

Work of Breathing During Spontaneous Ventilation in Anesthetized Children: A Comparative Study Among the Face Mask, Laryngeal Mask Airway and Endotracheal Tube

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Work of breathing (WOB) increases during general anesthesia in adults, but such information has been limited in pediatric patients. We studied WOB in 24 healthy children (mean age 2 ± 1.9 yrs), during elective urogenital surgery under 1 minimum alveolar anesthetic concentration halothane-nitrous oxide anesthesia with a caudal block while breathing spontaneously. WOB was measured with an esophageal balloon, miniature flowmeter, and a computerized (Bicore) system. In each patient, WOB was computed under four conditions: a mask without oral airway (-AW), a mask with oral airway (+AW), a laryngeal mask airway (LMA), and an endotracheal tube (ETT). With each apparatus WOB was studied both with continuous positive airway pressure (CPAP) (5–6 cm H₂O) and without CPAP (or zero end-expiratory pressure [ZEEP]). Under ZEEP, WOB (g · cm/kg) among the four apparatus were (mean \pm SEM): mask (-AW)

(64 ± 19.2) > mask (+AW) (44 ± 17.2), LMA (42 ± 15.6) > ETT (25.4 ± 12.4) ($P < 0.05$). WOB with CPAP significantly ($P < 0.05$) decreased from WOB with ZEEP in three groups (mask [-AW], mask [+AW], and LMA), but not in the ETT group. Tidal volume (both ZEEP and CPAP) and end-tidal Pco₂ (with CPAP only) were significantly ($P < 0.05$) decreased only in the ETT group, whereas no significant difference was found in respiratory rate or minute volume among the four airway apparatus groups, either with or without CPAP. The reduction in WOB, when breathing through ETT was primarily attributable to decreases in tidal volume and volume work. The finding that WOB decreases with CPAP in all groups except for the ETT group suggests that the decrease is a result of improved patency of the upper airway rather than of increases in functional residual capacity and lung compliance.

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Brief pediatric surgical procedures not involving the thorax or abdomen are often performed while the patients are breathing spontaneously, particularly with the widespread use of the laryngeal mask airway (LMA). It is therefore clinically relevant to know how anesthesia and resistance added by anesthetic airway apparatuses affect the work of breathing (WOB) in infants and children. WOB is increased in spontaneously breathing adult patients during general anesthesia. This information in children, however, is limited. General anesthesia results in increased physiologic WOB, probably because of partial upper airway obstruction, increased tissue viscoelastic resistance (resistive work), and reduced functional residual capacity (FRC) with resultant decreases in lung and

thoracic compliance (elastic work), airway caliber or their combinations (1–4). The anesthetic breathing circuit including valves, connectors, and the airway apparatus itself (e.g., an endotracheal tube [ETT], LMA or a face mask with or without oral airway) adds additional resistive work (imposed WOB) (5). An excessive increase in WOB would increase respiratory muscle loading and oxygen consumption, and potentially predispose the patient to respiratory muscle fatigue and failure (2,5). Some studies have suggested that LMA reduces WOB compared with ETT (6–8). We evaluated the efficacy of LMA in reducing WOB as compared with the standard ETT and face mask (with versus without oral airway) and with versus without added “physiologic” continuous positive airway pressure (CPAP) on spontaneously breathing pediatric patients during general anesthesia. We hypothesized that anesthesia causes partial upper airway obstruction resulting from pharyngeal muscle relaxation and results in increased WOB and that LMA decreases

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WOB, as compared with a mask without oral airway, by minimizing upper airway obstruction. We further hypothesized that an addition of low CPAP improves upper airway patency thereby decreasing WOB.

Methods

Twenty-four children with a mean age of 2 ± 1.9 yr (median 1.0 yr; range, 8 mo to 6 yr), ASA physical status 1, using general anesthesia for elective urogenital surgery (not involving the upper abdomen or thorax) were included in this study. The study was approved by our IRB. Parental informed consent was obtained for all patients.

