Introduction
Continuous Insufflation of Oxygen
Transtracheal Oxygen Administration
Transtracheal Jet Ventilation
High Frequency Jet Ventilation
Intratracheal Pulmonary Ventilation
Tracheal Gas Insufflation
Summary

Over the past 50 years, a variety of techniques have been developed that have in common the insufflation of gas into the central airway to facilitate carbon dioxide (CO₂) clearance. These include continuous insufflation of oxygen, transtracheal jet ventilation, high frequency jet ventilation, transtracheal oxygen administration, intratracheal pulmonary ventilation, and tracheal gas insufflation (TGI). Continuous insufflation of oxygen is a technique used to enhance CO₂ removal in the presence of apnea. Transtracheal jet ventilation and high frequency jet ventilation promote bulk gas flow into the lungs. Some techniques, such as transtracheal oxygen administration, provide insufflation of oxygen as an adjunct to spontaneous ventilation. However, other techniques, such as TGI, are used as an adjunct to positive pressure ventilation. Intratracheal pulmonary ventilation provides positive pressure ventilation while bypassing the upper airway. Although some of these techniques are promising adjuncts to mechanical ventilation and may help reduce ventilator-associated lung injury, much remains to be learned about their role in the care of patients with acute lung injury.

Key words: tracheal gas insufflation, transtracheal oxygen, transtracheal jet ventilation, high-frequency jet ventilation, intratracheal pulmonary ventilation, mechanical ventilation. [Respir Care 2001;46(2):119–129]
Continuous Insufflation of Oxygen

Apneic oxygenation is a technique in which the subject is hyperoxygenated by ventilation with 100% oxygen, and then has ventilation interrupted. During the ensuing period of apnea, arterial partial pressure of oxygen (P_{aO2}) is maintained above normal because of the very high P_{aO2} at the initiation of apnea. The duration of apneic oxygenation is limited not by the decline in P_{aO2}, but rather by the rise in arterial partial pressure of carbon dioxide (P_{aCO2}). In 1961, Eger and Severinghaus reported the rate of rise in alveolar partial pressure of carbon dioxide (P_{ACO2}) in 5 healthy apneic anesthetized adult patients. In the first minute of apnea there was a rapid rise in P_{ACO2}, as the alveolar P_{CO2} equilibrated with the mixed venous P_{CO2}. This was followed by a linear rise in P_{CO2} determined by the rate of tissue CO2 production. The slope of the increase in P_{ACO2} was 4 mm Hg/min without prior hyperventilation. The increase in P_{ACO2} was less with prior hyperventilation, occurring at a rate of 3 mm Hg/min. At this rate of P_{CO2} increase, the duration of apneic oxygenation was limited by the concomitant respiratory acidosis. From these and other studies published from the mid-1950s to the early 1970s, it was established that the rate of rise in P_{CO2} during apnea in humans is about 3–5 mm Hg/min.

It has been known for 50 years that continuous insufflation of oxygen (CIO) into the trachea or bronchi of experimental animals can slow the rate of P_{ACO2} increase during apneic oxygenation. In 1951, Jacoby et al reported that tracheal insufflation at 15 L/min slowed the rise in P_{ACO2} in apneic dogs. In the 1980s there were a number of published studies evaluating this technique in animal models. With two catheters, one positioned 3.5 cm into each bronchus (Fig. 1), and a total flow of 40 L/min (20 L/min to each catheter), dogs can be maintained eucapnic and that they extend into the mainstem bronchi. PEEP = positive end-expiratory pressure. (From Reference 18, with permission.)

Hypoxemia is a recognized complication of endotracheal suctioning. Most commonly, this complication is avoided by pre-oxygenation with 100% oxygen and limitation of procedure duration. CIO during suctioning has been suggested as an alternative method to prevent suctioning-related hypoxemia. Smith et al evaluated a double-lumen suction catheter, with oxygen insufflation through one lumen alternating with suction through the other. With this technique, they were able to prevent hypoxemia during suctioning without pre-oxygenation. Brochard et al evaluated CIO during suctioning using a specially designed endotracheal tube incorporating five 0.7 mm diameter capillaries into its wall. Gas from these capillaries exits 1 cm from the distal tip of the tube. Oxygen insufflation at 12 L/min minimized arterial desaturation during suctioning in severely hypoxic patients with acute respiratory failure (ARF). Further, the decline in lung vol-

