Anesthesiology
74:980–987, 1991

A Single-blind Study of Combined Pulse Oximetry and Capnography in Children

Charles J. Coté, M.D.,* Norbert Rolf, M.D.,† Letty M. P. Liu, M.D.,* Nishan G. Goudsouzian, M.D.,‡ John F. Ryan, M.D.,‡ Alan Zaslavsky, Ph.D.,§ Ronald Gore, M.D.,¶ I. David Todres, M.D.,‡ Susan Vassallo, M.D.,¶ David Polaner, M.D.,¶ James K. Alifimoff, M.D.**

This single-blind study examined four levels of monitoring in 402 pediatric cases. Patients were randomly assigned to one of four groups: 1) oximeter and capnograph; 2) only oximeter; 3) only capnograph; or 4) neither oximeter nor capnograph data available to the anesthesia team. An anesthesiologist, not involved in patient care, observed all cases and continuously recorded hemoglobin oxygen saturation (Sp_{O_2}), ECG, expired CO_2, and the oximeter plethysmographic output. Mean age, weight, ASA physical status, airway management (mask or endotracheal tube), and anesthetic technique were similar in each group. Two-hundred sixty problems were documented in 153 patients. Fifty-nine events in 43 patients resulted in "major" desaturation ($Sp_{O_2} \le 85\%$ for ≥ 30 s). Fifteen "major" capnograph events (esophageal intubation, disconnection, accidental extubation, or obstructed endotracheal tube) were observed in 11 patients; 8 of these also developed varying degrees of desaturation. One-hundred thirty "minor" desaturation events ($Sp_{O_2} \le 95\%$ for ≥ 60 s) and 79 "minor" capnograph events (hypercarbia or hypocarbia) were observed. A number of problems fulfilled criteria in multiple categories. Infants ≤ 6 months of age had the highest incidence of major desaturation events (18 of 65 [27%]) compared to toddlers 7–24 months of age or children >24 months of age ($P < 0.001$). Blinding the oximeter data increased the number of patients (12 *vs.* 31) experiencing major desaturation events ($P = 0.003$); blinding the capnograph data altered neither the frequency of desaturation events nor the incidence of major capnograph events. Blinding the capnograph data increased the number of patients with minor capnograph events (22 *vs.* 47; $P = 0.0026$). More patients experienced multiple problems when neither capnograph nor oximeter data were available compared to when both were available (23 *vs.* 11; $P = 0.04$). We conclude: 1) The pulse oximeter is far superior to either the capnograph or clinical judgment in providing the earliest warning of desaturation events. 2) Capnography can provide an early warning to potentially life-threatening problems, but such problems often result in desaturation. 3) Capnography reduces the incidence of hypercarbia and hypocarbia. 4) Infants ≤ 6 months of age are at greatest risk for major desaturation and major capnograph events. 5) The number of problems observed can be significantly reduced when both monitors are used. (Key words: Anesthesia: pediatric. Anesthesia complications: desaturation; hypercarbia. Anesthesia techniques: tracheal intubation. Monitoring: pulse oximetry; capnography.)

IN A PREVIOUS single-blind prospective study we demonstrated that pulse oximetry reduces the frequency and severity of desaturation events during pediatric anesthesia.[1] However, the contribution of capnography to the safety of anesthesia for children remains to be determined.[2] This study evaluated the usefulness of monitoring with pulse oximetry and capnography, alone and in combination, during anesthesia for infants and children.

Materials and Methods

This study was approved by the Subcommittee on Human Studies of the Massachusetts General Hospital, and informed written consent was obtained for all patients. Children of ASA physical status 1–4, scheduled for surgery under general anesthesia, were eligible for study; patients with cyanotic congenital heart defects and those scheduled for bronchoscopy were excluded. Anesthetic management was left to the discretion of the anesthesia team. All patients were monitored with a precordial stethoscope, automated blood pressure measurement (Dinamap®, Critikon, Tampa, FL), ECG (lead II), temperature, inspired oxygen concentration, pulse oximetry, and capnography (N-1000, Nellcor, Hayward, CA). The gas sample for capnography was obtained from the right-angle connector of the endotracheal tube (endotracheal tube larger than 4.5 mm ID) or the face mask. When an endotracheal tube smaller than 4.5 mm ID was used, a special endotracheal tube with a built-in gas port at the tip of the endotracheal tube was used whenever possible (ET_{CO_2} tracheal tube, Sheridan, Argyle, NY). A continuous strip-chart recording of hemoglobin saturation (Sp_{O_2}), the plethysmogram generated by the pulse oximeter, the capnogram, and the ECG were obtained from induction until the patient was transferred to the recovery room (Linearcorder Mark VII, WR3101, Western Graphtec, Irvine, CA). The Sp_{O_2} channel of the strip

* Associate Professor of Anaesthesia, Harvard Medical School; Associate Anesthetist, Massachusetts General Hospital.

