Laryngeal Resistance before and after Minor Surgery

Endotracheal Tube versus Laryngeal Mask Airway™

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Background: The placement of an endotracheal tube (ETT) may promote laryngeal swelling, which is an important cause of upper airway obstruction after extubation. The authors hypothesized that laryngeal swelling after ETT placement increases laryngeal resistance and tested that hypothesis by comparing postoperative laryngeal patency between patients with ETT placement and those with a Laryngeal Mask Airway™ (LMA™).

Methods: Fourteen adult patients who underwent elective minor surgeries were randomly allocated to two groups whose airway would be managed through ETTs (the ETT group) or LMA™ (the LMA™ group) during the surgery. While maintaining at sevoflurane 1 minimum alveolar concentration, the authors measured laryngeal resistance before and after surgery, during both spontaneous breathing and mechanical ventilation under complete paralysis. In addition, they endoscopically measured the vocal cord angle under complete paralysis.

Results: In association with marked swelling of the vocal cords, the vocal cord angle significantly decreased after surgery in the ETT group, whereas the angle did not change in the LMA group. Laryngeal resistance during mechanical ventilation significantly increased only in the ETT group. Laryngeal resistance during spontaneous breathing significantly increased after surgeries in both groups.

Conclusions: Postoperative laryngeal resistance increases at least in part because of laryngeal swelling in patients with ETT placement, whereas alteration of laryngeal neural control mechanisms has been also indicated. The use of the LMA™ has an advantage over ETT placement in order to avoid postoperative laryngeal swelling.

THE placement of an endotracheal tube (ETT) is a significant development in modern medicine, assuring positive pressure ventilation in a variety of clinical situations while separating airway and esophagus. Regardless of its usefulness, after removal of the ETT, respiratory complications sometimes occur,¹ as is evidenced by the study reported by Asai et al.,² who demonstrated that the incidence of respiratory complications was significantly higher after tracheal extubation than during induction of anesthesia. Although they did not clarify the nature of the respiratory complications, dysfunction of the upper airway, particularly the larynx, was considered to be responsible for these respiratory events.

Laryngeal edema is an important cause of upper airway obstruction after tracheal extubation, especially in children³,¹ and after prolonged intubations.⁴–⁵ While reports of several studies indicated that laryngeal edema after extubation occurred in 2–22% of patients,⁴–⁵ laryngeal resistance was not directly measured in any of these studies. Recently, we reported that laryngeal resistance after tracheal extubation was higher than it was before intubation.⁶ In that study, however, mechanisms of increased laryngeal resistance were not elucidated in detail, and we failed to provide evidence that laryngeal edema caused by the ETT placement contributes to the increased laryngeal resistance. In the present study, we compared laryngeal resistance before and after surgery in patients with either an ETT or a Laryngeal Mask Airway™ (LMA™) (LMA-Classic™; Laryngeal Mask Company, Nicosia, Cyprus) in place during surgeries, because we reasoned that the LMA placement would be less traumatic to the larynx, compared with the ETT placement. Furthermore, the measurements of the laryngeal resistance were performed during both spontaneous breathing and mechanical ventilation under complete paralysis with neuromuscular blocking agents. Comparison between the nonparalyzed and paralyzed conditions was designed to evaluate the contributions of neural regulation of the laryngeal aperture and of the anatomical properties of the larynx to the changes in laryngeal resistance.

Materials and Methods

Patients

After obtaining the approval from the Ethics Committee of Chiba University Hospital, we obtained informed consent from 14 patients (American Society of Anesthesiologist physical status I-II). All were to undergo general anesthesia for elective minor surgeries, such as partial mastectomy or minor urological or ENT procedures. None had clinical evidence of respiratory, cardiovascular, or neuromuscular disorders. Each patient was allocated randomly by means of sealed envelopes to one of...
two groups (the ETT or the \textit{LMA} group) comprised of seven subjects each and was then placed with either an ETT or an LMA.

