies[14-21] involving 481 critically ill adult patients. The sample sizes ranged from 18 to 152 patients. No study completely met all the validity criteria (Table 1). Most of the studies measured diagnostic accuracy only and neglected the clinical consequences of the technology. The study by Jubran and Tobin[19] used the most methodologically sound design and is discussed further later.

***Study setting and subjects:*** The description of the study setting and of illness type and acuity was acceptable in five of the eight articles reviewed. The quantification of acuity was inadequate in two studies (involving 175 of the 481 patients).[16,17]

***Diagnostic accuracy:*** The data on the accuracy of pulse oximetry are listed in Table 2. The bias (the mean of the $Sp_{O_2}$ − the $Sa_{O_2}$) and the precision (the SD of the $Sp_{O_2}$ − the $Sa_{O_2}$) were calculated in six of the eight articles, for a total of 1447 paired measurements over an $Sa_{O_2}$ range of 51% to 100%. In five of the articles[14,16,18-20] the diagnostic accuracy was clinically acceptable (defined as a bias of ±2% or less and a precision of ±3% or less); the bias ranged from −1.4% to +1.9% and the precision from ±1.6% to ±3.1%.

Overall, a favourable performance in the adult critical care setting was found. Nevertheless, some of the studies did raise concerns. The first was the effect of hypoxemia on the accuracy of the $Sp_{O_2}$ measurement. Niehoff and associates[17] examined the pulse oximeter's ability to detect hypoxemia in patients being weaned from mechanical ventilation after surgery. Oximetry was a sensitive indicator of the presence of "relative" hypoxemia (an $Sp_{O_2}$ of less than 95% correlated with a $Pa_{O_2}$ of less than 70 mm Hg, with a sensitivity of 100%), but relatively few patients were hypoxemic (had a $Pa_{O_2}$ of less than 60 mm Hg). The study by Jubran and Tobin[19] was more revealing. At an $Sa_{O_2}$ of 90% or less the accuracy of the $Sp_{O_2}$ readings greatly diminished (bias ± precision, 5.1% ± 2.7%). The authors therefore proposed an $Sp_{O_2}$ target of 92% to reliably ensure satisfactory oxygenation (a $Pa_{O_2}$ of 60 mm Hg or more 92% of the time). A recent study by Severinghaus, Naifeh and Koh[25] in which plateaus of profound hypoxia ($Sa_{O_2}$ of 70% to 40% for 30 to 45 seconds) were rapidly induced in healthy subjects demonstrated the inaccuracy of the internal calibration of many pulse oximeters over the lower saturation range, which resulted in unacceptable variations in bias (−9% to +13%) and precision (±3% to ±16%). Because suitable calibration data had previously been lacking for this lower range of $Sa_{O_2}$ values many manufacturers modified and significantly improved the algorithm of their instruments. Hence the importance of examining oximeter performance under conditions that challenge reliability.

The second concern was the effect of skin pigmentation and jaundice on the accuracy of $Sp_{O_2}$ measurements. Jubran and Tobin[19] found that the $Sa_{O_2}$ was significantly overestimated in black patients (bias ± precision, 3.3% ± 2.7%). The authors proposed a higher $Sp_{O_2}$ target, 95%, to ensure

Table 1: Criteria used to evaluate original research studies on pulse oximetry and capnometry*

| | Criterion | | | | | | |
|---|---|---|---|---|---|---|---|
| | Study description | | | Factors assessed | | | |
| Study | Setting | Illness type | Acuity | Diagnostic accuracy | Reliability | Clinical effectiveness | Economic impact |
| Pulse oximetry | | | | | | | |
| Tremper et al[14] | + | − | + | + | − | − | − |
| Mihm and Halperin[15] | + | + | + | ± | − | − | − |
| Cecil et al[16] | + | − | − | + | − | − | − |
| Niehoff et al[17] | + | + | − | ± | − | ± | ± |
| Gabrielczyk and Buist[18] | + | + | + | + | − | − | − |
| Jubran and Tobin[19] | + | + | + | + | − | + | − |
| Jones et al[20] | + | + | + | + | − | + | − |
| Clayton et al[21] | + | + | + | + | ± | − | − |
| Capnometry | | | | | | | |
| Niehoff et al[17] | + | + | − | ± | − | − | − |
| Hoffman et al[22] | + | + | + | + | − | − | − |
| Healey et al[23] | + | + | + | + | − | − | − |
| Yamanaka and Sue[24] | + | + | + | + | − | − | − |