† Research Fellow, Harvard Medical School; Massachusetts General Hospital.

‡ Associate Professor of Anaesthesia, Harvard Medical School; Anesthetist, Massachusetts General Hospital.

§ Assistant Professor of Statistics, Harvard University.

¶ Instructor in Anaesthesia, Harvard Medical School; Assistant in Anesthesia, Massachusetts General Hospital.

** Assistant Professor of Anaesthesia, Harvard Medical School; Assistant Anesthetist, Massachusetts General Hospital.

Received from Harvard Medical School and Massachusetts General Hospital, Boston, Massachusetts. Accepted for publication January 30, 1991. Supported by grants from the Anesthesia Patient Safety Foundation, Park Ridge, Illinois; by Nellcor Inc., Hayward, California; and by the Humboldt Foundation, Bonn, Federal Republic of Germany. Presented in part at the Section on Anesthesiology, American Academy of Pediatrics, the Association of University Anesthetists, and the American Society of Anesthesiologists.

Address reprint requests to Dr. Coté: Department of Anesthesia, Massachusetts General Hospital, Boston, Massachusetts 02114.

chart recorder was calibrated with an electronic simulator (074598, Nellcor), and the capnogram channel was calibrated with 5% CO_2 at the beginning of each study day; recordings were later examined for comparison with the events observed.

Patients were randomly assigned to one of four groups: 1) pulse oximetry and capnography; 2) only pulse oximetry; 3) only capnography; or 4) neither pulse oximetry nor capnography information available to the anesthesia team. The definitions of terms used to classify events are presented in table 1.

An additional anesthesiologist (N.R.) was present throughout each anesthetic to record intraoperative problems. Intraoperative "problems" were defined as any abnormality that could be detected by pulse oximetry or capnography; these events did not necessarily lead to desaturation, hypercarbia, or hypocarbia. Whenever there was an intraoperative problem, whether or not the data were available to the anesthesia team, the responsible anesthesiologist was interviewed about the nature of the problem and the presence and recognition of any clinical signs. The decision as to how to respond to the information provided by the monitors was left to the discretion of the anesthesia team. This individual informed the anesthesia team (resident and staff) of developing problems as defined by the following criteria in patients whose respective monitor data were *unavailable* to the responsible anesthesiologist: 1) $Sp_{O_2} \leq 85\%$ for ≥ 30 s; 2) $Sp_{O_2} \leq 95\%$ for ≥ 60 s; 3) no CO_2 tracing after tracheal intubation; and 4) end-tidal $CO_2 \leq 25$ mmHg or ≥ 55 mmHg or no CO_2 tracing for ≥ 60 s.

Each event was timed with a stop watch, and the observer and monitors were placed in such a position as to not compromise the blindness of the study. In order to accomplish this, two N-1000 Nellcor monitors were mounted back to back so that whenever either capnography or oximetry data were available, one monitor faced the anesthesia team; if a parameter was blinded, then the second monitor, facing the observer, was used.

TABLE 1. Definition of Terms

Events		
Oximeter	Major	$Sp_{O_2} \leq 85\% \geq 30$ s
	Minor	$Sp_{O_2} \leq 95\% \geq 60$ s
	Interesting	$Sp_{O_2} \leq 85\% < 30$ s
Capnograph	Major	Potentially life-threatening ventilation abnormalities: • Esophageal intubation • Endotracheal tube obstruction • Circuit disconnection • Accidental tracheal extubation
	Minor	Non-life-threatening ventilation abnormalities: • Hypercapnia end-tidal $CO_2 \geq 55$ mmHg ≥ 60 s • Hypocapnia end-tidal $CO_2 \leq 25$ mmHg ≥ 60 s

The time during the anesthetic procedure when a problem occurred was recorded. The induction period was defined as the beginning of anesthetic administration until the trachea was intubated or until ventilation *via* mask was easily maintained and the patient was positioned for surgery; maintenance was defined as the interval from the end of induction until anesthetic agents were discontinued; and awakening was defined as the period from the discontinuation of anesthetic agents until transfer of the patient to recovery room.

