Usefulness of Continuous Oxygen Insufflation into Trachea for Management of Upper Airway Obstruction during Anesthesia

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Background: Severe complications associated with upper airway obstruction often occur during the perioperative period. Development of a simple and reliable technique for reversing the impaired airway patency may improve airway management. The purpose of the current study is to evaluate the usefulness of transtracheal oxygen insufflation (TTI) for management of upper airway obstruction during anesthesia and to explore the mechanisms of TTI in detail.

Methods: During propofol anesthesia in eight spontaneously breathing patients, the upper airway cross-sectional area and pressure–flow measurements during neck flexion with TTI were compared with those during triple airway maneuvers (TAM) without TTI. Blood gas analyses assessed efficacy of CO₂ elimination during TTI in an additional nine patients.

Results: TTI achieved adequate Pa₇CO₂ and Pa₉O₂ levels equivalent to those during TAM. In addition to a significantly smaller cross-sectional area during TTI, the location and slope of the pressure–flow relation during TTI completely differed from those during TAM, indicating that upper airway resistance was much higher during TTI. Notably, minute ventilation during TTI was significantly smaller than that during TAM, suggesting reduced dead space or other mechanisms for CO₂ elimination.

Conclusions: TTI is capable of maintaining adequate blood gases through mechanisms different from those of conventional airway support in anesthetized subjects with upper airway obstruction. (Key words: Airflow mechanics; airway management; pressure–flow relation; respiration.)

UPPER airway management is one of anesthesiologists' greatest concerns during the perioperative period because of the high incidence of severe complications associated with upper airway obstruction.1–3 The triple airway maneuver (TAM; mandibular advancement, neck extension, and mouth opening), application of positive airway pressure through the mask, or even insertion of an artificial airway may not improve severe upper airway obstruction. Persistence of this condition can cause severe hypoxemia and pulmonary edema and eventually leads to cardiac arrest.4,5 Even after the widespread dissemination of the difficult airway algorithm proposed by the American Society of Anesthesiologists, fatal complications in association with failure of upper airway maintenance have not completely disappeared.6,7 Addition of a simple, reliable procedure for avoiding such a disaster may further improve airway management during perioperative period.

In 1956, Jacoby et al.8 reported that transtracheal oxygen insufflation (TTI) through the cricothyroid membrane successfully maintained oxygenation during induction of anesthesia in patients with upper airway obstruction caused by tumors. Despite this promising report, little attention has been paid to TTI for the management of difficult airway in patients with spontaneous breathing efforts. Accordingly, the purpose of the current study was to explore the mechanisms by which ventilation is maintained with TTI by analyzing airflow dynamics and behavior of the upper airway. Furthermore, we reevaluated whether TTI is capable of maintaining adequate blood gases in non-paralyzed subjects with upper airway obstruction.

Materials and Methods

Subjects
Adult subjects who were scheduled for elective surgeries during general anesthesia were invited to partici-
TRANSTRACHEAL INSUFFLATION AND UPPER AIRWAY OBSTRUCTION

Pharyngeal endoscope

Tracheal pressure

10 L/min oxygen
(polyethylene catheter, 10 Fr)

Fig. 1. Experimental setting.

Protocol 1: Evaluation of Flow Dynamics and Behavior of the Upper Airway

We examined the influence of TTI on airflow mechanics and behavior of the upper airway in nine persons. Their average age was 51.5 yr (range, 44.3–67.2 yr), and average heights and weights were 1.58 m (range, 1.47–1.64 m) and 60.2 kg (range, 46.3–67.9 kg), respectively (body mass index = 22.9 kg m⁻² (17.6–28.2 kg m⁻²).

They were premedicated with intramuscular administration of 0.5 mg atropine and 50 mg hydroxyzine 45 min before induction of anesthesia and also received intravenous administration of histamine H₂ receptor antagonists.