*+ = study met criterion; − = study did not meet criterion; and ± = study partially met criterion.

adequate oxygenation (a $Pa_{O_2}$ of 60 mm Hg or more 85% of the time) in these patients. The diminished accuracy may be related to the fact that the calibration curves were based on data from healthy white, rather than black, volunteers. Hyperbilirubinemia, on the other hand, does not interfere with hemoglobin saturation as measured by pulse oximetry. In a prospective clinical study of 29 icteric patients no direct influence of high plasma bilirubin levels (39 to 1442 μmol/L) on the accuracy of the $Sp_{O_2}$ readings was observed.[26]

The third concern is the effect of physiologic extremes on $Sp_{O_2}$ measurement. Tremper and collaborators[14] collected $Sp_{O_2}$ and $Sa_{O_2}$ data sets over a wide range of conditions: temperature 32.8°C to 39°C, cardiac index 1.4 to 8.7 L/min for each square metre and mean arterial blood pressure 37 to 141 mm Hg. "Low perfusion" alarms disallowed 57 (15%) of 383 data sets. The data sets, measured at the high and low physiologic extremes, had unacceptable biases. On the other hand, Mihm and Halperin[15] did not admit to this problem, although only 9 of 118 data sets were obtained during periods of hypotension. Signal failure did occur during monitoring of 4 (22%) of 18 patients, however, and 2 patients were taking vasopressor medications at the time of the attempted $Sp_{O_2}$ measurement. No demonstrable loss of accuracy was observed in patients who were hypothermic after cardiac surgery;[18] however, hypotension and hypoxemia were not present. Jones and colleagues[20] studied patients with acute respiratory illness who presented consecutively to the emergency department, but because patients with hemodynamic instability were excluded the effect of these physiologic extremes could not be evaluated.

Clayton and coworkers[21] designed the most discriminative study by examining only poorly perfused patients. Adult patients were studied 30 minutes to 2 hours after cardiopulmonary bypass surgery. Patients were hypothermic (mean temperature 35.1°C, SD 0.75°C) and were undergoing ventilation with intermittent positive pressure but had a normal $Sa_{O_2}$ (mean 96.7%, SD 1.7%). Twenty pulse oximeters with finger probes were evaluated on 120 patients. The bias varied from an underestimate of 4.5% to an

Table 2: Data on setting, accuracy and reliability from studies assessing pulse oximetry

| Study | Setting; type of patient | Oximeter type | No. of patients (data sets) | Range of arterial oxygen saturation (%) | Bias ± precision* (%) | Unreliability† | Agreement of measures‡ (%) |
|---|---|---|---|---|---|---|---|
| Tremper et al[14] | Surgical intensive care unit (ICU); critically ill | Ohmeda Biox III | 53 (326) | 81–100 | −1.4 ± 3.1 | 15% | NA |
| Mihm and Halperin[15] | Medical ICU; acute respiratory failure (ARF) | Nellcor N-100 | 18 (131) | 56–100 | NA | 4/18 | NA |
| Cecil et al[16] | ICU, emergency department and recovery room | Nellcor N-100 | 152 (330) | 62–100 | +0.59 ± 3.02 | 1.5% | NA |
| | | Ohmeda Biox III | 152 (333) | 62–100 | −0.31 ± 2.44 | 0.6% | NA |
| Niehoff et al[17] | Surgical ICU; postsurgical | Ohmeda Biox III | 23 (138) | 88–100 | NA | 0% | 95 |
| Gabrielczyk and Buist[18] | Surgical ICU; postsurgical | Nellcor N-100 | 21 (68) | 90–100 | +0.6 ± 1.6 | 2/21 | 95 |
| Jubran and Tobin[19] | Medical ICU; mechanical ventilation | Ohmeda 3700 or Nellcor N-100 | 54 (98) | 78–97 | +2.7 ± 2.3 | NA | |
| | | | | > 90 | +1.7 ± 1.2 | NA | |
| | | | | ≤ 90 | +5.1 ± 2.7 | | |
| | | | | White | +2.2 ± 1.8 | NA | 89 |
| | | | | Black | +3.3 ± 2.7 | | 73 |
| Jones et al[20] | Emergency room; ARF | Ohmeda Biox III | 40 (52) | 51–99 | +1.86 ± 3.11 | NA | NA |
| Clayton et al[21] | Cardiac surgery recovery ward; mechanical ventilation | 20 different ones | 120 (240) | Mean 97; SD 13 | −4.5 to +2.7 | 8.7% | 57–100 |