In order to reveal possible differences between the monitors in detecting certain problems better than others, the causes for the different problems were classified as: 1) "clinical" problems: *i.e.*, the clinical diagnosis is usually easy to establish (*e.g.*, airway obstruction, coughing in response to the endotracheal tube, laryngospasm, endobronchial intubation, or bronchospasm); 2) "capnograph" problems: *i.e.*, early diagnosis is expected to be facilitated by capnography (*e.g.*, esophageal intubation, accidental extubation, circuit disconnection, obstruction of the endotracheal tube, hypercarbia, or hypocarbia; and 3) "oximeter" problems: *i.e.*, pulse oximetry is assumed to provide an early diagnosis (*e.g.*, hypoventilation, laryngoscopy-associated desaturation, arteriovenous shunting, apnea, and unspecified causes). Whether the diagnosis of each problem was first made clinically, by the pulse oximeter, or by the capnograph, was determined on the basis of the intraoperative observation, the interview, and by review of the strip chart recording. Any desaturation events for which the plethysmograph recording suggested movement artifact were not included.

For statistical analysis, comparisons of proportions were performed using Fisher's exact test. These tests were applied to counts of *patients* rather than *events*, to ensure independence of counts when patients may have had multiple events (except in the analysis of events by time of event). *T* tests were performed using both pooled and unpooled variance estimates; the more conservative results are reported.

Results

Four hundred and two patients were studied; the number of patients whose airway was managed by endotracheal intubation or by face mask, the mean age, weight, and the duration of anesthesia, did not differ between groups (table 2). The mean age of the overall patient population was 4.4 ± 4.3 yr, and the mean weight was 19.6 ± 15.2 kg. Two hundred sixty intraanesthetic problems occurred

TABLE 2. Demographic Data of Patients Studied

	Group			
	1	2	3	4
Number	100	100	100	102
Age (yr)	4.9 ± 5.0	3.9 ± 4.2	4.8 ± 4.2	4.1 ± 3.9
Weight (kg)	21.6 ± 17.4	17.2 ± 12.8	20.1 ± 14.4	19.3 ± 15.4
ASA physical status				
I or II	95	96	97	98
III or IV	5	4	3	4
Airway management				
Intubation	55	47	43	51
Face mask	45	53	57	51
Anesthesia (min)	76 ± 57	70 ± 62	65 ± 41	73 ± 49

Means ± SD.
Groups: 1 = pulse oximetry and capnography available; 2 = only pulse oximetry available; 3 = only capnography available; 4 = neither pulse oximetry nor capnography available.

in 153 patients (table 3); 59 problems in 43 patients fulfilled the criteria of a major desaturation event, whereas 15 problems in 11 patients fulfilled the criteria of a major capnograph event. Five of the major capnograph events also became major desaturation events; 2 became minor desaturation events, 1 was an "interesting" desaturation event; and 7 were not associated with desaturation, hypercarbia, or hypocarbia. One hundred thirty problems fulfilled the criteria of minor desaturation events; 43 events were interesting desaturation events; 79 were minor capnograph events; and 10 others were problems that did not result in desaturation or capnograph abnormalities. Some events fulfilled criteria in two or more categories (fig. 1).

AIRWAY MANAGEMENT

Sixty-eight problems in 45 patients were associated with anesthetics managed by face mask; 192 problems in 108 patients were associated with cases managed with tracheal intubation (tables 4A and 4B). Six major desaturation events occurred in 6 of 206 patients managed by face mask (2.9%) and 53 major desaturation events were ob-

TABLE 3. Distribution of All Intraanesthetic Problems by Group and Category

Problem	Group 1	Group 2	Group 3	Group 4	Total	Percent
Clinical						
Airway obstruction	3	0	2	8	13	5.0
Bronchial intubation	5	1	5	4	15	5.8
Bronchospasm	1	0	1	2	4	1.5
Coughing	7	5	13	11	36	13.8
Laryngospasm	7	4	5	7	23	8.8
Capnograph						
Accidental extubation	0	0	1	0	1	0.4
Disconnect	1	0	0	2	3	1.1
Esophageal intubation	2	0	1	4	7	2.7
Tube obstruction	2	1	1	0	4	1.5
Hypercarbia	11	24	14	21	70	26.9
Hypocarbia	0	7	0	2	9	3.5
Oximeter						
Apnea	1	3	0	0	4	1.5
Hypoventilation	9	2	20	21	52	20.0
Laryngoscopy	2	6	3	3	14	5.4
Shunting	0	0	1	0	1	0.4
Undiagnosed cause	0	3	1	0	4	1.5
Total	51	56	68	85	260	100.0

