
Monitoring and Humidification during Tracheal Gas Insufflation

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Introduction

Monitoring

Tidal Volume

Peak Inspiratory Pressure

Intrinsic Positive End-Expiratory Pressure

Carbon Dioxide Elimination Efficiency

Humidification

Summary

In order to use tracheal gas insufflation (TGI) in a safe and effective manner, it is important to understand potential interactions between TGI and the mechanical ventilator that may impact upon gas delivery and carbon dioxide (CO₂) elimination. Furthermore, potentially serious complications secondary to insufflation of cool, dry gas directly into the airway and the possibility of tube occlusion must be considered during use of this adjunct modality to mechanical ventilation. Regardless of the delivery modality (continuous TGI, expiratory TGI, reverse TGI, or bidirectional TGI), conventional respiratory monitoring is required. However, TGI with mechanical ventilation can alter tidal volume and peak inspiratory pressure and can lead to the development of intrinsic positive end-expiratory pressure. Therefore, depending on the gas delivery technique used, it is important to carefully monitor these ventilatory parameters for TGI-induced changes and understand the potential need for adjustments to ventilator settings to facilitate therapy and avoid problems. Optimally, gas insufflated by the TGI catheter should be conditioned by addition of heat and humidity to prevent mucus plug formation and potential damage to the tracheal mucosa. Finally, patients must be closely monitored for increases in peak inspiratory pressure from obstruction of the tracheal tube and should have the TGI catheter removed and inspected every 8–12 hours to assess for plugs.

Key words: tracheal gas insufflation, monitoring, humidification, mucus plug. [Respir Care 2001;46(2): 185–192]

Introduction

The process of insufflating fresh gas directly into the trachea to augment gas exchange has been utilized for

more than 15 years, in spontaneously breathing patients, as transtracheal oxygen delivery.^{1–4} More recently this adjunctive technique has been used in conjunction with volume-controlled or pressure-controlled ventilation and is

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referred to as tracheal gas insufflation (TGI).⁵⁻²² The major effect of TGI is to enhance gas exchange efficiency by removal of carbon dioxide (CO₂) from the anatomic dead space.⁵⁻⁷ When used in conjunction with mechanical ventilation, TGI may alter other parameters that affect CO₂ elimination, such as tidal volume (V_T) and peak inspiratory pressure (PIP), and can lead to the development of intrinsic positive end-expiratory pressure (auto-PEEP).^{7,9,10,12-14,20-24} A thorough understanding of interactions between TGI and these ventilatory parameters is critical to utilizing TGI in a safe, effective, and efficient manner. It is equally important to understand how to monitor for adverse effects that may result from these interactions. To avoid potential complications caused by insufflation of cool, dry gas directly into the airway, humidification must also be considered when applying TGI clinically.²⁵⁻²⁹ This article reviews issues related to monitoring and humidification when using TGI and suggests possible methods to minimize and/or prevent adverse effects when using this adjunctive therapy.

Monitoring

The statement “appearances can be deceiving” is very applicable to the subject of monitoring during use of TGI. Based on early descriptions, TGI appeared to be a relatively simple therapy. However, complexities involved in its use became evident as utilization of this therapy increased. Authors have described a variety of interactions between TGI and mechanical ventilation that influence V_T, minute ventilation (V̇_E), airway pressure, and/or total PEEP (ventilator set PEEP + auto-PEEP).^{9-13,20-23} These interactions necessitate specific adjustments and patient/ventilator monitoring (Table 1).

Tidal Volume

Numerous studies have shown that continuous TGI (c-TGI) causes an increase in inspired V_T when used in conjunction with mechanical ventilation.^{9-11,21,23} This phenomenon is addressed in various ways, depending on the ventilatory mode and TGI delivery method.

During volume-controlled ventilation, the total V_T delivered is equivalent to the ventilator set V_T plus the V_T generated by the TGI catheter. That is: V_{Ttotal} = V_{Tvent} + V_{Tcath}.