*"Bias" is the mean of the differences between the pulse oximeter measurements of oxygen saturation and the measurements obtained by arterial blood gas (ABG) analysis; "precision" is the standard deviation (SD) of the differences.
†Signal failure: percentage of readings or proportion of patients.
‡The percentage of pulse oximeter readings within 3% or 4% of the ABG values. NA = not available.

overestimate of 2.7%. The precision varied from ±0.96% to ±5.78%. Only 2 of the 20 pulse oximeters were capable of clinically acceptable accuracy (i.e., $Spo_2$ readings within 3% of the $Sao_2$ 95% or more of the time). With this degree of accuracy an $Spo_2$ value of 93% would translate into a possible $Pao_2$ of between 59 and 85 mm Hg. To prevent hypoxemia (a $Pao_2$ of less than 60 mm Hg) an $Spo_2$ of 93% or more should be aimed for. This study best emphasizes the important differences between pulse oximeters when they are evaluated critically in a demanding clinical environment.

***Reliability:*** The study by Clayton and coworkers[21] raises concern regarding signal "dropout." Overall, signal failure occurred in 8.7% of the measurements, and 10 of 20 oximeters failed to give readings at least 10% of the time. None of the studies reviewed addressed specifically the extent to which pulse oximetry could provide reassurance to the beside caregiver.

***Clinical effectiveness:*** If the patient is to benefit from pulse oximetry the continuous information provided must lead to appropriate modifications in oxygen therapy that are the same as or different from those indicated by the results of direct ABG analysis. Jubran and Tobin[19] undertook a study to determine if $Spo_2$ values could reliably be substituted for ABG $Pao_2$ measurements during adjustments of the inspired oxygen fraction supplied to ventilator-dependent patients. Achieving an $Spo_2$ target of 92% reliably predicted a satisfactory level of oxygenation ($Pao_2$ 60 mm Hg or more) and avoided toxic levels of oxygen but only in white patients, for whom the positive predictive value was 92%. A higher $Spo_2$ target, 95%, was required in black patients; for the same $Pao_2$ the positive predictive value was 85%. Jones and colleagues[20] studied patients with acute respiratory illness who presented consecutively to the emergency department. The increases and decreases of 5% or more in the $Spo_2$ correlated positively and highly significantly with those in the $Sao_2$. Interventions directed at increasing the $Spo_2$ (through the provision of oxygen, bronchodilators and diuretics and through intubation) were successful in 11 of 19 patients. However, the $Spo_2$ remained below 90% in eight patients despite the initial resuscitation measures, and five of these required intubation and mechanical ventilation in the emergency department.

Unfortunately, none of the studies addressed whether the patient was better off when monitored at the bedside with pulse oximetry. An improvement in patient outcome (i.e., in the rate of illness or death) has never been documented for adult patients in a critical care setting through the use of this monitoring device. A study hinting at improved patient outcome was identified in the setting of pediatric anesthesia. Cote and associates[27] examined the efficacy of the pulse oximeter in the early recognition of hypoxia in 152 children undergoing elective or emergency surgery. The patients were prospectively monitored after being randomly assigned to an "$Spo_2$ available" or an "$Spo_2$ unavailable" group; the groups differed in whether oximetric information was given to the anesthetic team. The overall incidence of major hypoxemic events (an $Spo_2$ of 85% or less for 30 seconds or more) was significantly higher in the "$Spo_2$ unavailable" than in the "$Spo_2$ available" group (11 v. 24 events, $p = 0.02$); however, an increased death rate was not documented. Most of these events occurred in children aged 2 years or less. Cyanosis and vital-sign monitoring were insensitive in diagnosing arterial desaturation. The authors concluded that pulse oximetry, in contrast to changes in vital signs, provided early warning of developing hypoxemia in anesthetized children and guided anesthetic management.