All patients were anesthetized with a nitrous oxide (N_2O) - oxygen (O_2) mixture by mask and incremental concentrations of halothane using a Mapelson D (Bain) circuit. Once an adequate level of anesthesia was achieved, patients were turned to a left lateral decubitus position and caudal analgesia with 0.2% bupivacaine (1 mL/kg) was administered with a single shot technique (9) using a short bevel 22-gauge needle. Patients were then turned supine, a direct laryngoscopy was performed, and the vocal cords and upper trachea were sprayed with approximately 0.1 mL/kg (1 mg/kg) of 1% lidocaine to prevent airway responses to LMA and ETT. A surgical incision was then made. The anesthetic technique consisted of a fresh gas flow of N_2O 4 L/min and O_2 2 L/min with 1 minimum alveolar anesthetic concentration (MAC) end-tidal concentration of halothane as adjusted with a gas monitor (Capnomac Ultima; Datex, Helsinki, Finland). The size of LMA and ETT were chosen according to the weight and age of each child (10). The inspired concentration of halothane was briefly increased to permit the insertion of LMA or ETT.

Airway pressure and flow were measured with a miniature flow transducer (volume, 0.8 mL) at the proximal end of the airway apparatus and a computerized system (CP-100 Neonatal Pulmonary Monitor; Bicore Monitoring Systems, Irvine, CA). Inspiratory tidal volumes (V_T , mL/kg) were obtained by integrating the inspiratory gas flow signals. Inspiratory time, expiratory time, total respiratory cycle duration, and respiratory rate were also measured.

Esophageal pressure (P_{es}) changes were measured using thin-walled infant esophageal balloons (5 cm in length) that were provided by the Bicore system. An esophageal balloon was inserted after the induction of general anesthesia; the appropriate position of the balloon in the esophagus and the accurate transmission of P_{es} were determined by the occlusion test as previously described (11). Briefly, after the insertion of an esophageal balloon, the airway opening was briefly occluded while the patient made an inspiratory effort.

The positioning of the esophageal balloon was considered adequate if the maximal change in P_{es} was more than 80% of the maximal change in airway opening pressure (P_{ao}). Changes in P_{es} during the inspiratory phase of the tidal breathing (ΔP_{es}) were determined by subtracting baseline P_{es} from inspiratory P_{es} .

Inspiratory pulmonary WOB ($g \cdot cm/kg$) was calculated by computer integration of the area under the curve ($\Delta V_T \cdot \Delta P_{es}$) during inspiration (12). The calibration of the flow signals was adjusted for the use of N_2O and halothane instead of air as the inspired gas. Measurements of WOB were made after the surgical incision of the skin once a steady state was established for 10 min, and were averaged from ten consecutive uninterrupted breaths. The sequence of WOB measurements with various respiratory apparatuses was as follows: 1) mask without oral airway, 2) mask with oral airway, 3) LMA, 4) ETT, and 5) whenever possible with the duration of surgery, mask without oral airway (a repeat of Step 1). With each airway apparatus, WOB measurements were repeated without CPAP (zero end-expiratory pressure [ZEEP]) and with CPAP (5–6 cm H_2O), with the sequence of ZEEP and CPAP chosen randomly. Each measurement with ZEEP or CPAP was repeated at least twice. The results were averaged.

After the insertion of an appropriately sized LMA and the confirmation of its appropriate positioning (10), a flexible bronchoscope (LF-2, 3.4 mm outer diameter; Olympus, Tokyo) was inserted through the LMA whenever it was available to assess the adequacy of its positioning relative to supraglottic airway patency. The percentage of glottis blocked from view by the epiglottis was evaluated by at least two of the investigators and the results (% visibility of the glottis) were averaged.

$PETCO_2$ was measured with a gas monitor (Capnomac Ultima; Datex) by allowing complete rebreathing through the circuit while the fresh gas flow was temporarily turned off. A 5F catheter, whose distal opening was placed near the tip of the LMA, ETT, or oral airway, was connected to the capnograph for continuous gas sampling. The end-tidal P_{CO_2} reading after the fifth breath of rebreathing was marked as $PETCO_2$. Heart rate, blood pressure, axillary skin temperature, and oxygen saturation with pulse oximetry (SpO_2) were measured as part of routine anesthetic management during the measurement of WOB.