Figure 1 illustrates our experimental setting. General anesthesia was induced with a bolus injection of 2 mg/kg propofol and 1 μg/kg fentanyl followed by continuous infusion of propofol at a rate of 8–10 mg kg⁻¹ h⁻¹. Intravenous administration of succinylcholine (1 mg/kg) facilitated insertion of a 10-French double-lumen polyethylene catheter (3201-10, Salem Sump Tube, Nippon Sherwood, Tokyo, Japan) into the trachea through the vocal cords with a laryngoscope. The surface of the vocal cords was anesthetized using 8% lidocaine spray. The tip of the catheter was placed approximately 10 cm below the vocal cords. The catheter allowed for TTI delivery at a rate of 10 L/min with simultaneous measurement of intratracheal pressure by a pressure transducer (23NB005G; ICsensors, Silicon Valley, CA). A slim fiberoptic endoscope (FB15X, Pentax, Tokyo, Japan) connected to a video recording system (ETV9x, Nisco, Saitama, Japan) was inserted through a face mask and the nares to visualize the cross-section of the oropharynx (retroglossal airway space). The possibility of air leaks between the mask and the face was actively investigated by feeling around the mask and corrected when discovered. Flow rate through the face mask was measured using a pneumotachograph (Model 4719, Hans Rudolph Inc., Kansas City, MO) and a differential pressure transducer (TP-602T; Nihon Koden, Tokyo, Japan). All the measured variables were recorded on an eight-channel recorder (WS:682G, Nihon Koden). The data were also stored in a computer for five participants for construction of pressure–flow relations. An arterial catheter was inserted into the radial artery for continuous monitoring of blood pressure and blood gas analysis. Oxygen saturation as measured by pulse oximetry (SpO₂) and electrocardiogram were monitored throughout the experiment. The measurements were started at least 5 min after the establishment of steady spontaneous breathing. The inspired oxygen fraction (FiO₂) was maintained at 1.0 throughout the experiment. A control period of breathing while maintaining the TAM was conducted for at least 5 min (control). Thereafter, complete upper airway obstruction was produced by flexing the neck. Although the degree of the neck flexion was not controlled and may have differed among the subjects, complete airway obstruction at the level of the oropharynx was confirmed by the endoscopic image as well as by the flow tracing. Oxygen (10 L/min) was then insufflated into the trachea. Measurement was continued for at least 3 min after establishing stable breathing during TTI. The last five respiratory cycles of each condition were used to analyze flow mechanics and oropharyngeal cross-sectional area. Because the baseline of the flow signal shifted due to continuous oxygen insufflation during TTI, a new baseline for respiratory fluctuation of the flow signal was determined in reference to the tracheal pressure tracing. The tidal volume was obtained by integration of the inspiratory fluctuation of the corrected flow signal. After digitizing the luminal image of the pharynx, the cross-sectional area of the lumen was calculated in arbitrary units using a computer-controlled cursor and appropriate software (SigmaScan version 2.0, Jandel Scientific Software, San Rafael, CA). Pharyngeal area during TTI was obtained.

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as relative values to control condition. We compared the breathing pattern and pharyngeal airway cross-sectional area during the control measurement with those during TTI. The experiment was terminated with the occurrence of hypoxemia (SpO<sub>2</sub> < 90%), sustained respiratory instability, or other unexpected cardiorespiratory complications during TTI.

**Protocol 2: Blood Gas Evaluation**

In 11 additional participants, we analyzed arterial blood gases at the end of the following conditions in a successive fashion. Condition 1: TAM-maintained patent airway without TTI for 5 min. Condition 2: TTI continued for 3 min with neck flexion. Condition 3: TTI discontinued with neck flexion for 90 s. Condition 4: TTI resumed and maintained for 3 min with neck flexion. The average age of the participants was 63.0 yr (range, 49.0–70.4 yr), and the average height and weight were 1.63 m (range, 1.47–1.74 m) and 57.0 kg (range, 46.5–74.8 kg), respectively (body mass index = 23.9 kgm<sup>-2</sup> (21.0–25.5 kgm<sup>-2</sup>).