The additional volume delivered by the catheter can be determined by calculating the amount of TGI-generated V_T and subtracting this value from the ventilator-set V_T. With this adjustment a consistent V_T is delivered to the patient prior to and following initiation of TGI. For example, consider a patient on assist-control ventilation with a set V_T of 700 mL, respiratory rate of 15 breaths per

minute, and inspiratory time (T_I) of 1.5 seconds. If TGI is initiated at 6 L/min, the V_T derived from TGI is calculated as follows:

$$V_{T\text{TGI}} = (V_{\text{TGI}} \text{ L/min})(T_I)(1 \text{ min}/60 \text{ s})(1,000 \text{ mL/L})$$

$$= 150 \text{ mL}$$

where V_{TGI} = TGI flow in L/min, T_I = inspiratory time in seconds, the calculation 1 min/60 s converts from seconds to minutes, and the calculation 1,000 mL/L converts from liters to milliliters.

The TGI-derived V_T (150 mL) is then subtracted from the ventilator set V_T to obtain the adjusted ventilator V_T setting. Thus, in this example:

$$550 \text{ mL(adjusted } V_T)$$

$$= 700 \text{ mL (set } V_T) - 150 \text{ mL (} V_{T\text{TGI}})$$

This V_T adjustment prevents an increase in the total delivered V_T during TGI.

During pressure-controlled ventilation (PCV) and c-TGI, the ventilator and catheter function together to deliver gas over the preset T_I. As the catheter delivers gas, ventilator flow decreases because the catheter’s added gas contributes to achieving the set inspiratory pressure.²⁵ Under certain conditions (eg, c-TGI flows ≥ 10 L/min, long T_I, low resistance), set inspiratory pressure may be reached before the end of inspiration. Accordingly, flow from the ventilator ceases and the expiratory valve remains closed until the end of inspiration. However, the catheter continues to deliver gas into the lung, resulting in an increase in delivered V_T. This problem can be easily corrected by inserting a pressure relief valve (Bird, #04230, Bird Products, Palm Springs, California) into the ventilator circuit, allowing TGI flow (excess volume) to be vented into the atmosphere (Fig. 1).²³ If set inspiratory pressure is changed, adjustments must be made to the pressure relief valve. Delgado et al recently tested a prototype flow relief valve (Respironics, Murrysville, Pennsylvania) that removes gas from the circuit at a set flow (eg, 10 L/min) (Fig. 2).³⁰ Use of this valve may simplify monitoring during TGI administration because it eliminates the need to use a pressure relief valve and make adjustments to the pressure relief valve if set inspiratory pressure is changed.

Use of expiratory TGI (e-TGI) during volume-control ventilation prevents the delivery of additional inspired V_T because gas flow is only activated during expiration. However, during PCV, the volume of gas delivered to the airway depends on the pressure gradient between peak intrapulmonary pressure and end-expiratory lung pressure. If this pressure gradient decreases because of the development of auto-PEEP, the V_T delivered to the patient will

MONITORING AND HUMIDIFICATION DURING TRACHEAL GAS INSUFFLATION

Table 1. Monitoring and Ventilator Adjustments during Tracheal Gas Insufflation

Variable	Ventilatory Mode	TGI Delivery Mode	Action
Tidal volume	VCV	Continuous	Reduce inspired V_T to compensate for TGI flow during inspiration (see text for calculation) or insert a flow-relief valve
		Expiratory	No modification required
		Reverse	Reduce inspired V_T to compensate for TGI flow during inspiration (see text for calculation) or insert a flow-relief valve
		Bidirectional	No modification required if flow-relief valve is used
Airway Pressure	PCV	Continuous	Insert pressure or flow-relief valve
		Expiratory	May need to increase set inspiratory pressure to maintain V_T
		Reverse	May need to increase set inspiratory pressure to maintain V_T
		Bidirectional	No modification required if flow-relief valve is used
Auto-PEEP	VCV	Continuous	Reduce ventilator PEEP if PIP increases. Clinically, a 5 cm H_2O reduction in set PEEP is typically required @ TGI flows of 10 L/min
		Expiratory	Same as with continuous
		Reverse	An increase in ventilator PEEP may be necessary if NEEP is generated or total PEEP is decreased
		Bidirectional	No adjustment necessary
Auto-PEEP	PCV	Continuous	Same as with VCV
		Expiratory	Same as with VCV
		Reverse	Same as with VCV
		Bidirectional	No adjustment necessary

TGI = tracheal gas insufflation. VCV = volume-control ventilation. V_T = tidal volume. PCV = pressure-control ventilation. auto-PEEP = intrinsic positive end-expiratory pressure. PIP = peak inspiratory pressure. NEEP = negative end-expiratory pressure.

decrease.^{22,24} To maintain a constant V_T it is therefore necessary to increase set inspiratory pressure by an amount equivalent to the amount of auto-PEEP generated, or decrease set PEEP by the amount of auto-PEEP generated.