For statistical analysis, we used analysis of variance for repeated measures, and the Student-Newman-Keuls test and two-tailed paired *t*-tests. For the evaluation of WOB in relation to the degree of upper airway obliteration, a least square linear regression analysis was used. A *P* value of <0.05 was considered statistically significant. Values were expressed as mean \pm SEM.

Results

Blood pressures and heart rates were stable throughout the study. Axillary temperatures stayed within the clinically acceptable range (35.8–37.0°C) in all patients studied and were stable with each patient throughout the procedure.

The measurement of WOB with ETT was not always possible because of the time limit imposed by the duration of surgical procedures. Of the 24 patients in the present study, WOB with ETT was completed in 16. The final measurement of WOB with face mask after ETT was made in nine (see below).

The inspiratory WOB (mean \pm SEM) for the different airway apparatuses is presented in Fig 1. Inspiratory WOB was significantly increased ($P < 0.05$) during spontaneous face mask breathing without airway (63.4 \pm 3.93 g \cdot cm/kg) than with either a face mask with airway (44.2 \pm 2.34 g \cdot cm/kg) or LMA (41.3 \pm 2.26 g \cdot cm/kg). The use of ETT was associated with the least inspiratory WOB (23.8 \pm 1.76 g \cdot cm/kg), which was significantly ($P < 0.05$) less than the other three groups (Table 1).

Figure 2 compares the mean (\pm SEM) inspiratory WOB among the four respiratory apparatuses; namely, mask without oral airway, mask with oral airway, LMA, and ETT with CPAP (5–6 cm H₂O). An addition of CPAP was associated with a significant reduction in WOB from those with ZEEP during spontaneous breathing with a mask, both without and with oral airway (63.4 \pm 3.93 vs 45.2 \pm 3.49 and 44.2 \pm 2.34 vs 35.5 \pm 2.06 g \cdot cm/kg, respectively, $P < 0.05$) (Fig. 3). An addition of CPAP to breathing with LMA also reduced WOB significantly as compared with that with LMA with ZEEP (41.3 \pm 2.26 vs 31.0 \pm 1.54 g \cdot cm/kg, $P < 0.05$). With CPAP there was no statistically significant difference among WOB with LMA versus WOB with a mask without and with oral airway. In contrast, when breathing through ETT, there was no statistically significant difference in WOB with ZEEP versus CPAP (23.8 \pm 1.76 vs 21.1 \pm 1.60 g \cdot cm/kg). WOB through ETT remained significantly less ($P < 0.05$) than other groups (Fig. 3) (Table 1).

In the subgroup of nine patients in whom the measurement of WOB with a face mask without oral airway was repeated after ETT was removed, the mean inspiratory WOB (mean \pm SEM) measurements of this subgroup were as follows: 50.2 \pm 5.06 (first) and 46.3 \pm 4.59 g \cdot cm/kg (last) with ZEEP and 36.0 \pm 3.97 (first) and 33.9 \pm 3.28 g \cdot cm/kg (last) with CPAP. There was no statistical difference in the first and last measurements of WOB with mask without oral airway with ZEEP as well as with CPAP.

There were no time-related changes in respiratory indices between the first and last study periods when the patients were breathing through a mask (with or without an airway). The average value of the two

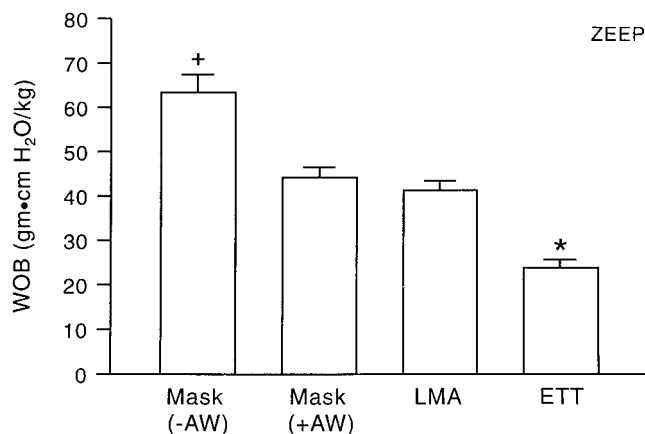


Figure 1. A comparison of inspiratory work of breathing (WOB) [mean \pm SEM (bar)] using four airway apparatuses: *viz.* face mask without oral airway [mask (-AW)], face mask with oral airway [mask (+AW)], laryngeal mask airway (LMA), and endotracheal tube (ETT). Continuous positive airway pressure was not applied (ZEEP). * $P < 0.05$ as compared with other groups; + $P < 0.05$ as compared with the mask (+AW) and LMA groups.

study periods in each patient was therefore used for statistical comparison with the study periods using ETT (Table 2).

