Intraoperative events diagnosed by expired carbon dioxide monitoring in children

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Expired carbon dioxide measurements ($PECO_2$) were used (1) to assess the adequacy of initial alveolar ventilation, and (2) to document intraoperative airway events and metabolic trends. Three hundred and thirty-one children were studied. Thirty-five intraoperative events were diagnosed by continuous $PECO_2$ monitoring; 20 were potentially life-threatening problems (malignant hyperthermia, circuit disconnection or leak, equipment failure, accidental extubation, endobronchial intubation, or kinked tube); only two of these were also diagnosed clinically. The duration of anaesthesia may be a factor: 3.9 hours for cases with events vs. 2.5 hours for cases without events ($p < 0.002$). There was a higher incidence of hypercarbia (peak expired $PECO_2 \geq 50$) in children who were not intubated (29 per cent) compared to those who had an endotracheal tube in place (12 per cent) ($p = 0.0001$). Hypocarbia (peak expired $PECO_2 \leq 30$) was more frequent in intubated cases (11 per cent) than in unintubated cases (three per cent) ($p = 0.03$). There was a high incidence of hypocarbia in infants less than one year of age ($p = 0.02$). We conclude: (1) life-threatening airway problems are common during anaesthesia in paediatric patients; (2) quantitative measurement of $PECO_2$ provides an early warning of potentially catastrophic anaesthetic mishaps; (3) the incidence of events increases with duration of anaesthesia.

Key words
ANAESTHESIA; paediatric; AIRWAY; obstruction; CARBON DIOXIDE MEASUREMENT; tension, expired; COMPLICATIONS; accidents; INTUBATION; tracheal, endobronchial, oesophageal.

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Anaesthetic mishaps due to airway problems or leaks and disconnections in the anaesthesia system often develop and become apparent only when a crisis occurs.[1–4] Modern anaesthetic circuits and multiple connections increase the opportunities for leaks and disconnections; the variable compliance of these systems also make accurate assessment of the adequacy of alveolar ventilation difficult.[5] We therefore undertook a prospective analysis using expired carbon dioxide measurements ($PECO_2$) from paediatric anaesthesia patients at the Massachusetts General Hospital (MGH) and the Shriners Burns Institute (SBI) to examine two issues: (1) the adequacy of alveolar ventilation at the time $PECO_2$ measurement was instituted, and (2) the incidence and type of intraoperative problems diagnosed primarily as a result of continuous $PECO_2$ monitoring during routine anaesthetic practice.

Methods

This study was approved by the Subcommittee on Human Studies at the Massachusetts General Hospital and verbal consent was obtained from the

parents. The anaesthetic technique, drugs, mode of ventilation, and choice of airway management (endotracheal intubation or mask) were left to the discretion of the anaesthetists managing the case. There was no attempt to alter anesthetic management, since the purpose of this study was to determine the adequacy of alveolar ventilation and the incidence of anaesthetic problems during routine clinical cases. All data were recorded by either the attending anaesthetist or an anaesthesia assistant. Any child who had significant pulmonary disease was eliminated from the study. Anaesthetic drugs, age, weight, surgical procedure, initial mode of ventilation (controlled, assisted (defined as a controlled breath between several spontaneous breaths), or spontaneous), type of airway management (mask or intubation), and duration of anaesthesia were recorded. All of the anaesthetists caring for patients were aware of the purpose of this study.

Part 1 of the study examined the adequacy of alveolar ventilation as regulated by clinical judgment alone. Expired carbon dioxide was measured by a capnograph (Hewlett-Packard 47210A or Datex CD 1022702 with strip chart recorder), and the P_ECO_2 recorded. A measurement obtained 15 to 20 min following induction was defined as the initial P_ECO_2. If the initial P_ECO_2 was satisfactory, i.e., no adjustment in ventilation was clinically indicated as judged by the attending anaesthetist and resident, the value was recorded and noted as such; if this initial P_ECO_2 was unsatisfactory, the value was recorded, and notations made as to changes made in the ventilatory pattern and the reasons for making the adjustments. There were no fixed criteria for satisfactory or unsatisfactory initial P_ECO_2 values because there was no attempt made to alter anaesthetic practice. For purposes of analysis hypercarbia is defined as peak expired $P_ECO_2 \geq 50$ torr and hypocarbia as ≤ 30 torr.

Part 2 of the study examined intraoperative events which were diagnosed primarily as a result of the capnograph data. Incidents which occurred were described, and the action taken recorded; whenever an arterial line was in place the P_ECO_2 (peak expired) was compared to $PaCO_2$.