**Fig. 1.** Catheter position for continuous flow ventilation (CFV) in dogs. Note that the catheters are exterior to the endotracheal tube and that they extend into the mainstem bronchi. PEEP = positive end-expiratory pressure. (From Reference 18, with permission.)
Tracheal Gas Insufflation and Related Techniques

ume that typically occurs with suctioning was ameliorated by use of oxygen insufflation. Although potentially beneficial, oxygen insufflation during suctioning has not become popular, probably because the closed suction system is commonly employed to minimize suction-related complications.

The necessity of ventilation during cardiopulmonary resuscitation (CPR) has been questioned. Hallstrom et al recently reported that the outcome after CPR with chest compressions alone was similar to that after chest compressions with mouth-to-mouth ventilation. Several studies have evaluated the use of CIo during CPR. In a canine model of cardiac arrest, Branditz et al showed that hypercapnia did not occur and that arterial oxygen saturation was maintained using 15 L/min of transtracheal oxygen. Brochard et al studied CIo at 15 L/min through an endotracheal tube in a porcine model of cardiac arrest. They noted similar \( P_{aO_2} \) and \( P_{aCO_2} \) with either standard CPR or oxygen insufflation CPR, the latter including chest compressions and insufflated oxygen without additional ventilation. Further, they found oxygen insufflation CPR led to improved hemodynamics relative to standard CPR. Saissy et al recently evaluated CIo during out-of-hospital CPR. Cardiac-arrested patients were randomized to stan-

Fig. 2. Effect of tracheal insufflation of oxygen at 2 L/min in dogs. Note that the arterial partial pressure of oxygen (\( P_{aO_2} \)) remains high, that the arterial partial pressure of carbon dioxide (\( P_{aCO_2} \)) reaches a plateau with oxygen insufflation, and that the \( P_{aCO_2} \) rises with a rapid slope without oxygen insufflation. (From Reference 19, with permission.)

Fig. 3. Gas delivery system for continuous insufflation of oxygen in human subjects. (From Reference 4, with permission.)
standard CPR or CIO plus chest compressions. They reported similar rates of successful resuscitation and levels of $P_{aO_2}$ and $P_{aCO_2}$ between the groups. CIO was provided through a specialized endotracheal tube with lateral channels in its wall allowing insufflation of oxygen at 15 L/min.

CIO has been studied as a technique to facilitate the determination of brain death in adults. It is commonly recommended that 6 L/min of 100% oxygen be administered through a catheter placed at the level of the carina during this procedure to maintain adequate oxygenation. With a starting $P_{aCO_2}$ of 40 mm Hg and pre-oxygenation with 100% oxygen, the expected rise in $P_{aCO_2}$ after initiation of apnea is 3–6 mm Hg/min (depending on tissue CO$_2$ production).

There are several reasons why CIO has not become widely accepted in the care of critically ill patients. Although this technique slows the rise in $P_{aCO_2}$, it does not provide adequate CO$_2$ clearance. This leads to the relatively rapid onset of unacceptable respiratory acidosis. Unlike the animals in which this technique has been studied, critically ill patients often are hypermetabolic and have elevated alveolar dead space, respectively increasing CO$_2$ production and decreasing CO$_2$ clearance. To maximize effective CO$_2$ clearance in CIO, high flows must be insufflated, producing the potential for airway injury. Critically ill patients also suffer elevated intrapulmonary shunt and require airway pressures greater than those provided by CIO alone in order to prevent alveolar derecruitment. Combined constant-flow and continuous PPV has been described, but only in an animal model. The use of CIO is thus effectively limited to relatively short-term applications such as apnea testing to establish brain death, airway suctioning, or CPR.

---

**Fig. 4.** Partial pressure of oxygen ($P_{O_2}$) and partial pressure of carbon dioxide ($P_{CO_2}$) with (closed circles) and without (open circles) continuous insufflation of oxygen in 5 patients during anesthesia. (From Reference 11, with permission.)

**Fig. 5.** Effect of transtracheal air on inspired minute ventilation of 7 patients. (From Reference 41, with permission.)