\textbf{Patient Preparation}

The experimental protocol is schematically shown in figure 1. All patients were premedicated with atropine 0.5 mg and midazolam 3 or 4 mg given intramuscularly 30 min before induction of anesthesia. Anesthesia was induced with inhalation of sevoflurane by the single-breath technique. After administration of succinylcholine (1 mg/kg), we inserted a polyethylene catheter into the trachea to reach 5 cm below the vocal cords for the measurement of subglottic pressure (P$_sg$), which was followed by the placement of an \textit{LMA} (size 3 or 4) for respiratory measurements (LMA-RM). Depth of the catheter was determined by the reference markers on the catheter. We confirmed the appropriate positioning of the LMA-RM with a fiberoptic endoscope (FB15H or FB10H; Pentax, Tokyo, Japan). We corrected the position of the LMA-RM so that both vocal cords were visualized in the fiberoptic image. Absence of leaks was verified by application of positive pressure. Anesthesia was maintained with sevoflurane in oxygen. End-tidal sevoflurane concentration was monitored with a respiratory gas analyzer (AS/3; Datex, Helsinki, Finland) and kept constant (sevoflurane, 1.7\%, 1.0 minimum alveolar anesthetic concentration). Airflow (V) was measured by a pneumotachograph, connected to a differential pressure transducer (TP-602T; Nihon Koden, Tokyo, Japan). End-tidal carbon dioxide tension was measured using a side-stream capnometer (CAPNOX; Colin, Aichi, Japan).

In addition to measurements of airway pressure at the proximal end of the LMA-RM (P$_{mask}$) and P$_{sg}$, pressure difference between the P$_{mask}$ and P$_{sg}$ (P$\Delta$) was directly measured with a pressure transducer (23NB005G; IC sensors, Silicon Valley, CA). (V), P$_{mask}$, P$_{sg}$, and P$\Delta$ were recorded on an eight-channel thermal recorder (WS-682G; Nihon Koden, Tokyo, Japan) and stored simultaneously in a personal computer with a sample frequency of 50 Hz by a data-logging software package (LABDAT 5.2 RHT; Infodat, Montreal, Quebec, Canada) for later analysis.

\textbf{Presurgical Respiratory Measurements}

After confirming at least 5 min of steady-state spontaneous breathing as indicated by no change in end-tidal carbon dioxide tension, tidal volume, and respiratory frequency, measurements of the ventilatory variables (V, P$_{mask}$, P$_{sg}$, P$\Delta$, end-tidal carbon dioxide tension) were made during spontaneous breathing while maintaining constant anesthetic level (1 minimum alveolar concentration [MAC]) (fig. 1). Because it took more than 15 minutes for breathing to stabilize after completion of the experimental setting, we assumed that the effect of succinylcholine administered at the time of anesthesia induction had worn off at the time of the measurements. Following the measurements, vecuronium 8–10 mg was administered intravenously and complete paralysis was confirmed by loss of response to ulnar nerve electric stimulation. Patients were mechanically ventilated by intermittent positive pressure ventilation mode with 10 breaths/min, a tidal volume of 10 ml/kg and an inspiratory-expiratory time (I:E) ratio of 1:2. Ventilatory vari-
ables were measured again under complete paralysis (fig. 1^2). Immediately thereafter, a fiberoptic endoscope connected to a camera (ETV8; Nisco, Saitama, Japan) was passed through the LMA-RM to visualize the laryngeal aperture. The glottic aperture image during apnea at the atmosphere pressure was videotaped for later analysis of glottic aperture angle (fig. 1^3). After completion of the respiratory measurements before surgery, both the LMA-RM and the polyethylene catheter were removed and then either a cuffed ETT (ID 7.0 mm for females, 8.0 mm for male) or another LMA™ (size 3 or 4) for the surgery was inserted. During surgery, anesthesia was maintained with sevoflurane (end-tidal concentration 1–2%) and nitrous oxide (60–66%), and vecuronium was administered as necessary. In either group, we did not measure nor control intracuff pressure of each device.

Postoperative Respiratory Measurements

At the completion of surgery, the ETT or the LMA™ used during surgery was removed, and then both the subglottic catheter and the LMA-RM were reinserted. Again, we confirmed the appropriate LMA-RM positioning with fiberoptic endoscope. The residual effect of muscle relaxant was fully reversed with 1.0 mg of atropine and 2.0 mg of neostigmine administered intravenously. Complete reversal of neuromuscular blockade was confirmed by ulnar nerve electric stimulation. The patient was allowed to breathe spontaneously while maintaining at sevoflurane 1 MAC. After confirming a stable breathing pattern for at least 5 min, the same respiratory measurements during spontaneous breathing as in the period immediately before the surgeries were repeated (fig. 1^4). Following the measurement, muscle paralysis was achieved again by the administration of succinylcholine (1 mg/kg) and the respiratory and endoscopic measurements under paralysis were repeated (fig. 1).^5,6

Data Analysis

Each laryngeal image was printed on paper for the measurement of vocal cord angle, which was defined as the angle produced by lines connecting anterior and posterior commissures. Presence or absence of laryngeal swelling was also evaluated from the endoscopic laryngeal view. The extensive adhesion of membranous portion adjacent to the anterior commissure and the extended soft-tissue swelling around the vocal cord were considered significant laryngeal swelling. An investigator [SI], who was blinded to the patient group, evaluated the glottic aperture angle and laryngeal swelling.