Data were analyzed using Chi-square analysis, linear regression, and unpaired *t* tests for samples with unequal variances; results are expressed as mean ± SD and differences were considered significant if $p < 0.05$.

TABLE I Population characteristics (331 patients)

	Mean ± S.D.	*Range*
Age (yr)	7.6 ± 5.8	2 wk – 19 yr
Weight (kg)	29.0 ± 20.0	3 – 131
Anaesthesia time (hours)	2.7 ± 1.9	0.5 – 10.75

Results

Three hundred and thirty-one patients were studied; all children less than six months of age were intubated. The characteristics of this population are presented in Tables I and II. One hundred and sixty-six patients were studied at MGH and 165 at SBI; 90 were outpatients and 241 inpatients. The mean duration of anaesthesia was 2.7 hours (median 2.0).

Part 1

Seventy-five patients were managed by a face mask alone while 256 were intubated. Three patients managed by face mask were allowed to breathe spontaneously, ventilation was assisted in 49 and controlled in 23. Twenty-two of these mask cases (29 per cent) were initially hypercarbic vs. 31 of 256 intubated patients (12 per cent) ($p = 0.0001$). The frequency of intubation was unchanged from pre- and post-study values; thus the study itself did not appear to alter the choice of airway management.

Thirteen of the intubated patients were allowed to breathe spontaneously, 29 had ventilation assisted, 202 had ventilation controlled, and in 12 the mode of ventilation was not recorded. Twenty-eight of the intubated patients (11 per cent) were initially hypocarbic vs. two mask cases (three per cent) ($p =$

TABLE II Anaesthetic management (331 patients)

	Technique	
Mode of ventilation	*Intubated (256)*	*Not intubated (75)*
Spontaneous	13	3
Assisted	29	49
Controlled	202	23
Mode not recorded	12	0
Hypercarbia	31	22†
Hypocarbia	28*	2

*$p = 0.03$.
†$p = 0.0001$.

TABLE III Intraoperative events diagnosed by the capnograph

Event	*Number of cases*	*% of all cases*
Rising or falling P_ECO_2 secondary to temperature change	5	1.5
Malignant hyperthermia	1	0.3
Circuit leak or disconnection	8	2.4
Kinked endotracheal tube	4	1.2
Endobronchial intubation	4	1.2
Compliance change	4	1.2
Accidental extubation	1	0.3
Equipment failure	2	0.6
Hyper- or hypocarbia, etiology unspecified	6	1.8
Overall:	35	10.6

0.03). The mean initial peak expired P_ECO_2 value for all 54 hypercarbic patients (mask and intubated) was 54 ± 4.9 mmHg (range 50–70); eight were breathing spontaneously, 28 had assisted ventilation, and 18 controlled ventilation. The mean peak expired P_ECO_2 value for all 30 hypocarbic patients (mask and intubated) was 27 ± 3.2 mmHg (range 20–30); four had assisted ventilation while 26 had controlled ventilation.

Forty-three of the patients anaesthetized at MGH were infants less than one year of age while only three patients at SBI were less than one year of age; because of the skewed patient population who undergo surgery at SBI only the data from MGH patients were examined separately for age-related events. Eleven of the 43 infants were initially hypocarbic compared to 12/123 children greater than one year of age ($p = 0.02$). The incidence of hypocarbia for older children was not statistically different at the two institutions (seven per cent vs. ten per cent); the incidence of hypercarbia for infants was not different from older patients.

Part 2

Thirty-five intraoperative problems or trends were diagnosed in 33 of the 331 patients (ten per cent) and the incidence was similar in the two institutions (11 per cent vs. 10 per cent); the incidence in infants was the same as older patients. The majority of these problems were potentially life-threatening and included malignant hyperthermia, circuit malfunctions, kinked endotracheal tubes, endobronchial intubation, equipment failure, and accidental extubation (Table III). The accidental extubation and one case with a kinked endotracheal tube were diagnosed simultaneously with the stethoscope and the capnograph alarm; the case of malignant hyperthermia was not suspected on the basis of clinical signs and symptoms but presented with the sudden onset of hypercarbia.[6] No other event was diagnosed by observation or with the stethoscope. The Figure demonstrates normal and abnormal expired carbon dioxide curves. The incidence of these problems increased with duration of anaesthesia, 3.9 hours (mean) for cases with an event (median 3.5) vs. 2.5 hours (median 2.0) for cases without events ($p < 0.002$). The mean $PaCO_2$ was 38.2 ± 3.6 ($n = 104$) while the mean peak expired P_ECO_2 was 36.8 ± 5.8 ($r = 0.84$, $p = 0.001$); in most cases the peak expired P_ECO_2 was 1–3 torr less than the $PaCO_2$.