**Fig. 6.** Representative tracings of pleural pressure (Ppl) in a patient breathing room air with no transtracheal flow (top graph), while receiving transtracheal oxygen (middle graph), and while receiving transtracheal air (bottom graph). (From Reference 42, with permission.)

**Fig. 7.** Technique of percutaneous transtracheal jet ventilation. The needle is directed through the cricothyroid membrane (A), its position in the trachea is verified (B), and transtracheal ventilation is provided using a manual trigger (C). (From Reference 47, with permission.)
Transtracheal Oxygen Administration

Transtracheal oxygen administration delivers gas directly into the trachea via a small percutaneous catheter. A principal advantage of transtracheal oxygen administration is its efficiency, allowing a reduction in flow and concomitant decrease in the cost of oxygen therapy. Even in the initial reports of transtracheal oxygen use, it was recognized that patients also frequently reported less dyspnea. What was not initially recognized was that this was due to enhanced clearance of CO₂ from the upper airway—a tracheal gas insufflation (TGI) effect.

Bergofsky and Hurewitz studied 5 patients who had chronic hypercapnia and permanent tracheostomies, in whom 5 L/min of gas was delivered through an otherwise occluded tracheostomy tube. They reported a significant reduction in dead space and inspired minute ventilation using this method. In one patient the effect was so dramatic that the patient requested long-term application of the technique. In a follow-up investigation, Hurewitz et al. studied patients with transtracheal oxygen catheters and reported that increases in oxygen flow from 1–8 L/min produced progressive decreases in dead space volume, tidal volume (VT), and inspired minute ventilation.

Couser and Make studied 7 patients receiving oxygen therapy via transtracheal catheter. As the transtracheal oxygen flow increased, inspired minute ventilation decreased; at 6 L/min inspired minute ventilation was reduced by approximately 50%. To demonstrate that this effect was due to gas flow and not to oxygen supplementation, transtracheal air was substituted for oxygen with a similar reduction in minute ventilation. Benditt et al. studied 5 patients receiving transtracheal oxygen therapy and reported that the tension-time index of the diaphragm decreased as transtracheal flow of oxygen or air increased (Fig. 6). These data are consistent with a reduced ventilatory requirement with transtracheal gas flow, presumably due to a reduction in dead space.

Transtracheal oxygen insufflation has also been used for the treatment of obstructive sleep apnea. Schneider et al. found that 15 L/min of tracheal oxygen insufflation stabilized the breathing pattern by providing sufficient air flow for the patients to inspire during upper airway obstruction. They also reported that this flow resulted in laryngeal obstruction during transitional sleep, which could result in high tracheal pressure unless a pressure pop-off is used.

Transtracheal Jet Ventilation

Percutaneous transtracheal jet ventilation (TTJV) is a technique in which a large intravenous catheter is inserted through the cricothyroid membrane and ventilation is pro-

Fig. 8. Commercially available equipment for transtracheal jet ventilation: ACU 1060.1 transtracheal catheter (left) and BE 183-SUR manual jet ventilator (right). (Courtesy of Instrumentation Industries, Bethel Park, Pennsylvania.)

Fig. 9. High frequency jet ventilation. The jet effect at the proximal airway entrains flow from a secondary gas source. The tidal volume delivered is the combination of the primary jet flow and the entrained gas flow. (From Reference 51, with permission.)

Fig. 5. High frequency jet ventilation.
vided from a high-pressure gas source\textsuperscript{46,47} (Fig. 7). In addition to a 50 psi gas source and a 14–16 gauge catheter, the TTJV system requires low-compliance connecting tubing and a valve to control flow time to the catheter.\textsuperscript{46,47}

Valve systems are commercially available (Fig. 8). The chief advantage of TTJV is that it is quicker and simpler than percutaneous cricothyroidotomy. A syringe containing 10 mL of saline is attached to the catheter, which is advanced through the cricothyroid membrane into the tracheal lumen. Free return of air confirms catheter tip position. The catheter is advanced over the introducer needle into the trachea and attached to the flow-controlling valve. The catheter is held in place manually to avoid displacement. Ventilation is provided at a rate of 12–20 cycles per minute.