**Statistics**

Wilcoxon signed rank test was performed to compare respiratory and blood gas variables between control and TTI conditions (protocol 1). Friedman repeated measures analysis of variance on ranks was used to determine statistical significance of the blood gas variables in protocol 2. The Dunnett test assessed significance between condition 1 and other conditions. P < 0.05 was considered to be significant. All values were expressed as median (10th–90th percentiles).

**Results**

**Protocol 1**

In protocol 1, one person showed marked abdominal distention after neck flexion during TTI which was probably caused by inflow of oxygen into stomach. Furthermore, tracheal pressure progressively increased to more than 20 cm H<sub>2</sub>O following neck flexion, suggesting that TTI failed to reverse upper airway obstruction induced by neck flexion. No further observations or maneuvers were performed in this patient. TTI was successfully performed in the remaining eight subjects.

Typical changes in respiratory variables and oropharyngeal cross-sections are presented in figure 2. TAM fully dilated the oropharyngeal airway. No discrepancy was observed between the patterns of changes in the mask flow and the tracheal pressure during control condition, indicating that flow limitation did not occur during control. In the absence of TTI, neck flexion produced complete airway closure, resulting in no flow through the mask despite augmenting respiratory efforts. The administration of TTI successfully stabilized breathing by reversing the airway obstruction. In contrast to breathing during control measurement, however, significant narrowing of the oropharyngeal airway and increased tracheal pressure fluctuation were observed during neck flexion with TTI. The tracheal pressure at the beginning of inspiratory effort during TTI (9 cm H<sub>2</sub>O) was much higher than that during control measurement (2 cm H<sub>2</sub>O), which was produced by intrinsic mechanical resistance of the anesthetic circuit. It should be noted that the baseline of mask flow shifted

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above zero due to continuous flow of insufflated oxygen into trachea during TTI. Respiratory-related fluctuation of the flow signal was remarkably decreased during TTI. Estimated minute ventilatory volume during TTI (2.6 l/min) was much smaller than that of the control condition (5.2 l/min). Surprisingly, partial pressure of alveolar carbon dioxide (Paco₂) during TTI (49.1 mmHg) was not particularly high compared with that of the control condition (46.5 mmHg), even though the minute ventilation was markedly lower during TTI.

Table 1 presents differences in breathing pattern, pharyngeal airway size, and blood gas condition between control and TTI participants. Minute ventilation during TTI was significantly smaller than that in the control condition, mainly because of significant decreases in tidal volume during TTI. Paco₂ did not differ between the conditions despite the significant reduction of the minute ventilation through the mask during TTI. Sufficiently high Paco₂ was maintained in both conditions. Tracheal pressure at the beginning of inspiratory effort during TTI was significantly higher than that during control, suggesting that functional residual capacity had increased during TTI.

Figure 3 illustrates pressure-flow relations during control and TTI in five persons. The location of the pressure-flow curves during TTI indicates that tracheal pressure was always greater than mask pressure and the exhalation flow was always present during TTI. The slope of the curves was much steeper during the control condition than during TTI, indicating that upper airway resistance was much higher during TTI than in the control condition. This finding was supported by the evi-