***Economic impact:*** No study persuasively documented the cost-effectiveness of routine pulse oximetry. Niehoff and associates[17] tried to do so but in no way satisfied accepted economic objectives, particularly a comparison of the costs of the new technology with its potential benefits. Their study only examined whether pulse oximetry (and capnometry) decreased the need for ABG determinations or the duration of intubation during weaning from mechanical ventilation. Fewer ABG determinations were needed for patients monitored with pulse oximetry than for control patients not so monitored (means 5.9 [SD 2.7] v. 10.5 [SD 1.8], $p < 0.001$), although no difference in the duration of intubation was apparent. A comparison of the costs of the technology with the costs of fewer ABG determinations was not carried out.

## *Capnometry*

The selection process yielded four studies[17,22-24] involving 96 critically ill adult patients. The sample size ranged from 17 to 39 patients. No study met all the validity criteria (Table 1). Three studies were designed to measure only the diagnostic accuracy of the technology.

***Study setting and subjects:*** The description of the study setting and illness type was acceptable in all the articles reviewed. The quantification of illness acuity was adequate in three studies.

***Diagnostic accuracy:*** The studies evaluating the diagnostic accuracy of the capnometer as a substitute for ABG sampling or as a monitor of $Paco_2$ trends are listed in Table 3. The bias and precision of the $Paco_2$–$Petco_2$ gradient were calculated in three of the four studies, for a total of 153 paired measurements over a $Paco_2$ range of 19 to 72 mm Hg. The

bias varied greatly, from 2.35 to 18 mm Hg (i.e., the $PETCO_2$ underestimated the $PaCO_2$), as did the precision, from ±5.3 to ±10 mm Hg. Within individuals the gradient also varied greatly, from −9.5 to +39 mm Hg; in the study by Yamanaka and Sue[24] the gradient correlated closely with the dead space:tidal volume ratio, but many other factors were likely involved. With the $PaCO_2$–$PETCO_2$ gradient (bias 4.0 and precision ±5.3 mm Hg) of Hoffman and collaborators[22] 95% (±2 SD) of the $PETCO_2$ values obtained at one time would be between 14.6 mm Hg less and 6.6 mm Hg more than the actual $PaCO_2$. By comparison, the bias and precision of the gradient in normal patients have been calculated as 4.0 and ±2.5 mm Hg;[9] in this case 95% (±2 SD) of the $PETCO_2$ measurements made at one time would be between 9 mm Hg less and 1 mm Hg more than the actual $PaCO_2$.

Also of concern is how well changes in the $PETCO_2$ predict changes in the $PaCO_2$. In the 20 sample sets of Healey and colleagues[23] a reasonably good coefficient of correlation, 0.82, was found between changes in the two types of measurement. However, the precision meant that 95% of the measured changes in the $PETCO_2$ could have been between 14.2 mm Hg less and 7.8 mm Hg more than the actual change in the $PaCO_2$. In one patient a 10 mm Hg rise in the $PaCO_2$ was unaccompanied by a change in the $PETCO_2$. In the study by Hoffman and collaborators[22] changes in the $PETCO_2$ did not correlate well with changes in the $PaCO_2$ ($r$ = 0.58, 116 sample sets) when changes in ventilation were made. In fact, only 18% of the changes in the $PETCO_2$ were within 20% of the corresponding changes in the $PaCO_2$. In 4 of the 20 patients the trend in the $PETCO_2$ was in the direction opposite from the trend in the $PaCO_2$. Niehoff and associates[17] examined the efficacy of capnometry in the postoperative weaning of patients from a ventilator in a surgical intensive care unit. At a $PETCO_2$ of more than 40 mm Hg only 25 (27%) of 91 episodes of hypercarbia ($PaCO_2$ greater than 45 mm Hg) were identified.

In summary, these limited studies do not support the use of $PETCO_2$ measurements as a substitute for $PaCO_2$ measurements obtained by ABG analysis or as a monitor of the trend in the $PaCO_2$. Given the doubtful accuracy of capnometry there is certainly no evidence that it will become a cost-effective means of monitoring in respiratory care units.[28]

## Summary

### *Pulse oximetry*

Pulse oximetry is widely used in clinical situations in which rapid, continuous monitoring of arterial saturation is important. Its ease of use, portability and noninvasiveness are other attractive features. It is clear why the use of the pulse oximeter has extended into the critical care environment. However, a thorough evaluation of its ability not only to provide accurate information but also to improve patient care and disease outcome is required before widespread dissemination is recommended. Such studies are seriously lacking. If pulse oximetry is to become routine at the bedside of critically ill patients whose oxygen levels are precarious, then proper clinical trials will be necessary to