Discussion

End-expired carbon dioxide levels are a reasonably accurate reflection of $PaCO_2$ and alveolar ventilation in healthy patients.[7–10] Our study underscores the difficulty in determining appropriate ventilation parameters on a purely clinical basis in anaesthetized paediatric patients who vary greatly in age, weight, and medical condition. This study was prospective in nature with all participants involved aware that their actions were being recorded; this may have influenced the results by increasing the degree of vigilance and perhaps reducing the actual incidence of these events.

Several recent papers concerning anaesthetic mishaps have emphasized that the majority of life-threatening complications occur during elective surgery in healthy patients; most can be avoided.[11–13] In our study, a high incidence of intraoperative problems (one in ten) were initially diagnosed by the change in the expired carbon dioxide concentrations. It is interesting that the majority of these problems were not diagnosed with the aid of the stethoscope or through visual observations. The incidence of endotracheal tube-related complications in our study stresses the importance of meticulous attention to endotracheal tube taping, positioning, and length of insertion in children. The anaesthetic circuit-related problems encountered mandate a careful check of the entire breathing system prior to beginning anaesthesia and re-

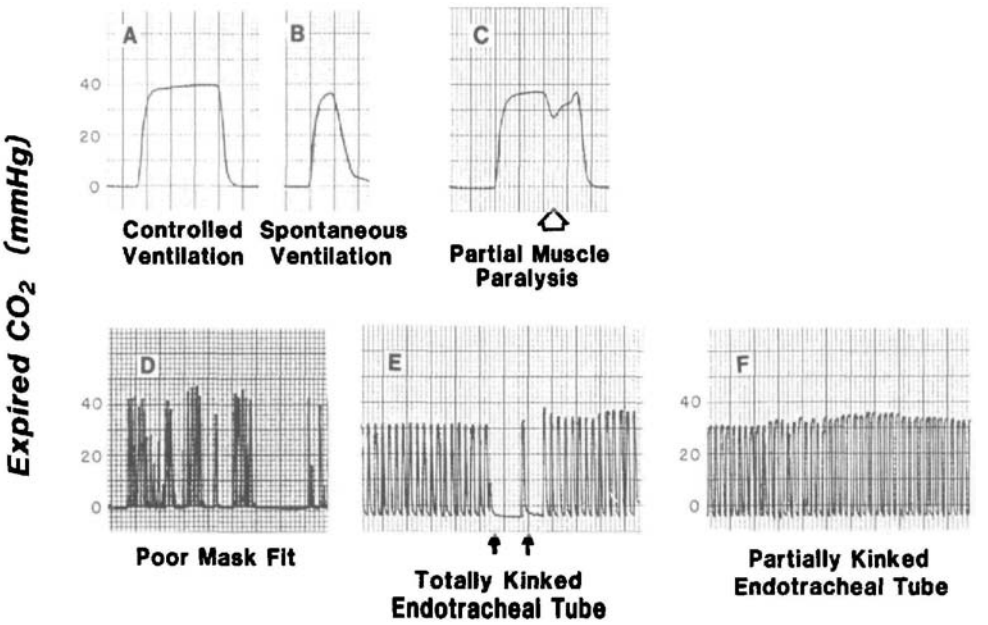

FIGURE Expired CO_2 tracings (A, B, C = rapid recording; D, E, F = trend recording).
A: Normal wave form with long plateau indicating good alveolar gas sampling during controlled ventilation (slow respiratory rate).
B: Spontaneous ventilation producing short plateau (rapid respiratory rate).
C: Patient with partial muscle paralysis: note CO_2 change due to inspiratory movement (arrow) during expiratory phase of ventilator.
D: Poor mask fit, demonstrated by only intermittent CO_2 detection.
E: Demonstrates a totally kinked endotracheal tube. Note that no CO_2 wave form (between arrows) is recorded. A similar trace would result from a circuit disconnect or oesophageal intubation.
F: Demonstrates a partially kinked endotracheal tube. Note the slow rising P_ECO_2 from baseline. A similar slow change from baseline could occur with a mucus plug, endobronchial intubation, change in compliance, circuit malfunction, or hyperthermia. The reverse would occur with air embolism, hypothermia, improved compliance, or change in ventilator settings.

checking again whenever a new piece of circuitry (e.g., humidifier) is added.