No statistically significant difference was found in inspiratory V_T among patients breathing through a mask without an airway, a mask with an airway, and LMA with ZEEP or CPAP. In contrast, the inspiratory V_T while breathing through ETT was significantly smaller ($P < 0.05$) than those of the other three groups, both without and with CPAP. Within the same airway apparatus groups, there was no significant difference in V_T with ZEEP versus CPAP, except for the ETT group in which V_T with CPAP was diminished further than V_T with ZEEP ($P < 0.001$). There was no significant difference in respiratory rate in all four airway apparatus groups either with ZEEP or CPAP. There was no significant difference in inspiratory minute volume among the four breathing apparatus groups, although the mean inspiratory minute volume was the smallest in the ETT group. In the ETT group, there was a trend of decreased inspiratory minute volume with CPAP ($P < 0.1$). There was no statistically significant difference in P_{ETCO₂} among all respiratory apparatus groups when the patients were breathing without CPAP (*i.e.*, ZEEP). When breathing through ETT with CPAP, P_{ETCO₂} was significantly more than those in mask groups ($P < 0.05$).

In 12 of the 24 patients, we evaluated the degree of supraglottic obstruction by pharyngeal soft tissue as viewed from a fiberoptic bronchoscope inserted through LMA. In 10 of these 12 patients, there were various degrees of glottis view obliteration by the epiglottis, including total obliteration in one, whereas in the remaining two patients the glottic view was unobstructed. A regression analysis showed a linear correlation between the percentage of supraglottic

Table 1. Comparison of Inspiratory Work of Breathing with Four Airway Apparatuses with Continuous Positive Airway Pressure (CPAP) (5–6 cm H₂O) and ZEEP (no CPAP)

Pressure	Mask (-AW)	Mask (+AW)	LMA	ETT
ZEEP	63.4 ± 3.93*	44.2 ± 2.34	41.3 ± 2.26	23.8 ± 1.76*
CPAP	45.2 ± 3.49†	35.5 ± 2.06†	31.0 ± 1.54†	21.1 ± 1.60*

Mask (-AW) = face mask without oral airway, Mask (+AW) = face mask with oral airway, LMA = laryngeal mask airway, ETT = endotracheal tube.
* $P < 0.05$ as compared with other airway groups.
† $P < 0.05$ as compared with ZEEP.

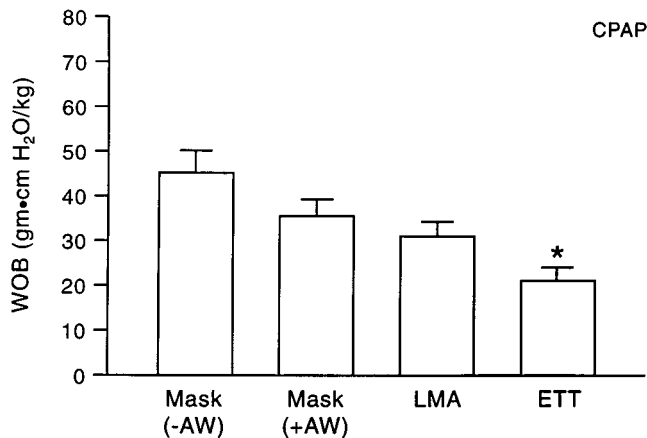


Figure 2. A comparison of inspiratory work of breathing (WOB) [mean ± SEM (bar)] with continuous positive airway pressure (CPAP) (5–6 cm H₂O) using four airway apparatuses: *viz.* face mask without oral airway [mask (-AW)], face mask with oral airway [mask (+AW)], laryngeal mask airway (LMA) and endotracheal tube (ETT). * $P < 0.05$ as compared with other groups.