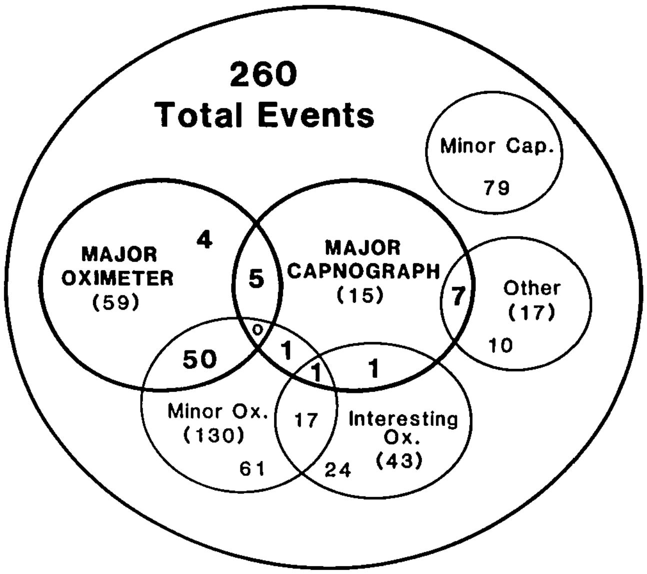

FIG. 1. This figure illustrates the 260 events observed in 153 of the 402 patients studied. Major desaturation events and major capnograph events are within the bold circles; all major events are numbered in bold type. The total number of events that fulfilled the criteria for each category are in parentheses. Note that some events fulfilled criteria in two or more categories.

TABLE 4A. Problems Associated With Anesthetics Managed by Mask

Problem	Group 1	Group 2	Group 3	Group 4	Total	Percent
Airway obstruction	0	0	0	4	4	5.9
Coughing	0	0	0	2	2	2.9
Disconnect	0	0	0	1	1	1.5
Esophageal intubation	0	0	0	3	3	4.4
Hypercarbia	6	12	2	6	26	38.2
Hypoventilation	3	0	9	11	23	33.8
Laryngospasm	3	1	2	3	9	13.2
Total	12	13	13	30	68	100.0

served in 37 of 196 patients managed by tracheal intubation (18.9%). Both the number of patients with problems and the number of those with major desaturation events were greater in patients whose airway was managed by tracheal intubation ($P < 0.0001$).

AGE EFFECTS

Table 5 presents the number of patients and associated problems and major desaturation events. The mean age (± standard deviation [SD]) of patients with intraanesthetic problems and with major desaturation events was significantly lower than the mean age of all patients, at 3.4 ± 4.1 yr (problems) ($P = 0.002$) and 2.4 ± 3.3 yr (major desaturation events) ($P = 0.0001$) *versus* 5.1 ± 4.4 yr (no problems or events). A significantly larger number of infants ≤ 6 months of age experienced major desaturation events (18 of 65 = 27.7%) compared to toddlers 7–24 m (9 of 113 = 8.0%) or children > 24 months of age (16 of 224 = 7.1%) ($P < 0.001$). There was no significant difference between children 7–24 months *versus* those > 24 months of age. The number of infants ≤ 6 months of age who experienced a major capnograph event (4 of 65 = 6.1%) was greater than for children > 24 months (3 of 224 = 1.3%) ($P = 0.05$) but not greater compared to toddlers 7–24 months (4 of 113 = 3.5%).

MONITOR EFFECTS

Fifty-nine of 153 patients with intraoperative problems experienced more than one problem; 11 were in group 1 (both oximeter and capnograph data available) and 23 were in group 4 (neither oximeter or capnograph data available) ($P = 0.04$). Thirty-two patients experienced the same problem two or more times. Blinding the pulse oximeter information from the anesthesia team increased the number of patients with major desaturation events from 12 to 31 ($P = 0.003$) (fig. 2). When the capnograph information was not available (groups 2 and 4), the number of patients with major desaturation events was not

TABLE 4B. Problems Associated With Anesthetics Managed by Endotracheal Intubation

Problem	Group 1	Group 2	Group 3	Group 4	Total	Percent
Accidental extubation	0	0	1	0	1	0.5
Airway obstruction	3	0	2	4	9	4.7
Apnea	1	3	0	0	4	2.1
Bronchial intubation	5	1	5	4	15	7.8
Bronchospasm	1	0	1	2	4	2.1
Coughing	7	5	13	9	34	17.7
Disconnect	1	0	0	1	2	1.0
Esophageal intubation	2	0	1	1	4	2.1
Hypercarbia	5	12	12	15	44	22.9
Hypocarbia	0	7	0	2	9	4.7
Hypoventilation	6	2	11	10	29	15.1
Laryngoscopy	2	6	3	3	14	7.3
Laryngospasm	4	3	3	4	14	7.3
Shunting	0	0	1	0	1	0.5
Tube obstruction	2	1	1	0	4	2.1
Unspecified cause	0	3	1	0	4	2.1
Total	39	43	55	55	192	100.0

TABLE 5. Frequency of Major Desaturation Events and Total Intraanesthetic Problems

	Group 1		Group 2		Group 3		Group 4	
	M	P	M	P	M	P	M	P
Problems (n)	10	51	6	56	24	68	19	85
Patients	7	32	5	39	16	34	15	48

M = major desaturation event; P = intraanesthetic problem.

significantly different compared to the groups with the information available (groups 1 and 3) (23 *vs.* 20 patients). The number of patients with problems of *any variety* was not greater when the pulse oximeter was unavailable compared to the number when it was available (table 5). However, the overall number of patients with *problems of any variety* was less when the capnograph data were available (66 of 200 *vs.* 87 of 202) ($P = 0.04$).