First, we estimated the resistive pressure reduction due to LMA-RM, because it contributes to Pδ. By measuring pressure difference across the LMA-RM while blowing 100% oxygen gas at various flow rates with flow going in both directions, we found that the resistance of the LMA-RM (R_{LMA}) varies with size and V, and can be calculated by the following Rohrer’s equation for each

<table>
<thead>
<tr>
<th>Table 1. Anthropometric Characteristics and Duration of the Surgeries for Each Group</th>
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<tr>
<td>ETT Group</td>
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<tr>
<td>No. of patients</td>
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<tr>
<td>Age, y</td>
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<tr>
<td>Sex (M/F)</td>
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<tr>
<td>Height, cm</td>
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<td>Weight, kg</td>
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<td>Operation time (min)</td>
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Values are expressed as median (range).

LMA-RM size: LMA-RM of size 4: R_{LMA=4} = 0.785 + 0.951 * V (cmH₂O · l⁻¹ · s), LMA-RM of size 3: R_{LMA=3} = 0.751 + 0.871 * V (cmH₂O · l⁻¹ · s). Translaryngeal pressure (P_{larynx}) was, therefore, calculated by subtracting R_{LMA} * V from Pₐ (P_{mask} - P_{aq}) for each flow rate. Then we plotted the P_{larynx}–V relationship. Using computer software (ANADAT 5.1 and 5.2; RHT-Infodat Inc., Montreal, Quebec, Canada), a variety of equations were tested to fit the P_{larynx}–V curve adequately. Finally, we calculated laryngeal resistances at a constant flow rate of 0.15 l/s (R_{larynx=0.15}) during inspiration and expiration. Furthermore, minute volume was calculated from the flow signal.

Statistical Analysis

The Mann–Whitney rank sum test was used to compare the anthropometric characteristics and operation time between the groups. The Fisher exact test was used to evaluate differences of the incidence of laryngeal swelling between the groups. The Wilcoxon signed-rank test was used to determine the differences between the variables before and after surgeries. The Spearman rank test was used to assess correlation between the variables. All values were given as median (tenth to ninetieth percentiles). Statistical differences were considered significant when P < 0.05.

Results

Anthropometric characteristic of the patients and operation time for the ETT and LMA™ groups are presented in table 1. There were no significant differences in these parameters between groups. In one LMA™ group patient, measurements under mechanical ventilation were not made and only measurements under spontaneous breathing were available for further analysis.

Glottic Aperture and Laryngeal Resistance

Both minute ventilation and end-tidal carbon dioxide did not change before and after surgery in both groups. As demonstrated by the representative images of the laryngeal aperture before and after surgery (fig. 2), the incidence of laryngeal swelling after surgery was deter-
mined to be significantly higher in the ETT group (6 of 7) than in the LMA™ group (1 of 6) \( (P = 0.029) \). Furthermore, we found significant decrease in the glottic aperture angle after surgeries only in the ETT group, in addition to significant increase in the laryngeal resistance (fig. 3). In the ETT group, both \( R_{\text{larynx}} \) during inspiration and expiration significantly increased and nearly doubled after surgery (fig. 4). Conversely, in the LMA group, \( R_{\text{larynx}} \) during inspiration did not increase after surgery whereas \( R_{\text{larynx}} \) during expiration significantly increased by approximately 30% after surgery (fig. 4).

**Pressure-flow Relationships of the Larynx before and after Surgeries**

Figure 5 illustrates examples of \( P_{\text{larynx}} - V \) relationships before and after surgery in patients of both groups during spontaneous breathing and during mechanical ventilation. The pressure-flow curves were curvilinear, and marked hysteresis of the curves with clockwise rotation was observed for both conditions. In ETT group patients, the \( P_{\text{larynx}} - V \) relationships significantly changed after surgery in both conditions. In these patients the slope of both the inspiratory and expiratory portions of the curves representing resistive components of the larynx increased after surgery, whereas in the LMA™ group patients, \( P_{\text{larynx}} - V \) relationships after surgery were not altered in either condition.