Table 3: Data on setting and accuracy from studies assessing capnometry

| Study | Setting; type of patient | Capnometer type | No. of patients (data sets) | Range of $PaCO_2$* (mm Hg) | Bias ± precision;† range (mm Hg) | Changes in $PaCO_2$ and $PETCO_2$ mean ± SD (mm Hg) |
|---|---|---|---|---|---|---|
| Niehoff et al[17] | Surgical ICU; postsurgical | Hewlett-Packard 2538 | 39 | 21–83 | NA‡ | NA |
| Hoffman et al[22] | ICU; mechanical ventilation, ARF | Lifespan 100 | 20 (116) | 19–63 | +4 ± 5.3; −9.5 to +19.5 | In graphic form§ |
| Healey et al[23] | Medical and surgical ICU; postsurgical, ARF | Lifespan 100 | 20 (20) | 29–72 | +2.35 ± 5.65 | +3.2 ± 5.5 |
| Yamanaka and Sue[24] | Medical ICU; mechanical ventilation, ARF | Hewlett-Packard 47210A | 17 (17) | 22–64 | +18.0 ± 10.0; 0 to 39 | NA |

*Arterial carbon dioxide ($CO_2$) tension.
†"Bias" is the mean of the differences between the measurements of arterial $CO_2$ tension ($PaCO_2$) obtained by ABG analysis and the end-tidal $CO_2$ ($PETCO_2$) measurements obtained by capnometry; "precision" is the standard deviation of the differences.
‡A $PETCO_2$ value greater than 40 mm Hg predicted hypercarbia ($PaCO_2$ greater than 45 mm Hg) with a sensitivity of only 28%.
§Changes in $PETCO_2$ (measured from baseline) did not correlate well with changes in $PaCO_2$ ($r$ = 0.58), and only 18% of the $PETCO_2$ changes were within 20% of the corresponding $PaCO_2$ changes.

document the advantages over the present monitoring approach (intermittent ABG determinations).

The studies reviewed confirm the manufacturers' specifications that the precision of pulse oximeters is within ±2% to ±3% when the $Sa_{O_2}$ is 90% or more; the precision is thus ±4% to ±6% if a 95% confidence interval (± 2 SD) is desired. For example, if the $Sp_{O_2}$ is 94%, then the true $Sa_{O_2}$ may be as low as 88% or as high as 100% for 95% of the measurements. This translates into a wide range of $Pa_{O_2}$ values. Adequate arterial oxygenation will result if a target $Sp_{O_2}$ of 92% or more is achieved in white patients and 95% or more in black patients.[19]

Pulse oximetry may fail to record accurately the true $Sa_{O_2}$ during severe or rapidly produced desaturation and during physiologic extremes (e.g., hypotension, hypothermia, unstable hemodynamic factors and agitation). More information is required concerning the prevalence of signal failure with the regular use of pulse oximetry and the effect this has on nursing and medical care (e.g., Does frequent signal failure lead to greater demands on nurses to reposition the probe and to frequent, annoying alarms?).

The provision of a pulse oximeter at every bedside cannot be justified until clinical effectiveness and economic efficiency in the routine care of critically ill patients have been satisfactorily documented. However, given the present level of clinical accuracy and effectiveness in documenting arterial desaturation it would be reasonable to support limited use: a number of portable pulse oximeters should be available for use during expected arterial desaturation (e.g., during intubation and bronchoscopy) and in patients with precarious oxygenation (e.g., those with adult respiratory distress syndrome requiring a high fractional intake of oxygen or positive end-expiratory pressure). However, their limitations should be borne in mind.

### *Capnometry*

$P_{ETCO_2}$ values may allow monitoring of changes in the $Pa_{CO_2}$ of the healthy, hemodynamically stable patient but not in the critically ill patient, because the $P_{ETCO_2}$ also reflects changes in pulmonary perfusion and dead space ventilation.

A significant change in the $P_{ETCO_2}$ may indicate that determination of the $Pa_{CO_2}$ by means of ABG analysis is required; however, a constant $P_{ETCO_2}$ does not ensure a constant $Pa_{CO_2}$. Trends in the $P_{ETCO_2}$ in the critically ill patient are often misleading because of the wide variability in the $Pa_{CO_2}$–$P_{ETCO_2}$ gradient in the individual patient (with ventilator changes alone[22]).