The pulse oximeter provided the first diagnostic evidence in 69.5% (41 of 59) of the major desaturation events; 22% (13 of 59) were first diagnosed clinically and 8.5% (5 of 59) were detected by the capnograph (fig. 3). In the four major desaturation events diagnosed by the capnograph there was a change in contour of the CO_2 waveform prior to desaturation. In one case the anesthesiologist noted the absence of the CO_2 waveform but was uncertain how to interpret the data until the Sp_{O_2} began to decrease. The observer had to inform the anesthesia team in 4 of these events.

There were 15 major and 79 minor capnograph events in the 402 patients. In 8 of the 15 major capnograph events, desaturation of varying degree occurred (fig. 1). The incidence of major capnograph events was unaffected by availability of capnography. The 79 minor capnograph problems consisted of either hypercarbia (70) or hypocarbia (9). A significantly higher number of patients with capnograph problems (major and minor) occurred when the capnograph data were unavailable (52 patients in groups 2 and 4 *vs.* 26 patients in groups 1 and 3; $P = 0.0015$). The number of patients with hypercarbia or hypocarbia was increased when capnography data were unavailable; all hypocarbia events (9) occurred in 8 patients, in the capnograph-unavailable groups ($P = 0.007$). The majority of capnograph events were accounted for by episodes of hypercarbia and hypocarbia (25 events in 22 patients with capnograph available *vs.* 54 events in 47 patients without capnograph available; $P = 0.026$).

THE FIRST DIAGNOSIS

The number of problems in the four groups classified into three types (clinical, capnograph, and oximeter) is shown in table 6. The number of "oximeter" problems

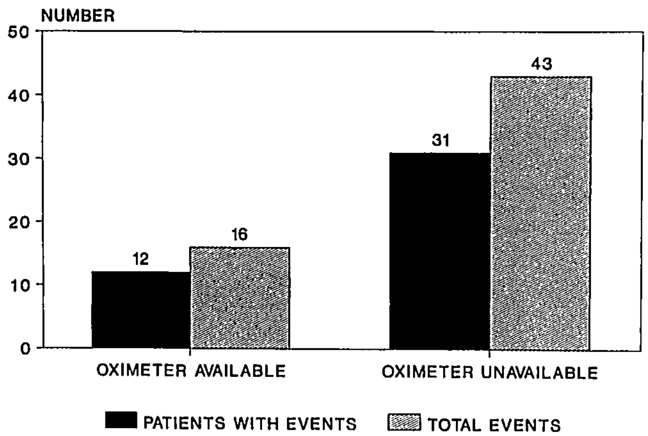

FIG. 2. Major desaturation events. The number of patients (filled bars) with major desaturation events and the number of events (hatched bars) both were significantly higher when oximeter data were unavailable to the anesthesia team ($P = 0.003$). When capnography data were unavailable there was no significant effect on the incidence of events leading to desaturation.

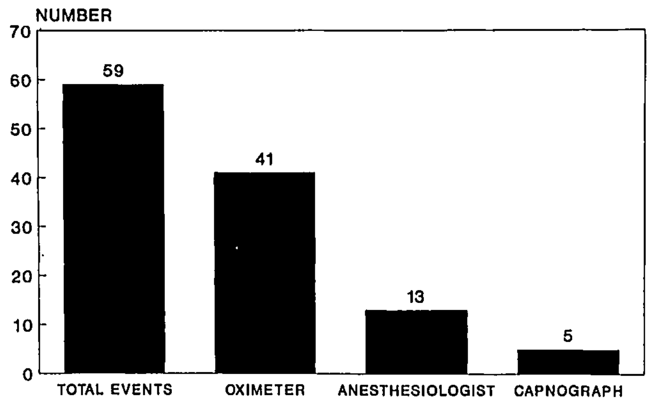

FIG. 3. Major desaturation events: first diagnosis. Nearly 70% of major desaturation events were first diagnosed by the oximeter; 22% were first diagnosed by the anesthesiologist; and the remaining cases were first diagnosed by the capnograph. The observer had to inform the anesthesiologist in four of the five desaturation events first diagnosed by the capnograph.