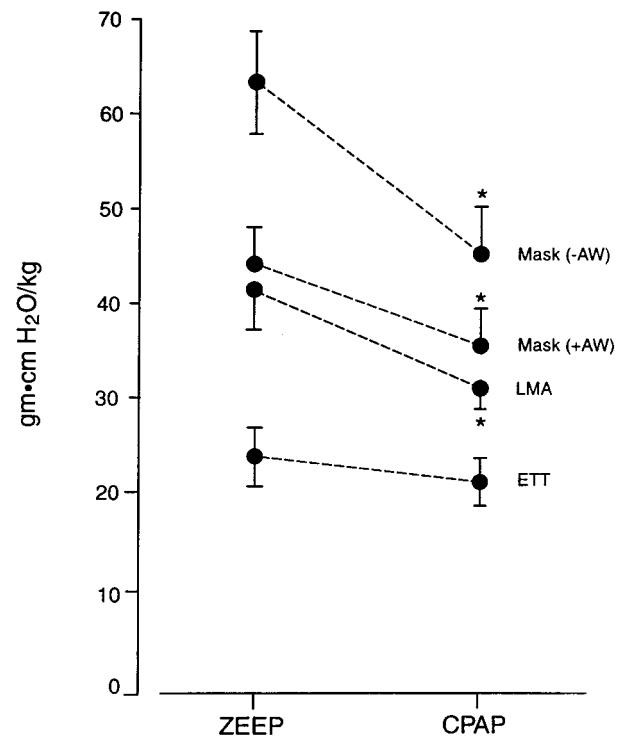


Figure 3. A comparison of inspiratory work of breathing (WOB) [mean ± SEM (bar)] without continuous positive airway pressure (ZEEP) versus with continuous positive airway pressure (CPAP) (5–6 cm H₂O) using four airway apparatuses *viz.* face mask without oral airway [mask (-AW)], face mask with oral airway [mask (+AW)], laryngeal mask airway (LMA), and endotracheal tube (ETT). ZEEP and CPAP values in each airway apparatus group are connected with a dashed line. ● $P < 0.05$ compared with ZEEP.

obliteration and WOB ($r^2 = 0.62$, $P < 0.01$ without CPAP and $r^2 = 0.47$, $P = 0.02$ with CPAP) (Figure 4).

Discussion

WOB by the respiratory muscles to expand the lung tissue during spontaneous inspiration (pulmonary work of breathing) is usually determined from a pressure-volume curve expressing the relationship between the transpulmonary pressure, as derived from an esophageal balloon pressure in relation to atmospheric pressure, and corresponding changes in V_T during a tidal inspiration (13). The respiratory work to the lung by a spontaneously breathing patient through an airway apparatus includes the work required to overcome the elastic recoil pressure of the lung during inspiration (elastic work) and the work required to overcome flow resistance of the airways and viscoelastic resistance of pulmonary tissues (resistive work) (12,13). The imposed work (work performed by the patient to breathe spontaneously through an airway apparatus) is an additional flow-resistive workload (5–7). Expiration is normally produced passively by the energy stored during inspiration in the lung and thoracic tissues (elastic recoil); expiratory work of

breathing was not measured in the present study. The WOB is defined as pressure (force) × volume (distance) and is expressed in joules or g · cm (= 0.0000981 joule/L) (14).

Cook et al. (15) measured the mechanics of respiration in healthy newborn infants. WOB per breath ranged between 20 and 139 g · cm. (3.7–58.7 g · cm/kg, $n = 24$). Thibeault et al. (16) measured WOB, O₂ cost of breathing and mechanical efficiency in nondistressed term and preterm infants. WOB values ranged from 1045 g · cm · min⁻¹ to 14000 g · cm · min⁻¹ (17–190 g · cm/kg, $n = 7$). Zapletal et al. (13) reported WOB in healthy children and adolescents (6–18 yr, $n = 67$). There was a linear negative correlation between the height and WOB; it ranged between 0.6 and