With reverse TGI (r-TGI), other monitoring issues may arise. Several studies have examined interactions between volume and pressure when using r-TGI alone and in combination with e-TGI.^{14,16–18} In those studies, r-TGI produced equivalent PEEP, compared with conventional ventilation at low flows, but negative end-expiratory pressure was generated when \dot{V}_E was increased (double or tripled) for 10–20 seconds.¹⁶ Decreases in total-PEEP were also generated when r-TGI was delivered only during expiration at 10 L/min, subsequently reducing lung volume.¹⁴ These observations are important when monitoring patients receiving TGI, because the V_T delivered during PCV depends on the pressure gradient between peak intrapulmonary pressure and end-expiratory lung pressure.

Peak Inspiratory Pressure

Typically, PIP and V_T exhibit a direct relationship when compliance and resistance are unchanged. As V_T is increased, PIP increases. Conversely, as V_T is decreased, PIP decreases. Therefore, the changes in PIP that occur when using a ventilator mode in conjunction with a spe-

cific TGI delivery method will be directly related to those observed in V_T .

Intrinsic Positive End-Expiratory Pressure

Though there is controversy regarding the impact of different TGI delivery methods on increases in total PEEP, there is consensus that TGI often creates auto-PEEP.^{7,9,10,12–14,20–24} Miro et al²⁰ proposed a theoretical framework to depict the interactions between TGI and ventilator mode, V_T , and PIP that result in the development of auto-PEEP (Fig. 3). During volume-controlled ventilation, when ventilator PEEP is left constant, V_T remains constant, but there is an increase in end-expiratory pressure and, therefore, peak airway pressure because of TGI-induced auto-PEEP. During PCV, when ventilator PEEP and peak airway pressure are kept the same as baseline, V_T excursions (and hence \dot{V}_E) are reduced because of TGI-induced auto-PEEP. When ventilator PEEP is reduced by an amount equivalent to TGI-induced auto-PEEP, V_T , peak airway pressure, and total PEEP remain the same as baseline during PCV. This conceptual framework demonstrates the impact of TGI on these ventilatory parameters, and the importance of monitoring for the development of auto-PEEP during TGI administration.

Several mechanisms may contribute to an increase in auto-PEEP when using TGI. The TGI catheter decreases