Because we observed marked hysteresis of the \( P_{\text{larynx}} - V \) relationships as shown in figure 5, we adopted the modified form of the Rohrer equation\(^8\) as follows:

\[
P = (\Lambda * (dV/dt)) + (K_1 * V + (K_2 * V) * \text{abs}V)
\]

where \( P \) is \( P_{\text{larynx}} \), \( V \) is gas flow, \( dV/dt \) is acceleration of
the gas flow calculated by differentiation from gas flow, abs\(V\) is absolute value of airflow, and \(A\), \(K_1\), and \(K_2\) are constants obtained by the fitting analysis. The abs\(V\) is necessary for identification of inspiration and expiration. Data on inspiration and expiration were analyzed together. As the nature of the equation indicates, both \(K_1\) and \(K_2\) represents resistive components of the larynx. A nonlinear least-square technique was used for the curve fitting; the quality of the fitting was provided by coefficient \(R^2\) (SigmaPlot version 6.0; SSPS Inc., Chicago, IL). The results of the curve fitting analyses are presented in table 2. The pressure-flow relationships were well fitted by the equation, with small deviations between the actual relationships and fitted curves during both spontaneous and mechanical breathing. The \(R^2\) values were uniformly high (\(> 0.979\)), indicating that the differential equation we adopted fitted the \(P_{\text{larynx}}-\dot{V}\) data reasonably well in our experimental conditions. Constant \(K_1\) obtained by the fitting analysis did not significantly change before and after surgeries. In contrast, constant \(K_2\) significantly increased after surgery in the ETT group in both conditions (table 2).

**Physiologic Meaning of the \(K_2\) Value**

In order to assess the physiologic meaning of the \(K_2\) value, we plotted all \(K_2\) values obtained during spontaneous breathing against corresponding \(R_{\text{larynx}-0.15}\) values. As clearly shown in the figure 6A, we found direct correlation between the variables, indicating that in our study, the \(K_2\) value is likely to reflect resistance of the laryngeal airway. This was also confirmed by significant correlation between \(K_2\) values obtained during mechanical ventilation and glottic aperture angles obtained under complete paralysis (fig. 6-B). On the other hand,

<table>
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<th>Table 2. (K_1), (K_2), (R^2), and (A) Values of Each Group before and after Operation</th>
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<tr>
<td><strong>ETT Group</strong></td>
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<td>(K_1)-spont</td>
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<td>(K_1)-vent</td>
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<td>(A)-vent</td>
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Values are expressed as medians (10–90%).

* \(P < 0.05\) vs. before insertion ETT or LMA™, \(K_1\), \(K_2\), and \(A\) are constants obtained by fitting translaryngeal-flow relationship to the differential equation \(\dot{P} = (A \cdot \frac{d\dot{V}}{dt}) + (K_1 \cdot \dot{V}) + (K_2 \cdot abs\dot{V})\), where \(P\), \(\frac{d\dot{V}}{dt}\), \(\dot{V}\), and abs\(\dot{V}\) denote translaryngeal pressure, acceleration calculated by differentiation from gas flow, gas flow, and absolute value of gas flow, respectively. Quality of fit is provided by coefficient \(R^2\).

ETT = endotracheal tube; LMA™ = Laryngeal Mask Airway™; spont = spontaneous breathing; vent = mechanical ventilation under complete paralysis.
there were no significant correlation between $K_1$ values and $P_{\text{larynx}}$-$0.15$ ($P = 0.199$) or glottic aperture angle ($P = 0.410$).

Discussion

The major findings of this study were: (1) significant narrowing of the glottic aperture in association with marked swelling of the vocal cords was observed in patients with ETT placement; (2) the glottic aperture did not narrow after surgeries in patients with LMA™ placement; (3) directly measured laryngeal resistance significantly increased after surgery in patients with ETT placement, whereas the resistance increased only on expiration in patients with LMA™ placement; (4) pressure-flow relationship of the larynx was well fitted by the modified Rohrer equation during both spontaneous and mechanical ventilation; (5) the constant $K_2$ obtained by the fitting analysis was significantly correlated with measured laryngeal resistance and glottic aperture angle; and (6) the $K_2$ value in both paralyzed and nonparalyzed conditions significantly increased in patients with ETT placement, whereas the increase of $K_2$ value was observed only in nonparalyzed condition in patients with LMA™ placement.