Flow through a 16-gauge catheter at a driving pressure of 50 psi is about 500 mL/s. Because of the high velocity of gas exiting the catheter in the trachea, additional flow may be entrained from the upper airway. The peak inspiratory pressure during TTJV depends on the cross-sectional area of the trachea, the length and diameter of the catheter, the degree of upper airway obstruction, the compliance of the respiratory system, and the inspiratory time. Because exhalation occurs through the upper airway, complete up-

Fig. 10. The reverse-thrust catheter used for intratracheal pulmonary ventilation (ITPV). During inspiration (left) the expiratory valve is closed and thus all of the gas flow is directed into the lungs. During expiration (right), the expiratory valve is open and the catheter flow and expiratory flow from the patient’s lungs are expired simultaneously through the endotracheal tube. (From Reference 64, with permission.)

Fig. 11. A simple circuit for tracheal gas insufflation. (From Reference 71, with permission.)

Fig. 12. With no tracheal gas insufflation (TGI) (left), the central airways contain CO\textsubscript{2} at end-expiration and this CO\textsubscript{2} is delivered to the alveoli during the subsequent inspiration. With TGI (right), the CO\textsubscript{2} from the central airways is flushed during the expiratory phase, which reduces the CO\textsubscript{2} delivered to alveoli during the subsequent inspiration. (From Reference 72, with permission.)
per airway obstruction is a contraindication to TTJV. Reported complications of TTJV are infrequent; they include hemorrhage at the insertion site, subcutaneous and mediastinal air, esophageal injury, and pneumothorax. Patel reported 5 years' experience with TTJV in 29 patients. Two important benefits of TTJV were suggested. First, TTJV provided adequate oxygenation, allowing time for definitive airway management. Second, TTJV improved visualization of the glottic aperture, thereby promoting subsequent translaryngeal intubation.

High Frequency Jet Ventilation

High-frequency jet ventilation (HFJV) is a form of life support in which high velocity jets of gas are injected into the airway at frequencies higher than those used with conventional ventilators (100–660 per minute). The driving pressure applied to the jet is typically 35–50 psi. This technique was originally applied using a specialized endotracheal tube incorporating a lumen designed to permit passage of the gas stream. Because of the undesirability of reintubating critically ill patients, techniques allowing the jet stream to be applied to the proximal endotracheal tube were subsequently introduced. The volume of gas delivered through the jet is relatively small (2–5 mL/Kg). However, because of the high velocity at which gas exits the jet, additional gas is entrained (Fig. 9), resulting in estimated $V_T$ of 3–5 mL/Kg. The construction of these jet ventilation devices virtually precludes measurement of exact $V_T$. With HFJV, alveolar ventilation depends on the driving pressure to the jet, jet frequency, inspiratory-to-expiratory ratio, and overall pulmonary mechanics.

The efficacy of HFJV for patients with acute respiratory distress syndrome has been disappointing. Carlon et al. reported that HFJV provided no better oxygenation and ventilation than conventional techniques. Further, survival was not improved with the use of HFJV. Gluck et al. reported improved gas exchange and reduced airway pressure during a 24-hour trial of HFJV. As this study was uncontrolled, however, it is impossible to know whether similar effects could have been achieved with conventional ventilation. In addition, the short-term nature of the study prevented assessment of such important outcomes as survival.

Although HFJV has been virtually abandoned in the adult intensive care unit, it is used occasionally in neonates and in the operating room. In many neonatal intensive care units, high-frequency oscillatory ventilation is now used in place of HFJV. In the operating room, HFJV is used during head and neck surgery, allowing the patient to be oxygenated and ventilated without a large endotracheal tube obscuring the airway.

Concerns related to HFJV include adequate humidification of the jet gas flow and intrinsic positive end-expiratory pressure due to the short expiratory time. Tracheal injury following HFJV in neonates has been reported.

Intratracheal Pulmonary Ventilation

Intratracheal pulmonary ventilation (ITPV) is a technique that introduces a continuous-flow catheter into the endotracheal tube. The distal tip of the catheter is positioned about 1 cm from the carinal tip of the endotracheal tube. A unique, reverse-thrust catheter design allows gas exiting the distal end of the catheter to be directed cephalad (Fig. 10). The exhalation port of the endotracheal tube is attached to the ventilator. When the exhalation valve is closed, flow is delivered into the distal lungs. When the exhalation port is open, the reverse-thrust catheter entrains gas from the distal airways to facilitate exhalation.