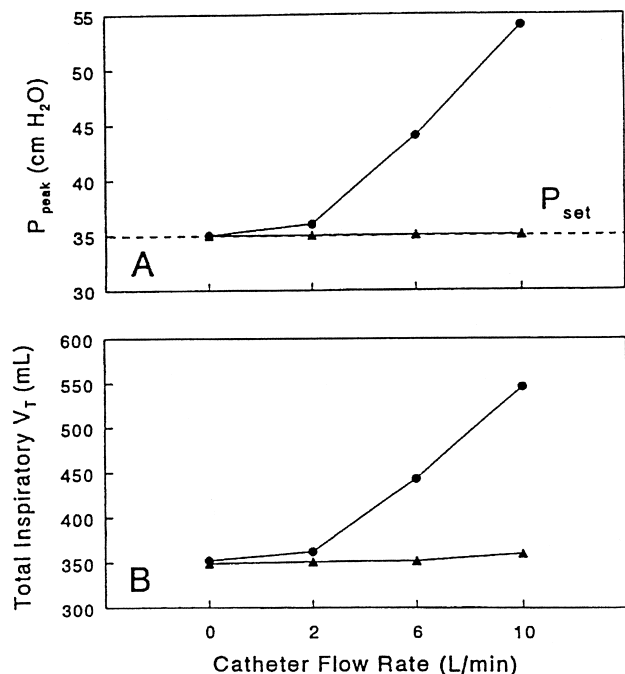


Fig. 1. Effects of catheter flow rate with (circles) and without (triangles) the pressure relief valve on (A) peak airway pressure (P_{peak}) and (B) total inspiratory tidal volume (V_T). Independent variables were constant at airway resistance = 20 cm H₂O/L/s, lung compliance = 0.01 L/cm H₂O, ventilator frequency = 10 breaths/min, and ratio of inspiratory time to total breathing-cycle time = 0.33. The horizontal dotted line at 35 cm H₂O represents the set inspiratory pressure (P_{set}). (From Reference 23, with permission.)

airway cross-sectional area and thereby increases expiratory resistance. The magnitude of this change is proportional to the outer diameter of the catheter. From this perspective, the "optimal" TGI catheter would have a small outer diameter or be incorporated into the endotracheal tube in a manner that does not reduce the inner diameter of the tube. Several studies have tested the efficacy of TGI delivered through a double-lumen endotracheal tube^{13,14} or an endotracheal tube that incorporates fine capillaries molded into the lumen.¹⁵ No problems were noted with use of these tubes. However, a major disadvantage is the need to use a special endotracheal tube in all patients who might need this therapy or the need to replace a conventional tube with a special tube in a compromised patient.

A second factor that can increase auto-PEEP is the amount of time dedicated to expiration. The expiratory phase is particularly critical during TGI administration. Expiratory time is inversely proportional to the amount of total PEEP generated, regardless of the method used to deliver TGI.^{21,23} Also, the majority of CO₂ washout during TGI occurs during expiration.¹⁰ Therefore, it is important to consider the impact of the inspiratory-expiratory ratio on the development of auto-PEEP.

A third factor to be considered is catheter configuration. Stagnation pressure (back pressure) can develop as forward flow from a straight-tip TGI catheter meets the opposing gas flow exiting the lung.⁷ Early studies postulated that the increase in back pressure (and, thus, auto-PEEP) was greater during c-TGI than during e-TGI because c-TGI delivers gas throughout the respiratory cycle.^{10,21} However, we have found that when \dot{V}_E is maintained constant, c-TGI and e-TGI produce equivalent levels of total PEEP when delivered with a straight-tip catheter.²⁴

Alternatively, TGI can be delivered with a reverse tip (reverse thrust) catheter or a catheter that delivers bidirectional flow (bi-TGI). With bi-TGI, gas is delivered into the airway simultaneously in forward and reverse directions. Of approaches evaluated to date, r-TGI and bi-TGI appear to be the most effective in preventing increased total PEEP during TGI administration.^{14,16–18} Delgado et al postulate that simultaneous insufflation of gas in opposite directions might reduce or eliminate the back pressure that produces auto-PEEP.³⁰ Four catheter configurations were studied in an artificial lung model during PCV under constant minute ventilation conditions (Fig. 4). During bi-TGI and r-TGI, levels of total PEEP were lower during PCV than during c-TGI and e-TGI, at each of the 3 inspiratory-expiratory ratios studied (1:1, 1:2, 2:1), and CO₂ elimination efficiency was comparable. If supported in animal and human studies, these findings suggest an important advantage of r-TGI and bi-TGI over c-TGI and e-TGI delivered in a forward flow direction.

Monitoring auto-PEEP can be quite challenging. The end-expiratory occlusion method cannot be used during any TGI technique that continues to deliver gas into the lungs, because a static end-expiratory pressure cannot be achieved.²⁶ The use of respiratory inductive plethysmography also presents difficulties because substantial baseline drift occurs over time.^{9,20} In addition, respiratory inductive plethysmography is not widely available. We have found that a 5 cm H₂O reduction in extrinsic (ventilator set) PEEP is typically required to keep total PEEP constant during c-TGI at 10 L/min.

Carbon Dioxide Elimination Efficiency

The efficiency of TGI is best measured by monitoring arterial carbon dioxide tension (P_{aCO_2}). However, this measurement is invasive and episodic and there are few data to provide guidelines about optimal times to measure P_{aCO_2} following initiation of TGI. Hoffman et al¹⁹ reported no difference in P_{aCO_2} measured at 30 minutes and 60 minutes after initiation of TGI in 8 acute respiratory distress syndrome patients. They therefore concluded that effectiveness of TGI was evident within 30 minutes, suggesting that the efficacy of this intervention could be rapidly determined.