**Table 1. Changes in Flow Mechanics and Pharyngeal Cross-section during Transtracheal Insufflation (TTI)**

<table>
<thead>
<tr>
<th>Airway intervention</th>
<th>Control</th>
<th>TTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTI (with 10 l/min oxygen)</td>
<td>TAM (-)</td>
<td>NF (+)</td>
</tr>
<tr>
<td>Respiratory rate (breaths/min)</td>
<td>16.6 (11.7-24.7)</td>
<td>15.0 (11.8-18.7)</td>
</tr>
<tr>
<td>Tidal volume (l)</td>
<td>0.24 (0.16-0.32)</td>
<td>0.16 (0.09-0.21)*</td>
</tr>
<tr>
<td>Minute ventilation (l/min)</td>
<td>5.1 (1.8-6.4)</td>
<td>2.7 (1.0-3.5)*</td>
</tr>
<tr>
<td>Tracheal pressure at BIF (cm H₂O)</td>
<td>1.5 (0.2-5.6)</td>
<td>11.7 (8.0-17.8)**</td>
</tr>
<tr>
<td>Pharyngeal area (% TAM)</td>
<td>100</td>
<td>17.3 (7.9-55.4)**</td>
</tr>
<tr>
<td>pH</td>
<td>7.31 (7.26-7.36)</td>
<td>7.28 (7.24-7.34)</td>
</tr>
<tr>
<td>PaO₂ (mmHg)</td>
<td>390 (336-467)</td>
<td>426 (378-468)</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>53.1 (47.7-66.1)</td>
<td>55.8 (49.2-67.5)</td>
</tr>
</tbody>
</table>

TAM = triple airway maneuver; NF = neck flexion; BIF = beginning of inspiratory effort.

*P < 0.05 versus control (Wilcoxon signed rank test) (n = 8).
**P < 0.01 versus control (Wilcoxon signed rank test) (n = 8).
Table 2. Results of Blood Gas Analyses in Four Different Experimental Conditions

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
<th>Condition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airway intervention</td>
<td>TAM</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>TAM</td>
<td>(-)</td>
<td>(+)</td>
<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td>pH</td>
<td>7.35 (7.32-7.38)</td>
<td>7.34 (7.32-7.39)</td>
<td>7.28 (7.26-7.31)*</td>
<td>7.34 (7.30-7.38)</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>424 (266-461)</td>
<td>440 (264-554)</td>
<td>437 (292-542)</td>
<td>472 (299-561)*</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>47.3 (41.7-51.9)</td>
<td>49.1 (42.7-52.9)</td>
<td>59.5 (54.3-63.6)*</td>
<td>48.4 (44.1-52.2)</td>
</tr>
</tbody>
</table>

TAM = triple airway maneuver; NF = neck flexion; TTI = transtracheal insufflation with 10 l/min oxygen.

* P < 0.05 versus control condition 1 (Dunnett test) (n = 9).

dence that the oropharyngeal area at the beginning of inspiratory effort during TTI was significantly smaller than that during the control condition (table 1). Accordingly, a fully dilated airway was not required during TTI to maintain adequate blood gas level.

Protocol 2

In protocol 2, two subjects exhibited severe, continuous coughing immediately after induction of TTI, and the breathing pattern did not stabilize throughout the experiment; therefore, the data for these persons were excluded from the analysis. Results of arterial blood gas analyses for each condition are presented in table 2. Mean partial pressure of alveolar oxygen (PaO₂) was maintained at approximately 400 mmHg in all conditions of the experiment. Although blood gas parameters during TTI (condition 2) did not differ from those in the control condition, discontinuation of TTI resulted in a significant increase in PaCO₂ and a significant decrease in pH (condition 3). Resumption of TTI, however, successfully brought back both PaCO₂ and pH to the control level within 3 min (condition 4).

Discussion

In this study, we demonstrated that TTI successfully maintained adequate PaO₂ levels in anesthetized, non-paralyzed persons with experimentally induced upper airway obstruction. Notably, TTI only partially reversed the airway obstruction, and minute ventilatory volume was significantly smaller during TTI than during TAM.