Table 2. Comparison of Respiratory Indices with the Different Airway Apparatus with ZEEP (no CPAP) and with CPAP (5–6 cm H₂O)

	Mask (-AW)		Mask (+AW)		LMA		ETT	
	ZEEP	CPAP	ZEEP	CPAP	ZEEP	CPAP	ZEEP	CPAP
V _T (mL/kg)	7.2 ± .47	6.6 ± .23	6.7 ± .34	6.5 ± .32	6.1 ± .32	5.4 ± .28	4.9 ± .15*	3.0 ± .17*
Rate (/min)	40 ± 1.5	40 ± 2.8	43 ± 1.7	45 ± 3.6	44 ± 2.3	45 ± 2.3	46 ± 1.7	48 ± 1.1
Ṁ _I (mL/kg/m)	293 ± 26.3	287 ± 13.1	277 ± 14.5	282 ± 37.8	268 ± 15.6	236 ± 14.4	233 ± 14.1	214 ± 13.9
P _{ETCO₂} (mm Hg)	43 ± 1.9	42 ± 1.2	42 ± 1.0	43 ± 0.7	45 ± 1.6	49 ± 1.3	40 ± 1.6	51 ± 1.2†

Mask (-AW) = face mask without oral airway, Mask (+AW) = face mask with oral airway, LMA = laryngeal mask airway, ETT = endotracheal tube, CPAP = continuous positive airway pressure; ZEEP = zero end-expiratory pressure (no CPAP), V_T = tidal volume, Ṁ_I = inspiratory minute volume, P_{ETCO₂} = end-tidal P_{CO₂}.

* P < 0.05 as compared with other airway apparatus groups.

† P < 0.05 as compared with the mask groups.

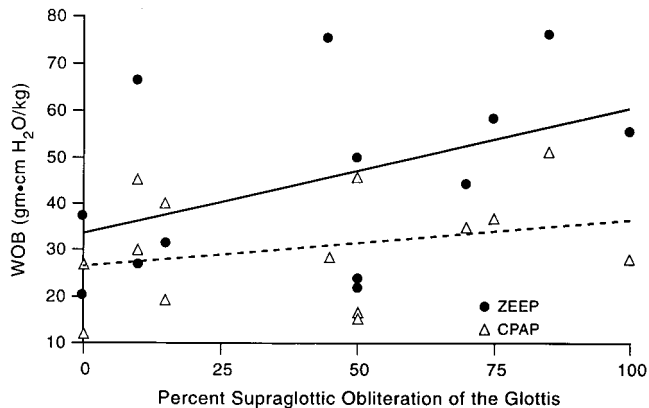


Figure 4. Work of breathing in 12 of 24 subjects in relation to the degree (per cent) of supraglottic obliteration of the epiglottis as seen by means of a flexible bronchoscope. The regression line for the without continuous positive airway pressure (ZEEP) (dots and a solid line) and with continuous positive airway pressure (CPAP) (open triangles and a broken line) conditions are shown (see text).

0.1 joules/L, which translate roughly to the range between 200 (youngest) and 15 g · cm/kg (oldest). Thus, the range of WOB in the current study is within the values reported in healthy sleeping infants and awake children. In adults, the accepted clinical range is 0.3–0.6 joules/L (14).

An increase in respiratory muscle loading secondary to an increase in physiologic and/or imposed WOB results in increased force and duration of diaphragmatic contraction, increased oxygen consumption and respiratory muscle fatigue (17). Freedman and Campbell (18) found that, during anesthesia, respiratory compensation for added inspiratory loading is diminished, whereas Nunn and Ezi-Ashi (19) and Moote et al. (20) reported that compensation for added inspiratory and expiratory loading was rapid and complete even during anesthesia.

Insertion of an oral airway during spontaneous mask breathing in the present study reduced inspiratory WOB significantly from that without an airway. This reduction is consistent with previous reports on the effect of an oral airway on relieving upper airway

obstruction (10). General anesthesia preferentially depresses the genioglossus muscle and other pharyngeal dilators (21–23). Studies in anesthetized cats show that the depression of the genioglossus muscle is more prominent in kittens than in adult cats (21,24). Clinically, anesthetic effect on upper airway muscles may be more prominent in infants and young children because upper airway obstruction seems to occur more frequently and severely in this age group (25).