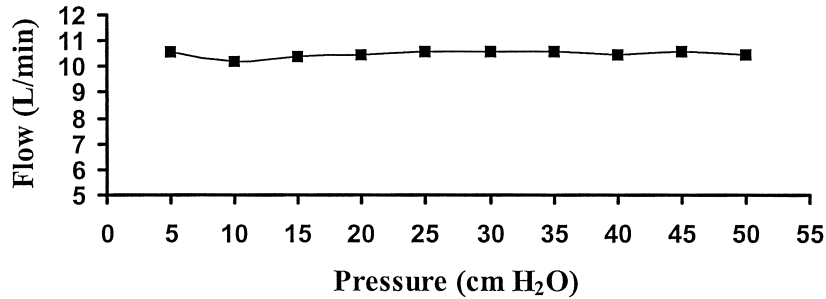


Fig. 2. Insertion of a prototype flow relief valve into the ventilator circuit maintains consistent venting of 10 L/min gas flow and provides consistent delivered volume during continuous tracheal gas insufflation under varying inspiratory pressures.

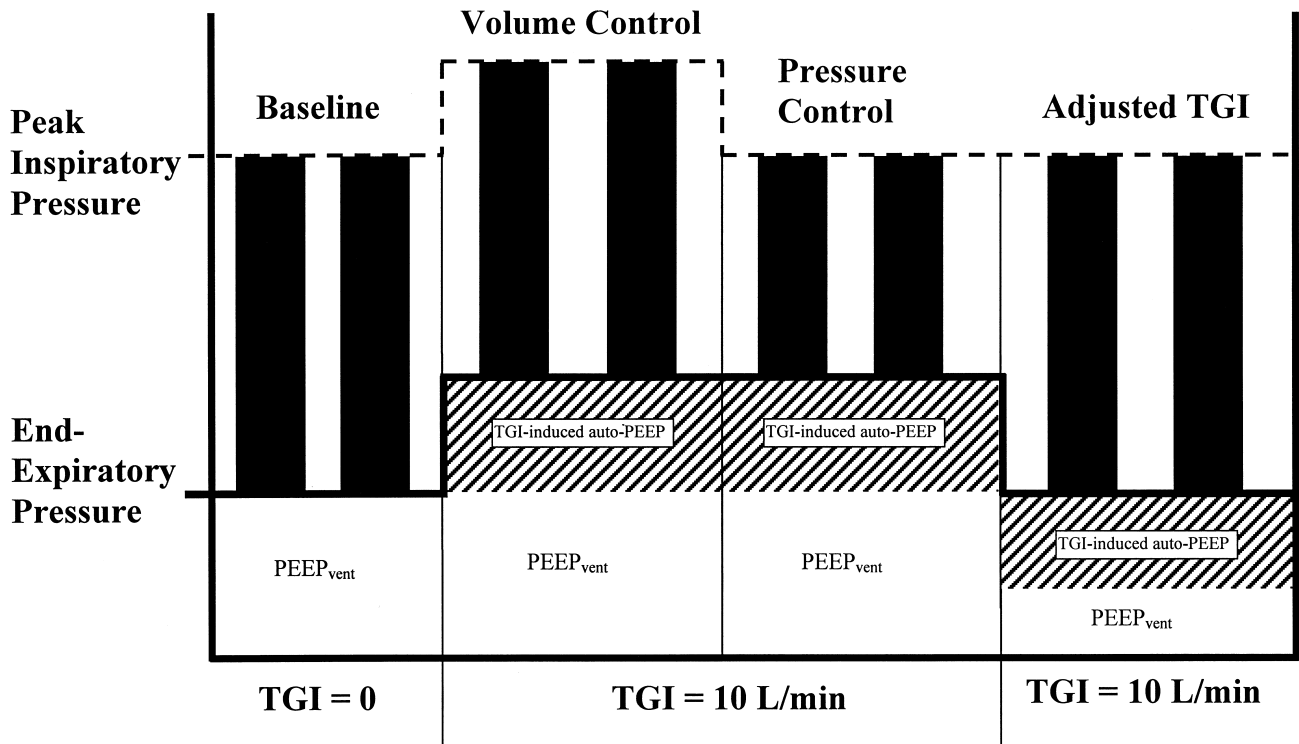


Fig. 3. Theoretical framework that illustrates interactions between tracheal gas insufflation (TGI), ventilator mode, minute ventilation (tidal volume), and intrinsic positive end-expiratory pressure (auto-PEEP). During volume-controlled ventilation, when ventilator PEEP (height of clear areas labeled PEEP_{vent}) is left constant, tidal volume (height of black bars) remains constant, but there is an increase in end-expiratory pressure and, therefore, peak airway pressure, because of TGI-induced auto-PEEP (height of cross-hatched areas). During pressure-controlled ventilation, when PEEP_{vent} and peak airway pressure are kept the same as baseline, tidal volume excursions (and, thus, minute ventilation) are reduced because of TGI-induced auto-PEEP. When PEEP_{vent} is reduced by an amount equivalent to TGI-induced auto-PEEP, tidal volume, peak airway pressure, and total PEEP remain the same as baseline during pressure-control ventilation. (Adapted From Reference 20, with permission.)