TABLE 6. Distribution of All Intraanesthetic Problems

	Group				
Problem Category	1	2	3	4	Total
Clinical	23	10	26	32	91
Capnograph	16	32	17	29	94
Oximeter	12	14	25	24	75
Total	51	56	68	85	260

increased significantly, from 26 events in 21 patients in the patients with oximeter data available (groups 1 and 2) to 49 events in 36 patients without oximeter data available (groups 2 and 4) ($P = 0.045$). The pulse oximeter diagnosed 97% (73 of 75) of the oximeter-related problems. Likewise, 91% (86 of 94) of the capnograph-associated problems were first detected by capnography. Only 36% (33 of 91) of the clinical problems were actually diagnosed clinically; in 54% (49 of 91) the diagnosis was made by the pulse oximeter and in 9% (8 of 91) by capnography.

CYANOSIS

In 77% (33 of 43) of the major desaturation events that occurred when the pulse oximeter data were unavailable to the anesthesia team, the anesthesiologist was not aware of any problem at the time the observer informed him or her of the problem. Cyanosis was described in 30 episodes of desaturation; interestingly, only 19 of these patients would have had 5.0 g of desaturated hemoglobin. Nine patients were described as cyanotic, with < 5.0 g of desaturated hemoglobin, and 10 others were described as not cyanotic even though they had > 5.0 g of desaturated hemoglobin. The mean Sp_{O_2} at which desaturation was recognized was 70 ± 8%. The mean hematocrit (± standard error [SE]) for all patients was 36.1 ± 4.9 (range 49–26%); the mean hematocrit for patients with major desaturation events was 35.4 ± 3.2 (range 45–32%).

DISTRIBUTION OF EVENTS

The distribution of major desaturation events during the conduct of anesthesia appeared to be the same; however, a significantly greater number of major desaturation events occurred during induction and maintenance but not during awakening from anesthesia when comparing data-available to data-unavailable groups ($P < 0.02$–0.04) (table 7). There was no relationship between major desaturation events and duration of anesthesia or to the experience of the resident anesthesiologist; the mean number of months of residency training and the mean number of weeks of training in pediatric anesthesia of the resident anesthesiologist were nearly identical for patients with or without major desaturation events.

Discussion

Pulse oximetry has been shown to reduce the incidence of critical desaturation events in children undergoing general anesthesia; the current study was performed to determine the additional value provided by capnography.[1] Our experience and that of others has been that capnography is very helpful in guiding anesthetic management and detecting airway complications; however, no previous studies have directly compared both monitors.[2–4] We studied primarily ASA physical status 1 and 2 patients because we wished to focus on problems occurring during routine management of pediatric anesthesia. The efficacy of pulse oximetry in preventing events that lead to hypoxemia was confirmed by the higher frequency of major desaturation events in the groups with the pulse oximeter unavailable compared to those with the pulse oximeter available. More importantly, this study demonstrated that the number of patients with major desaturation events was reduced (5.9 *vs.* 15.3%). This study also reaffirms the findings of our first blinded oximeter study—that events are as likely to happen during very brief as during very long surgical procedures, and that they can happen even in the hands of experienced anesthesiologists.[1] These observations are particularly impressive because the residents and staff knew that they were being observed; if anything, there was bias against the monitors.

In contrast to pulse oximetry, the availability of capnography did not reduce the number of major desaturation events. The data clearly demonstrate minimal contribution of expired CO_2 monitoring in preventing the majority of events that lead to desaturation. Even with examination of the strip chart recordings, we found that the capnograph provided the first diagnostic evidence in only 8.5% of the major desaturation events and was less efficient than clinical judgment, which first diagnosed 22% of the major desaturation events.

Comparing pulse oximetry and capnography on the basis of major desaturation events alone underestimates

TABLE 7. Distribution of Major Desaturation Events during Anesthesia

	Induction	Maintenance	Awakening
Oximeter available	7	1	8
Oximeter unavailable	20*	8†	15‡
Total major events	27	9	23

* $P < 0.02$ compared to available.
† $P < 0.04$ compared to available.
‡ P = not significant compared to available.