Reignier et al. (8) have compared two groups of children breathing spontaneously during halothane anesthesia with LMA versus ETT. They suggested that the use of LMA was associated with a lesser degree of inspiratory rib cage distortion and larger V_T and minute ventilation than with ETT. When appropriately placed, LMA appears almost ideal for relieving upper airway obstruction to prevent pharyngeal soft tissue collapse. Previous studies, however, have shown that malpositioning of LMA is common in children, even when the placement is clinically appropriate and its function may appear satisfactory (26). Malposition of LMA, however, is not always easily detectable from clinical observations and may require fiberoptic bronchoscopy for confirmation (27). Our findings demonstrated that, even when LMA appeared to be appropriately placed and functioning well clinically, there existed varying degrees of obliteration of supraglottic patency. The magnitude of obstruction correlated significantly with increases in WOB. The addition of CPAP significantly reduced WOB, probably because of “stenting” of the pharyngeal soft tissue, preventing the tissue from being sucked together by negative intraluminal pressure.

Under general anesthesia, FRC is decreased (1,3,4). This effect is more prominent in young children because of the lower outward elastic recoil of the chest wall as compared with the inward recoil of the lungs (25). An addition of CPAP, therefore, would restore FRC toward normal levels and would improve lung compliance (28), thereby reducing the elastic work of breathing. In infants and children <6 yr of age using general anesthesia, a positive end-expiratory pressure

of 5 cm H₂O was found to be sufficient to restore FRC to the mid position of the pressure-volume curve of the respiratory system and prevent atelectasis (29,30). In the present study, this level of low CPAP was applied to see the possible effect of FRC on WOB. In addition to increases in overall intrathoracic airway caliber with increased FRC, the application of CPAP would also decrease WOB by stenting the pharyngeal airway from collapse by inspiratory negative pressure (25). In the present study, an addition of CPAP significantly reduced WOB when breathing through a face mask with and without oral airway and with LMA. In contrast, the addition of CPAP did not significantly change WOB with ETT.

These findings imply that the beneficial effects of CPAP on WOB are primarily related to the prevention of upper airway collapse and the reduction of upper airway resistance, rather than an increase in FRC toward normal levels with resultant increases in compliance of the respiratory system and a decrease in elastic work. It was a surprise to see such a drastic decrease in WOB with a relatively low level of CPAP because clinically, a higher level of CPAP (10–20 cm H₂O) is often necessary to improve the upper airway patency during inhaled induction of general anesthesia with a face mask. In the present study a higher level of CPAP was not tried, to avoid possible interference with venous return and resultant hemodynamic instability.

ETT with a relatively smaller diameter increases flow resistance and the resistive WOB while preventing upper airway obstruction. Slee et al. (31) demonstrated a statistically significant increase in WOB associated with the use of a small ETT in adults breathing spontaneously using halothane anesthesia, although V_T was maintained by associated increases in inspiratory time. Bhatt et al. (6) compared the resistance and imposed WOB of both LMA and ETT and found that LMA exerted much less resistance. More recently, Faberowski and Banner (32) compared the imposed inspiratory WOB between LMA (sizes 1.0, 2.0, 2.5) and ETT (3.0, 4.5, 5.0 mm inner diameter), compatible for clinical use in children, using the same computerized infant respiratory monitoring system as in the present study. They reported a marked difference in imposed WOB between LMA and ETT, especially with increasing flow. These studies were performed using a simulator and faulty positioning of LMA in the larynx and the resultant effect on WOB was not addressed. It is interesting to note that the imposed WOB could be a substantial fraction of the total WOB when breathing through ETT.