Two studies evaluated the use of monitoring end-tidal carbon dioxide tension (P_{ETCO₂}), obtained by capnography, as a semiquantitative indicator of TGI efficiency.^{9,12} In 8 patients with acute respiratory failure, Ravenscraft et al⁹ found a moderate (r = 0.68) correlation between the percentage reduction in P_{aCO₂} (%ΔP_{aCO₂}) as a function of the percentage reduction in P_{ETCO₂} (%ΔP_{ETCO₂}) from the baseline value (Fig. 5). Kuo et al¹² compared the

%ΔP_{aCO₂} and %ΔP_{ETCO₂} from baseline values in 20 adults with acute respiratory distress syndrome. The %ΔP_{ETCO₂} correlated significantly (r = 0.75; p < 0.001) with the %ΔP_{aCO₂} (Fig. 6).⁷ Both authors concluded that, although P_{ETCO₂} is a poor estimate of P_{aCO₂} in patients with respiratory failure, these data may justify use of P_{ETCO₂} as a monitor of trends regarding changes in CO₂ elimination efficiency during TGI.

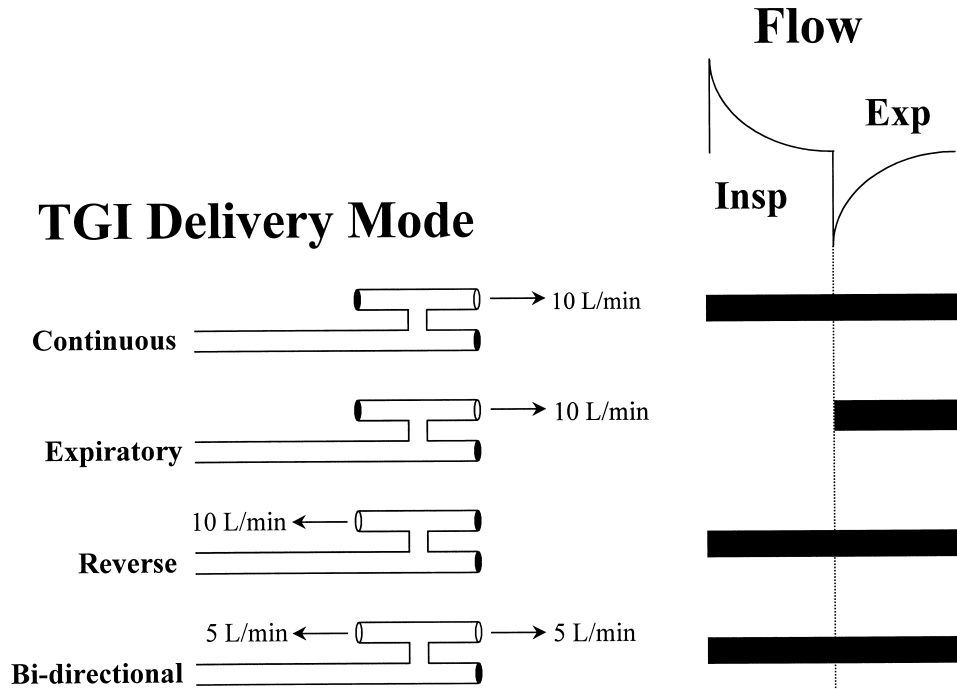


Fig. 4. Prototype H-shaped-tip catheter configurations and flow patterns with different tracheal gas delivery modes.