the value of capnography. The capnograph waveform may provide evidence of a problem before it develops into a major desaturation event, and the capnograph can diagnose abnormalities of ventilation which by themselves will not lead to desaturation, *e.g.*, hypercarbia.[3] It was for this reason that we labeled types of events as "major" and "minor" capnography events. Major capnography events were those that could potentially threaten the patient's life; these included esophageal intubation, circuit disconnections, accidental extubations, and endotracheal tube obstructions.[5-7] Of course, all of these events eventually will lead to desaturation, which would then be diagnosed by the pulse oximeter; however this study focused upon the *earliest diagnosis* of these problems. Fifteen problems in 11 patients fulfilled the criteria of a major capnography event and occurred with equal frequency in all four groups but with increased frequency in infants; the incidence of major capnography events is similar to the incidence we reported previously in a nonrandomized study of capnography.[3] Capnography provided the earliest diagnosis of one accidental extubation, two of three disconnections, two of seven esophageal intubations, and two of four endotracheal tube obstructions. The observation that only 8 of 15 major capnograph events proceeded to desaturation suggests that this monitor may have provided an early warning to the anesthesia team in some instances; *i.e.*, the diagnosis in seven major capnograph events was made prior to the development of desaturation. The availability of capnography data did not affect the incidence of major capnography events most likely because of their low incidence; *i.e.*, the presence or absence of a capnograph cannot be expected to alter the basic incidence of uncommon events. A much larger study is required to confirm this.

The importance of capnography as an aid to the diagnosis of esophageal intubation was documented by the fact that at least two of seven were first diagnosed by the capnograph. Our experience and that of others is that the majority of esophageal intubations are readily diagnosed clinically. However, we have had several patients, particularly small infants with a distended abdomen, for whom it has been very difficult to be certain that the endotracheal tube was positioned correctly.[5-7] Although one could argue that esophageal intubation should have been included in the category of clinical diagnosis, our experiences suggested to us that this problem belonged in the capnograph category.

It appears that both monitors performed as expected: the oximeter provided the earliest warning of events leading to desaturation while the capnograph provided the earliest warning of abnormalities in ventilation. Some events were diagnosed by both monitors, often with the oximeter confirming the early warning provided by the capnograph. The number of patients with intraoperative problems related to ventilation, *i.e.*, minor capnograph events, was significantly greater in the capnograph-unavailable compared to the capnograph-available group (54 problems in 47 patients *vs.* 25 problems in 22 patients). Capnography monitoring had an impact on the management of ventilation, since the incidence of hypercarbia and hypocarbia was significantly lower in patients whose anesthesiologist had capnography data available.

The number of major, minor, and interesting oximeter events and of minor capnograph events were decreased by the availability of either respective monitor. These data strongly suggest that the availability of oximetry reduces the number of interesting and minor desaturation events that would otherwise progress to major desaturation events. Comparing the two extremes—both oximeter and capnography available *versus* neither available (group 1 *vs.* 4)—one finds a two-fold increase in the number of patients with multiple intraoperative problems; there is a strong suggestion that the overall number of problems also is higher (51 *vs.* 85) when neither monitor is available. The combined clinical impact of these monitors is confirmed by the fact that capnography made the first diagnosis in 91% of all capnography problems and pulse oximetry made the first diagnosis in 97% of oximetry problems, but the clinician made the first diagnosis in only 36% of clinical problems.

In our previous blinded study of pulse oximetry, we found a higher incidence of major desaturation events in children $\leq$ 2 yr of age.[1] In the current study, with a much larger number of patients, we found that infants $\leq$ 6 months of age had the highest incidence of both major desaturation and major capnograph events but that the rate in toddlers (7 − 24 months) was similar to children (> 24 months). The majority of problems involved patients whose airway was managed by tracheal intubation. On the surface this suggests that intubation itself was a major source of complications. Since all but four infants were managed with an endotracheal tube, it is difficult to clearly determine whether the intubation procedure itself or whether age, the technical difficulties of caring for neonates and infants, or the increased metabolic consumption of oxygen are the most important factors.[8] It is our clinical judgment that each contributes. These data do not imply that there would be fewer problems if endotracheal intubation was avoided, since it is likely that other problems would have occurred that would have been a greater threat to patient safety. There is no question that the care of neonates and infants is associated with a much higher incidence of problems, with the vast majority involving desaturation events.

Measurement of end-tidal CO_2 tension is less accurate with a nonrebreathing circuit compared to a circle system.[9] However, the most important information concerns problems that threaten the patient's life (unrecognized esophageal intubation, accidental extubation, blocked endotracheal tube, and disconnections); all such events are rapidly diagnosed by the simple presence or absence of expired CO_2. We believe that it is important to obtain, when feasible, the expired gas sample prior to mixing of inspired and expired gases, since this provides the most accurate information; however, if this is not possible, the practitioner should not abandon the capnograph but rather seek an alternate site that will monitor the simple presence or absence of expired CO_2. This will allow the diagnosis of major capnograph events but will not provide for accurate end-tidal CO_2 tension determination. One can accept this degree of inaccuracy since moderate hypercarbia or hypocarbia in the absence of hypoxemia is unlikely to harm the majority of patients.