Upper Airway Behavior during Transtracheal Oxygen Insufflation

Reversal of upper airway obstruction is essential for success of TTI in maintaining ventilation. This is primarily achieved by an increase in tracheal pressure opening and splinting the obstructed airway. Lung volume increase during TTI is also considered to contribute to the airway opening, because the pharyngeal collapsibility is reported to depend on lung volume, probably through a tracheal traction mechanism. Interestingly, we found that the upper airway cross-sectional area was much smaller during TTI than during conventional airway support, whereas the values of blood gases were essentially similar. Furthermore, pressure-flow relations during TTI completely differed from those during control conditions in terms of position and slope of the curves. The upper airway resistance remained relatively high during TTI, whereas an endpoint of conventional airway supports such as TAM or nasal continuous positive airway pressure is to reduce the resistance for breathing. This evidence indicates that TTI maintains ventilation by means of mechanisms that are completely different than those with conventional airway support. TTI only partially reverses upper airway obstruction, and a fully dilated airway is not required for adequate breathing, suggesting that TTI may be successful even in patients with airway narrowing.

Possible Mechanisms of Carbon Dioxide Elimination during Transtracheal Oxygen Insufflation

Partial pressure of alveolar carbon dioxide did not differ between the conditions despite the significant reduction of the minute ventilation during TTI. This indicates that there must be mechanisms, other than lung volume changes, that are responsible for CO₂ elimination during TTI. The tip of the TTI catheter was located just above the carina, and mask flow indicated continuous exhalation of the gas during TTI. Accordingly, the anatomic dead space cranial to the tip of the catheter, including the trachea and the upper airway, was considered to be no longer than the dead space of the airway during TTI. This reduction in dead space is estimated to be more than 100 ml in adult humans and may partly account for effective CO₂ elimination despite the reduced minute ventilatory volume during TTI. The

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The effectiveness of TTI on reduction of dead space has been well documented in paralyzed and mechanically ventilated patients with acute respiratory failure. Furthermore, continuous oxygen flow delivered through a TTI catheter with a small diameter may significantly alter the flow profile along the airway and therefore may influence CO₂ elimination through the airway.

Comparison of Our Results with Previously Reported Animal and Human Data

Our results are completely in agreement with the pioneer report of Jacoby et al., who successfully demonstrated the effectiveness of 4-l/min TTI on reversal of upper airway obstruction and hypoxemia during induction of anesthesia in five patients with massive upper airway tumors. Unfortunately, the level of Pa₄ during TTI was not evaluated in their study. Our results clearly indicate that TTI is able to maintain adequate Pa₄ level as well as oxygenation. For the achievement of an adequate Pa₄ level, the rate of continuous oxygen flow appears to be crucial. In fact, Cote et al. reported that 1-l/min TTI failed to prevent an increase in Pa₄ in anesthetized and spontaneously breathing dogs with severe upper airway obstruction, but it did prevent development of hypoxemia. In turns, excessive continuous flow of oxygen may cause high tracheal pressure and overinflation of the lung, possibly leading to barotrauma and pneumothorax. This study did not address the optimal range of oxygen flow rate capable of maintaining adequate blood gases with minimal risk of adverse effects of TTI.

Clinical Implications

TTI may be useful in managing patients with high risk of upper airway obstruction, particularly at tracheal extubation. Asai et al. reported that the incidence of respiratory complications occurred more frequently after removal of an endotracheal tube than during induction of anesthesia. Because the outcome of tracheal extubation is at times difficult to predict, severe upper airway obstruction after extubation can lead to the development of life-threatening hypoxemia. Reintubation with a laryngoscope is often difficult or not desirable in patients with marked upper airway swelling after prolonged placement of the endotracheal tube or abnormal upper airway anatomy after head and neck surgeries. Our results strongly suggest that the prophylactic application of TTI may be an effective way to secure a difficult airway by placing a catheter inside the trachea prior to withdrawing the endotracheal tube. In this context, a jet-style endotracheal catheter would allow for the application of TTI or transtracheal jet ventilation (TTJV) as well as reintubation without difficulty, as Bedger and Chang demonstrated. Compared with TTJV, TTI may be equally effective and may be more safely and easily performed, particularly in persons with upper airway obstruction.