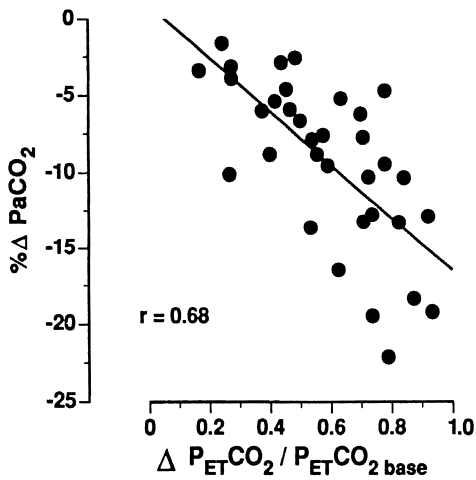


Fig. 5. Percentage reduction of arterial carbon dioxide tension (%ΔP_aCO₂) from baseline as a function of the reduction in the end-tidal carbon dioxide tension (P_{ET}CO₂) from the baseline value (P_{ET}CO₂base) in 8 patients suffering acute respiratory failure and receiving tracheal gas insufflation. As the difference between P_{ET}CO₂ and P_{ET}CO₂base increased, P_aCO₂ decreased. (From Reference 9, with permission.)

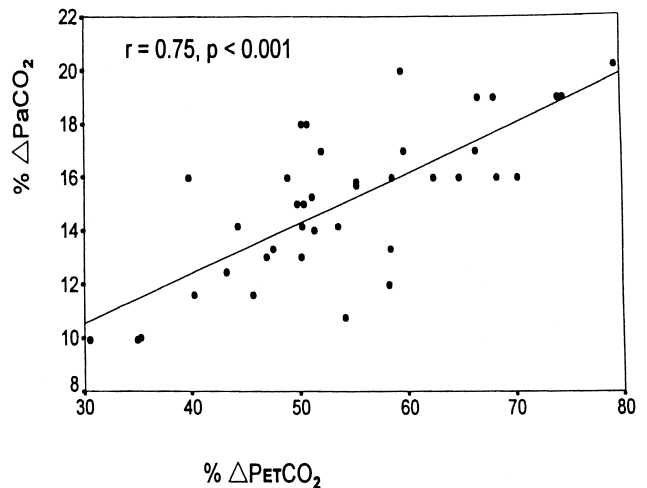


Fig. 6. Relationship between percent reduction of arterial carbon dioxide tension (%ΔP_aCO₂) and percent reduction in end-tidal carbon dioxide tension (%ΔP_{ET}CO₂) from baseline values in 20 patients suffering from acute respiratory distress syndrome and receiving tracheal gas insufflation. (From Reference 12, with permission.)

Humidification

Humidification during TGI is an important issue that has received little study. The data available are mainly derived from studies investigating long-term use of tran-

stracheal oxygen delivery in spontaneously breathing patients, whereas most TGI studies have been conducted in patients on full ventilatory support.

The respiratory tract performs a role in a variety of functions, including ventilation, gas conditioning, production and inactivation of bioactive substances, filtering,

smell, communication, mucociliary transport, and surfactant production.^{27,28} When a patient is endotracheally intubated, some of these functions are interrupted or bypassed, whereas others (including the integrity of secretions) are affected by the temperature and humidity of the inspired gas. In a preliminary report, Shapiro et al²⁹ found that TGI significantly cooled the central airways and that the conditioned gas delivered by the ventilator cannot compensate for this effect. Further, patients who require mechanical ventilation are more likely than spontaneously breathing patients to be more susceptible to having more secretions and more susceptible to the effects of jets of gas striking the tracheal wall.²⁵