In the current study, ETT contributed the least to inspiratory WOB. This paradoxical finding was associated with a significant decrease in V_T, especially with CPAP, as compared with both mask groups and

the LMA group. PETCO₂ with ETT was indeed significantly increased, reflecting the reductions in V_T and minute volume, although the latter did not reach statistical significance. Significant increases in PETCO₂ were also observed when CPAP was applied. It is not clear why an addition of CPAP was associated with a decrease in ventilation only when breathing through ETT. In the awake state, added resistive and/or elastic load is compensated by increased neuronal inspiratory drive. Under general anesthesia, however, a compensatory increase in respiratory drive may be depressed or incomplete as previously discussed (18). One possible explanation may be that an added elastic load against breathing by CPAP while breathing with a face mask or LMA was compensated by improved upper airway patency with decreased resistive load; whereas with ETT, there was no change in resistive load with CPAP. CPAP may also decrease inspiratory drive by the Herring-Breuer inflation reflex, although this effect should apply to breathing with all other airway apparatuses (25).

The present study was performed after placement of a caudal block that could possibly have interfered with intercostal muscle function. This study was also performed during surgical procedures that might have affected ventilatory response and effort to an unknown degree. We decreased the concentration of local anesthetics that would decrease the potential effect on thoracic motor function, but would still provide sufficient sensory block to prevent a response to pain. The possible effect of these clinical factors on the WOB, however, should have been minimal because all patients acted as their own controls for the comparison of different airway apparatuses.

In the present study, efforts were made to minimize the possible effects of anesthesia, surgery and changes in respiratory apparatus on the measurement of WOB within the same subject. The initial measurement of WOB was not initiated until the caudal block had been effective, the steady state of anesthetic concentration had been established, and surgical incision had been made without hemodynamic responses. Shortly after the induction of anesthesia, topical anesthesia was used to the pharynx and larynx to minimize airway responses to the insertion and removal of LMA and ETT. In addition, before the insertion of LMA and ETT, the halothane concentration was briefly increased and a steady state of 1. MAC halothane was then reestablished before the subsequent WOB measurement.

Ideally, the order of use of various respiratory apparatuses should have been randomized to avoid the possible effect of time on the measurement of WOB. Clinically however, such randomization was neither practical nor justifiable. Of 16 patients in whom the duration of surgery was long enough to study WOB with ETT, measurements of WOB with a face mask

without oral airway were repeated before the conclusion of surgery and anesthesia, to see the possible effect of time on WOB. The values were amazingly consistent between the two sets of WOB values, which were at least 30 min apart before and after repeated measurements of WOB under LMA and ETT. This finding indicates that the time effect on the comparison of WOB with different airway apparatuses was minimal.

It is difficult to assess the effects of increased WOB over a prolonged period of time on increased O₂ consumption, respiratory muscle fatigue, and respiratory failure in infants and children. No changes with time in PETCO₂, oxygenation, or respiratory rate were noted during this study. The relatively short duration of the study period and the fact that all of the patients were healthy (ASA physical status I) precludes us from testing the long-term effects of increased WOB or speculating about the effects on patients with cardiorespiratory disease.

In conclusion, inspiratory WOB using general anesthesia in spontaneously breathing children was markedly increased with a face mask without oral airway. This increase in WOB was apparently a result of narrowing of the pharyngeal airway, even though breathing appeared clinically acceptable with minimal or no apparent upper airway obstruction. The insertion of an oral airway significantly decreased WOB by improving the patency of the upper airway to the level of WOB with LMA. An addition of relatively low CPAP (5–6 cm H₂O) significantly decreased WOB with all three airway apparatuses, i.e., a face mask without or with oral airway and with LMA. This decrease in WOB was apparently a result of further improvements of upper airway patency, probably because of stenting of the pharyngeal airway against collapse by inspiratory negative pressure. This decrease in WOB with CPAP was not a result of an increase in FRC and resultant decrease in elastic work of breathing because WOB with ETT did not decrease with CPAP. Unexpectedly, measured WOB with ETT was significantly lower than WOB with other airway apparatuses, despite ETT's higher resistive load; the reduction in WOB was because of a decrease in tidal volume and resultant decrease in elastic WOB. Based on these findings, it is advisable that a low level of CPAP be added when children are breathing spontaneously under general anesthesia with a face mask or LMA. The insertion of an oral (or nasal) airway is recommended even when there are no apparent clinical signs of upper airway obstruction. Finally, when a patient is intubated for prolonged periods, ventilation should be assisted or controlled to avoid excess WOB and hypercapnia.

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