This study documented all problems related to Sp_{O_2} but included only those with well-defined criteria, *i.e.*, major, minor, and interesting events; we also included all ventilation problems regardless of their severity. This accounts in part for the large number of problems and the large number of patients with problems. There were many other transient episodes of desaturation that did not fulfill the problem criteria and therefore were not included. It was, however, common to observe very transient desaturation whenever ventilation was interrupted, *e.g.*, during administration of medications or changing of intravenous solutions. This study again confirmed the difficulty of clinically diagnosing cyanosis, as demonstrated by the nine episodes of patients described as cyanotic who had < 5.0 g of desaturated hemoglobin and the 10 others labeled as not cyanotic who had ≥ 5.0 g of desaturated hemoglobin.[10,11]

One additional area of interest was the fact that the decrease in Sp_{O_2} in many children while they were coughing in response to the endotracheal tube. We placed this problem in the clinical category because coughing is immediately obvious to the anesthesiologist; we were surprised with the frequency of desaturation (14% of all problems), especially when the oximeter data were blinded. A recent study suggests that coughing and episodes of desaturation are reduced if the trachea is extubated while patients are "deeply" anesthetized.[12] We did not specifically examine this issue and cannot recommend alteration in practice on the basis of our study. It is important simply that all patients who cough should be carefully observed for evidence of desaturation.

In summary, this study confirms the efficacy of pulse oximetry in diagnosing desaturation with greater accuracy than clinicians, and, by providing an early warning, reducing the number of desaturation episodes that progress from mild to severe desaturation. Capnography can provide the earliest warning of events with the potential for significant morbidity prior to the onset of desaturation, *e.g.*, esophageal intubation and disconnections; however, we were unable to demonstrate that the incidence of these types of events were affected by capnography. Capnography does reduce the incidence of hypercarbia and hypocarbia. Clearly, both monitors have a clinically important function in the safe anesthetic care of children, but pulse oximetry is superior in providing an early warning of events that can potentially cause desaturation. Children ≤ 6 months of age are at the highest risk for major capnography events and events that lead to desaturation.

The authors thank Mr. Mark Marshall, Bioengineering Technician, Mr. Charles Wickens, Associate Clinical Engineer, and Mr. Richard DeCesare, Clinical Engineering Manager, for their help in modifying and maintaining the monitoring equipment. They also thank all participating pediatric anesthesia residents and pediatric surgeons.

References

1. Coté CJ, Goldstein EA, Coté MA, Hoaglin DC, Ryan JF: A single-blind study of pulse oximetry in children. ANESTHESIOLOGY 68:184–188, 1988
2. Cohen DE, Downes JJ, Raphaely RC: What difference does pulse oximetry make? ANESTHESIOLOGY 68:181–183, 1988
3. Coté CJ, Liu LMP, Szyfelbein SK, Firestone S, Goudsouzian NG, Welch JP, Daniels AL: Intraoperative events diagnosed by expired carbon dioxide monitoring in children. Can Anaesth Soc J 33:315–320, 1986
4. Murray IP, Modell JH: Early detection of endotracheal tube accidents by monitoring carbon dioxide concentration in respiratory gas. ANESTHESIOLOGY 59:344–346, 1983
5. Linko K, Paloheimo M, Tammisto T: Capnography for detection of accidental oesophageal intubation. Acta Anaesthesiol Scand 27:199–202, 1983
6. Andersen KH, Hald A: Assessing the position of the tracheal tube: The reliability of different methods. Anaesthesia 44:984–985, 1989
7. Vaghadia H, Jenkins LC, Ford RW: Comparison of end-tidal carbon dioxide, oxygen saturation and clinical signs for the detection of oesophageal intubation. Can J Anaesth 36:560–564, 1989
8. Cross KW, Tizard JPM, Trythall DAH: The gaseous metabolism of the newborn infant. Acta Paediatr 46:265–285, 1957
9. Badgwell JM, McLeod ME, Lerman J, Creighton RE: End-tidal PCO_2 measurements sampled at the distal and proximal ends of the endotracheal tube in infants and children. Anesth Analg 66:959–964, 1987
10. Comroe JH, Botelho S: The unreliability of cyanosis in the recognition of arterial anoxemia. Am J Med Sci 214:1–6, 1947
11. Blount GS, Jr.: Cyanosis: Pathophysiology and differential diagnosis. Prog Cardiovasc Dis 13:595–605, 1971
12. Pounder DR, Blackstock D, Steward DJ: Tracheal extubation in children: Halothane *vs.* isoflurane, anesthetized *vs.* awake. ANESTHESIOLOGY 74:653–655, 1991