The objective of ITPV is to reduce $V_T$ and thus alveolar distending pressure. This may be achieved by several mechanisms associated with this technique. First, the $V_T$ is delivered directly into the trachea, bypassing the proximal dead space. Second, the proximal dead space is flushed during the expiratory phase. Third, the jet effect of the reverse-thrust catheter facilitates gas flow from the distal lungs. An additional effect of ITPV that has been reported is augmented clearance of mucus from the inner lumen of the endotracheal tube. Most ITPV research has occurred in animal models. The reported human experience has been limited primarily to neonatal and pediatric patients, although its use for patients with acute respiratory distress syndrome has been recently reported.
The future role of ITPV in adult patients with ARF remains to be determined.\textsuperscript{59–71}

**Tracheal Gas Insufflation**

TGI is the injection of fresh gas into the central airways for the purpose of improving the efficiency of alveolar ventilation and/or minimizing the ventilatory requirement.\textsuperscript{71,72} It is used as an adjunct to mechanical ventilation. A catheter is placed into the central airway proximal to the carina (Fig. 11). Flow is introduced through the catheter to flush the proximal airways of CO\textsubscript{2}-laden gas (Fig. 12). The result is less CO\textsubscript{2} rebreathing on the subsequent inspiration, which effectively lowers the dead space. TGI has been studied extensively in lung models\textsuperscript{73–75} and animals.\textsuperscript{76–88} In recent years there have been an increasing number of reports of the use of TGI for patients with ARF.\textsuperscript{89–97} As it has become more widely recognized that alveolar overdistention during mechanical ventilation may result in increased morbidity and mortality,\textsuperscript{3} there is considerable academic and clinical interest in TGI as a technique to reduce the ventilatory requirement of patients with ARF.

A variety of approaches to TGI have been reported. The catheter can be introduced into the trachea either beside the endotracheal tube or through the endotracheal tube, or can be incorporated into the endotracheal tube design. Catheters can introduce flow either toward the carina or away from the carina (retrograde or reverse-thrust catheters). The flow can be continuous throughout the respiratory cycle, restricted to the expiratory phase (Fig. 13), or constrained to a specific portion of the expiratory phase. Regardless of the approach that is used, a concern with the use of TGI is the interaction between the TGI flow and the ventilator.\textsuperscript{71}

A recently described alternative to TGI is aspiration of airway dead space—tracheal gas exsufflation (TGE).\textsuperscript{98} With this technique, airway dead space gas is aspirated from the distal endotracheal tube and replaced by fresh gas from the ventilator circuit. Potential advantages of this approach are elimination of TGI-related problems such as airway injury due to jet streams from the catheter and difficulties with humidification of the TGI gas flow. Takahashi et al\textsuperscripts{99} described the effects of combined TGE and TGI, in which TGE is applied early in the expiratory phase and TGI is applied late in the expiratory phase (Fig. 14). In a lung model and in experimental animals, they reported that combining TGE and TGI allowed precise control of end-expiratory lung volume and effective CO\textsubscript{2} elimination.

**Summary**

A variety of techniques have been developed that have in common the insufflation of gas into the central airway to facilitate CO\textsubscript{2} clearance. Some of these techniques are...
used to enhance CO₂ removal in the presence of apnea (eg, CIO). Others are used to promote bulk gas flow in the lungs (eg, TTIJV and HFIJV). Some are used as an adjunct to spontaneous ventilation (eg, transtracheal oxygen administration), whereas others are used as an adjunct to PPV (eg, TGI). Some provide PPV while bypassing the upper airway (eg, ITPV). Although some of these techniques are promising adjuncts to mechanical ventilation and may help reduce ventilator-associated lung injury (eg, TGI), much remains to be learned about their role in the care of patients with acute lung injury.

REFERENCES

TRACHEAL GAS INSUFFLATION AND RELATED TECHNIQUES

93. Takahashi T, Bugedo G, Adams AB, Bliss PL, Marini JJ. Effects of tracheal gas insufflation and tracheal gas exsufflation on intrinsic positive end-expiratory pressure and carbon dioxide elimination. Respir Care 1999;44(8):918–924.