Recently Murray *et al.* used capnography in a dog model to examine the problems of extubation, oesophageal intubation, partial and complete endotracheal tube obstruction.[7] They found the capnograph to be very useful for those problems in which the flow of respiratory gas was completely interrupted, but less useful in detecting partial or intermittent obstruction, particularly if there was no wave tracings. They felt that peak carbon dioxide detectors were of less value. Our experience with children concurs with their laboratory study in may ways; however, measurement of peak expired carbon dioxide did help to diagnose many potentially life-threatening events such as kinked endotracheal tubes, endobronchial intubation, malignant hyperthermia, circuit disconnects or leaks and equipment failures. In addition, other problems, such as those related to changes in metabolism (e.g., fever or hypothermia), were also detected.

Once a steady-state has been reached, most clinically important ventilatory complications may be readily diagnosed with a peak carbon dioxide detector by setting narrow limits on the capnograph alarms. A strip chart recorder attached to the capnograph offers a greater advantage by documenting trends as well as problems which alter the shape of the expired CO_2 wave form. The capnograph supplies accurate and reliable information regarding carbon dioxide homeostasis and, when combined with a recorder, also provides additional

information regarding mask fit, muscle relaxation, compliance, metabolism, air emboli, and unobsered changes in fresh gas flow or circuit malfunction. Familiarity with the principles of capnography and the interpretation of capnograph tracings can provide information that far exceeds simple measurement of carbon dioxide.[14] The value of this non-invasive monitor lies in the immediate feedback of information which can lead to an early diagnosis of potentially life-threatening problems.

Currently many manufacturers are developing carbon dioxide sensors which do not quantitate the concentration of expired carbon dioxide but simply determine its presence or absence. Such devices would diagnose disconnections and oesophageal intubations, but would not diagnose the majority of life-threatening events and metabolic trends that are readily diagnosed with quantitative measurement of expired carbon dioxide concentrations.

In this study the children who were managed by face mask were more likely to be hypercarbic while intubated patients were more likely to become hypocarbic. These findings emphasize the importance of determining the adequacy of ventilation in children who are allowed to breathe spontaneously during anaesthesia, especially those managed by mask.[15] The high incidence of hypocarbia in infants, however, points out the ease with which overventilation is accomplished. In normal healthy patients this is not a clinically important problem; however, should the patient be hypotensive, extreme hyperventilation could have an adverse effect on cerebral blood flow.

In summary, we found that (1) life-threatening airway events are very common during the anaesthetic management of paediatric patients; (2) the constant quantitative measurement of expired carbon dioxide provides an early warning of potential catastrophic anaesthetic mishaps as well as metabolic trends; and (3) the incidence of critical events increases with the duration of anaesthesia.

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Résumé

L'étude du CO_2 en fin d'expiration ($PECO_2$) a été utilisée afin d'évaluer (1) la fonction respiratoire initiale et (2) pour documenter les événements per-opératoires touchant les voies aériennes ainsi que les changements métaboliques. 331 enfants ont été étudiés. 35 événements per-opératoires ont été diagnostiqués par une surveillance constante de la $PECO_2$; 20 représentaient des problèmes mettant en danger la vie (hyperthermie maligne, disconnection de circuit, fuite, bris d'équipement, extubation accidentelle, intubation endobronchique, ou tube endotrachéal coudé); seulement deux de ces événements ont été aussi diagnostiqués cliniquement. La durée de l'anesthésie pouvait aussi être un facteur: les présentants les accidents ont duré en moyenne 3.9 heurs contre 2.5 heures pour les cas n'ayant pas présenté de problèmes ($p < 0.002$). Il y avait un incidence plus élevée d'hypercarbie ($PECO_2 \geqslant 50$) chez les enfants qui n'étaient pas intubés (29 pour cent) a comparé à ceux dont le tube endotrachéal était en place (12 pour cent) ($p = 0.0001$). L'hypocarbie ($PECO_2 \leqslant 30$) était plus fréquente chez les patients intubés (11 pour cent) que chez ceux qui n'étaient pas intubés (trois pour cent) ($p = 0.03$). Il y avait une incidence plus grande d'hypocarbie chez les enfants âgés de moins qu'un an ($p = 0.02$). On colclut: 1) les problèmes de voies aériennes pouvant mettre en danger la vie sont fréquents lors de l'anesthésie pédiatrique; 2) la mesure quantitative de la $PECO_2$ fournie un signal d'alarme précoce pour les accidents anesthésiques potentiellement catastrophiques; 3) l'incidence des accidents augmente avec le temps.