Alternatively, TTI can be useful in emergency management of patients with cannot-ventilate–cannot-intubate (CVCI) situations in conjunction with a catheter inserted by a cricothyroid membrane puncture. Benumof and Scheller warned of the relatively high incidence of death associated with the CVCI situation during anesthesia. They emphasized the usefulness of TTJV for the management of the CVCI situation by reviewing animal and human experimental data as well as clinical experiences. Although the incidence of TTJV complications was relatively low, serious adverse effects such as pneumothorax and barotrauma, probably caused by high-pressure jet flow, were reported. Another limitation of TTJV, regardless of its effectiveness, is the requirement of special equipment allowing intermittent high-pressure oxygen delivery. Obviously, TTI as employed in this study is not a substitute for TTJV, but it could be used as an alternative to TTJV in nonparalyzed CVCI subjects. Although TTJV may produce unexpectedly high tracheal pressure in the presence of severe upper airway obstruction, our results suggest the possible usefulness of TTI in maintaining adequate blood gas levels, even in persons with severe upper airway obstruction. Continuous monitoring of tracheal pressure is mandatory, however, because the failure to reverse complete airway obstruction may cause abdominal distention and pneumothorax during TTI administration. Cough reflexes commonly observed at the initiation of TTI may further increase the risk of complications related to a transient but significant increase in tracheal pressure. Use of a double-lumen catheter, which allows both oxygen insufflation and measurement of tracheal pressure, may be appropriate for safe application of TTI.

In our study protocols, three of 19 patients (16%) failed to establish an appropriate pattern of breathing during the trial of TTI. This relatively high incidence of technical failure should be emphasized before actual use of TTI as a clinical tool. More detailed analyses of the mechanisms of the TTI failures may provide a key to understanding the potential limitations of TTI. Although reestablishment of adequate ventilation was clearly indicated by airflow monitoring in this study, it may be difficult to assess the efficacy of TTI in actual clinical conditions.
situations. Another unanswered question for clinical applications of TTI is the possibility of occurrence of pulmonary aspiration, because the airway is not separated from the esophagus during TTI. However, the presence of continuous expiratory airflow through the vocal cords during TTI may prevent aspiration of foreign materials into the tracheobronchial airways, as has been confirmed in TTJV.\textsuperscript{17} Clearly, further experiments in animals as well as humans should be directed to examine the security and efficacy of TTI before its clinical application.

\textit{Limitations of the Study}

We experimentally induced upper airway obstruction by neck flexion and examined whether TTI successfully overcomes the obstruction and \( P_{aCO_2} \) is maintained during TTI. Although we attempted to mimic severe upper airway obstruction, which is an essential problem for the survival in most CVCI situations, the nature and severity of the upper airway obstruction in actual CVCI situations may differ from those in our experimental model. The pharynx, where airway obstruction was produced in this study, is a highly compliant conduit.\textsuperscript{18} Therefore, the positive airway pressure produced by TTI should increase the airway size once the complete airway closure is reversed, as we demonstrated. In contrast, positive airway pressure may fail to reverse airway obstruction and improve severe airway narrowing at the level of the larynx and the upper trachea, where compliance is considered to be much lower than that of the pharynx. Accordingly, our results do not necessarily indicate efficacy of TTI in all CVCI circumstances.

Because of ethical reasons, we did not evaluate effectiveness of TTI in reversing hypoxemia and maintaining adequate oxygenation in this study. However we consider that an increase in lung volume during TTI is beneficial for oxygenation, and no adverse effect of TTI on oxygenation was observed in our study. In fact, Jacoby et al.\textsuperscript{8} beautifully demonstrated reversal of hypoxemia by TTI of 4 l/min oxygen during induction of anesthesia. Furthermore, usefulness of TTI for improvement of oxygenation has been well documented in paralyzed animals and humans.\textsuperscript{19-21}

Transtracheal oxygen insufflation is capable of maintaining adequate blood gas levels regardless of smaller cross-sectional area and decreased minute ventilatory volume in anesthetized persons with spontaneous breathing efforts. Our results suggest possible usefulness of this technique for airway management in patients with difficult upper airway maintenance.

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