In airway mucosa there are basically 3 heat and moisture paths. The heat and moisture given off during inspiration, the recovered heat and moisture during exhalation, and the heat and moisture obtained from systemic reserves.³¹ Therefore, it is logical to assume that the airways may be exposed to adverse effects if the inspiratory gas delivered by the ventilator and TGI system is not conditioned. Fletcher et al³² reported the development of an endotracheal mass (mucus plug 1.8 × 2.5 cm) after 9 days of transtracheal oxygen delivery at 3 L/min. In a report by Burton et al³³ a 50-year-old man with chronic obstructive pulmonary disease and pulmonary fibrosis developed severe dyspnea and subsequently expired after approximately 15 days of transtracheal oxygen delivery with a flow of 3 L/min. The autopsy report revealed a mucus plug obstructing the patient's trachea. Hoffman et al³ studied 40 patients receiving long-term transtracheal oxygen delivery and reported formation of mucus balls on the tip of the catheter in 25% during the time the tract is immature and the catheter is cleaned in place. A retrospective study of 56 patients using transtracheal oxygen catheters from 2 days to more than 6 years found a mucus plug prevalence rate of 38%.³⁴

Most tracheal gas insufflation studies completed on humans and animals have been short-term and either do not report whether the TGI gas was heated and humidified or report that a nonheated, dry gas was used. When a heated and humidified system was used to condition the gas during intratracheal pulmonary ventilation, Kolobow et al¹⁶ reported no damage to the tracheal mucosa and no encrustation. Danan et al¹⁵ reported using humidified and warmed TGI in 9 premature newborns for up to 31 days (mean 17 d). The tracheas of 3 newborns who died were examined and found normal. No problems due to mucus plug formation were reported in any subjects. In that study, the humidified and warmed (Fisher and Paykel MR600, Auckland, New Zealand) gas was derived from the inspiratory line of a conventional ventilator circuit and forced into the TGI capillaries of an endotracheal tube using a membrane pump (110 cm H₂O) at a rate of 0.5 L/min. Kuo et al¹² reported using humidified, nonheated TGI gas with a

straight-tip catheter continuously for up to 72 hours in 12 patients. TGI was discontinued in 2 patients because of intratracheal catheter obstruction, which occurred after 58 and 67 hours, respectively. Both events were detected immediately (by the whistling sounds emitting from the pressure release valve on the humidifiers) and caused no problems. When removed, both catheter tips were obstructed by inspissated mucus plugs. Nine patients completed up to 72 hours of TGI. Eight had no change in the tracheobronchial mucosa, and one had focal mucosal erythema adjacent to the carina on bronchoscopic examination.

To date, there have been no reports of airway occlusion secondary to mucus plugging during TGI. Nevertheless, it is important to monitor for this complication and institute preventive measures. If the expiratory circuit of the ventilator becomes occluded, the TGI catheter could deliver a large volume of gas, potentially resulting in serious barotrauma and hemodynamic compromise.⁹ A reliable mechanism to detect an increase in pressure and stop TGI flow needs to be developed to enable safe long-term provision of TGI.^{9,25,26} Until such mechanisms are commercially available, using prophylactic measures to avoid problems is important. These include monitoring for increases in PIP due to possible mucus plugging and removal of the TGI catheter every 8–12 hours to assess for plugs. One difference between the gas conditioning techniques described by Kolobow et al¹⁶ and Danan et al¹⁵ and that described by Kuo et al¹² was that the latter study did not heat the inspired gas. This observation suggests that additional attention needs to be given to developing a mechanism to heat and humidify TGI gas delivered in all systems.

Summary

The use of TGI as an adjunct to mechanical ventilation in the intensive care unit environment requires conventional monitoring, regardless of the TGI system used. In addition, monitoring of changes in V_T , PIP, and P_{aCO_2} are necessary. Monitoring for the development of auto-PEEP is also indicated. Optimally, gas insufflated by the TGI catheter should also be conditioned by addition of heat and humidity to prevent mucus plug formation and damage to the tracheal mucosa. Finally, patients should be monitored for increases in PIP due to mucus plugging, and the TGI catheter should be removed every 8–12 hours to assess for plugs.

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