The routine use of capnometry as a substitute for $Pa_{CO_2}$ measurement by means of ABG analysis or as a $Pa_{CO_2}$ trend monitor in the intensive care unit should be discouraged.

The availability of a capnometer may be desirable to some physicians in intensive care units for other specific functions; for example, to confirm esophageal intubation, to document a changing ventilation–perfusion ratio through a changing $Pa_{CO_2}$–$P_{ETCO_2}$ gradient or to demonstrate restoration of the circulation after cardiopulmonary arrest and resuscitation.[29]

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**Apr. 13-15, 1992:** International Conference on Systemic Lupus Erythematosus
London
Dr. G. Hughes, Rheumatology Department, St. Thomas' Hospital, London SE1 7EH, England

**Apr. 14, 1992:** University of Toronto Institute of Health Management Seminars on Continuous Quality Improvement in Healthcare, Series 1, part 4: The Voice of the Customer
Toronto
Fern Greenbaum, Conference Communications Plus, PO Box 573, Stn. Z, 413 Eglinton Ave. W, Toronto, ON M5N 2Z6; (416) 489-5932, fax (416) 489-0119

**Apr. 22-25, 1992:** International Symposium on Endothelium-derived Vasoactive Factors
Basel, Switzerland
Dr. T.F. Luscher, Division of Cardiology, Department of Internal Medicine, University Hospital, Petersgraben 4, CH-4031, Basel, Switzerland

**Apr. 26, 1992:** 4th Annual Symposium on Treatment of Headaches and Facial Pain
New York Marriott — East Side
Dr. Alexander Mauskop, director, Downstate Headache Center, 132 Atlantic Ave., Brooklyn Heights, NY 11201; (718) 935-9666

**Apr. 26-28, 1992:** International Conference on Calcium-Regulating Hormones
Florence, Italy
Secretariat, Organizazione Internazionale Congressi, Via Gustavo Modena 19, 50121 Florence, Italy

**Apr. 30, 1992:** 34th Annual Departmental Research Meeting and 12th Clement McCulloch Lecture
Koffler Institute for Pharmacy Management Auditorium, University of Toronto
Dr. David S. Rootman, Department of Ophthalmology, Rm. 5-311, Eaton Building, Toronto General Hospital, Toronto, ON M5G 2C4; (416) 340-4713

**Apr. 30-May 2, 1992:** National Conference on Out-of-Laboratory Testing — Moving out of the Laboratory: Facing the Challenge
Government Conference Centre, Ottawa
Dr. C. Prosser, Department of Clinical Biochemistry, St. Boniface General Hospital, 409 Tache Ave., Winnipeg, MB R2H 2A6; (204) 235-3336, fax (204) 231-2656

**May 3-5, 1992:** Canada Safety Council National Conference (in conjunction with "COPE '92" Conference on Protective Equipment)
Ottawa
Canada Safety Council, 6-2750 Stevenage Dr., Ottawa, ON K1G 3N2; (613) 739-1535, fax (613) 739-1566

**May 3-7, 1992:** World Conference on Tobacco and Health
Buenos Aires
Secretariat, Union Antitabaquica Argentina, Riobamba 1124, 1116 Buenos Aires, Argentina

**Du 7 au 9 mai 1992 :** ACOP '92 — La Recherche de la qualité de vie chez les patients, familles et professionels
Université Queen's, Kingston (Ont.)
Association canadienne d'oncologie psychosociale, a/s Wendy Stewart, Centre régional de cancer à Kingston, rue King ouest, Kingston, ON K7L 2V7; (613) 544-8968, fax (613) 544-9708

**May 7-9, 1992:** CAPO '92 — The Quest for Quality of Life for Patients, Families and Professionals
Queen's University, Kingston, Ont.
Canadian Association of Psychosocial Oncology, c/o Wendy Stewart, Kingston Regional Cancer Centre, King Street W, Kingston, ON K7L 2V7; (613) 544-8968, fax (613) 544-9708

**May 7-9, 1992:** Fleischner Society 22nd Annual Symposium on Chest Disease
Le Centre Sheraton Montreal
*CME credits available.*
Fleischner Society, Meeting Management, 110-5665 Oberlin Dr., San Diego, CA 92121; (619) 453-6222, fax (619) 535-3880

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