Study Design and Limitation

Until now, laryngeal edema has only been diagnosed by clinical symptoms such as dyspnea or stridor, and no objective assessment of the laryngeal swelling has been described. In this study, presence or absence of laryngeal swelling was evaluated by endoscopic laryngeal view. In addition, the vocal cord angle as an index of the laryngeal aperture size independent from the distance between the tip of the endoscope and vocal cords was measured as reported by Kuna et al.9 They demonstrated a curvilinear relationship between the vocal cord angle and cross-sectional area of the glottic aperture in awake human subjects. We adopted their methodology in this study and are first to report the glottic angle in anesthetized persons. In agreement with their results, we found significant correlation between laryngeal resistance and the vocal cord angle.

The glottic aperture size is modulated by interaction between the anatomical properties of the larynx and neural regulation of the larynx. As we previously reported, we evaluated anatomical properties of the pharynx independently of neural factors10 by eliminating the neural regulation of the larynx using a muscle relaxant under general anesthesia. Accordingly, comparison of the $P_{\text{larynx}}$-$V$ relationship during spontaneous breathing and during mechanical ventilation under paralysis allows us to estimate contribution of each factor to the laryngeal resistance. In addition, curve-fitting analysis of the $P_{\text{larynx}}$-$V$ relationship with use of the modified Rohrer equation allows assessment of dynamic behavior of the larynx, and is advantageous over calculation of the laryngeal resistance at a single point of the pressure-flow relationship. We found that in our experimental settings, $K_2$ values are particularly valuable in representing the resistive component of the laryngeal airway.

Our approach may have several methodological limitations. First, our study was performed using general anesthesia, and therefore the results of this study do not necessarily represent the laryngeal behavior during wakefulness or recovery from anesthesia in the post-esthestia care unit. Sevoflurane anesthesia at 1 MAC itself may have significant influence on the neural regulations of the laryngeal muscles. Second, the use of $P_{\text{larynx}}$ for construction of the $P_{\text{larynx}}$-$V$ curve disregards the background absolute pressure within the airway. In fact, mean airway pressure is greater during mechanical ventilation than during spontaneous breathing. Accordingly, the $K_2$ values evaluated during mechanical ventilation were possibly underestimated if the laryngeal airway was compliant. However, this possible underestimation of the $K_2$ values during mechanical ventilation would not have resulted in the $K_2$ differences before and after surgery. Third, because we did not measure and regulate the cuff pressure of ETT and LMA™, this might have influenced the postoperative laryngeal resistance. Fourth, the pressure catheter below the vocal cord may possibly be influenced by subglottic edema, which could not be evaluated by fiberoptic observation.

Mechanisms of the Increase in the $K_2$ values after ETT Extubation

Laryngeal resistance increases because of anatomical narrowing of the laryngeal aperture (anatomical mechanisms) and/or imbalance between the abductor and adductor of the vocal cords (neural mechanisms). We found significant increase in the $K_2$ values of the paralyzed larynx only in the ETT group, which indicates that anatomical narrowing of the larynx produced by laryn-
geal swelling only occurred in the ETT group. Significant increase in the $K_2$ values only during spontaneous breathing in the LMA™ group indicates that neural mechanisms play a role in the postoperative increase in the laryngeal resistance independent of the airway managements. Although our experimental design does not allow exploration of neural mechanisms, surgical stress might possibly influence the central modulation of UA muscles as we reported previously. Our results indicate that laryngeal resistance increases even after minor surgeries, and that the laryngeal swelling caused by placement of an ETT significantly contributes to the increment of laryngeal resistance.

**Clinical Implications**

Postoperative laryngeal swelling after extubation is believed to develop rarely in adult patients who had minor surgeries, based on the absence of the clinical symptoms such as dyspnea and stridor. In accordance with the previous studies, neither dyspnea nor stridor developed after tracheal extubation in this study, but we clearly demonstrated significant increase in laryngeal resistance due to marked laryngeal swelling in patients with ETT placement. The increased laryngeal resistance may not manifest clinical symptoms in subjects with normal pre-operative laryngeal function. However, the results should be seriously taken, alerting routine airway management procedure with ETTs, particularly in patients with preoperative laryngeal narrowing and small children who may have no clinical symptom preoperatively. While placement of LMA™ has several disadvantages such as possible occurrence of gastric insufflations of the air and pulmonary aspiration, our results suggest the superiority of the use of the LMA™ in maintaining laryngeal airway patency.

In conclusion, postoperative laryngeal resistance increases due to laryngeal swelling in patients with ETT placements, while alteration of laryngeal neural control mechanisms may also be present.

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