

Efficacy of Preoxygenation with Tidal Volume Breathing

Comparison of Breathing Systems

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Background: Preoxygenation before tracheal intubation is intended to increase oxygen reserves and delay the onset of hypoxemia during apnea. Various systems are used for preoxygenation. Designed specifically for preoxygenation, the NasOral system uses a small nasal mask for inspiration and a mouthpiece for exhalation. One-way valves in the nasal mask and the mouthpiece ensure unidirectional flow. This investigation compares the efficacy of preoxygenation using the standard circle system with the NasOral system and five different resuscitation bags.

Methods: Twenty consenting, healthy volunteers were studied in the supine position for 5-min periods of tidal volume breathing using the circle absorber system, the NasOral system, and five resuscitation bags in a randomized order. Data were collected during room air breathing and at 30-s intervals during 5 min of oxygen administration. Inspired oxygen, end-tidal

oxygen, and end-tidal nitrogen were measured by mass spectrometry.

Results: At 2.5 min of oxygenation, end-tidal oxygen plateaued at 88.1 ± 4.8 and $89.3 \pm 6.4\%$ (mean \pm SD) for the circle absorber and NasOral systems, respectively. This was associated with inverse decreases in end-tidal nitrogen. At no time did these end-tidal oxygen or nitrogen values differ from each other. Three of the resuscitation bags (one disk type and two duck-bill type with one-way exhalation valves) delivered inspired oxygen more than 90%, and the end-tidal oxygen plateaued between 77 and 89% at 2 min of tidal volume breathing. The other two resuscitation bags (both duck-bill bags without exhalation valves) delivered inspired oxygen less than 40% and the end-tidal oxygen values ranged between 21.8 ± 5.0 and $31.9 \pm 8.7\%$.

Conclusions: The circle absorber and NasOral systems were equally effective in achieving maximal preoxygenation during tidal volume breathing. Resuscitation bags differed markedly in effectiveness during preoxygenation; those with duck-bill valves without one-way exhalation valves were the least effective. Thus, the use of these bags should be avoided for preoxygenation. (Key words: Breathing circuits; denitrogenation; rapid-sequence induction and intubation; resuscitation bags.)

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PREOXYGENATION of the lungs before tracheal intubation is a well-recognized technique designed to increase oxygen reserves and thereby delay the onset of hypoxemia during apnea.¹⁻³ It is particularly advantageous when difficult intubation or ventilation are suspected and when manual ventilation is undesirable, as during rapid-sequence induction and intubation.⁴ Various systems have been advocated to accomplish preoxygenation.^{3,5-11} In the operating room, anesthetic circuits are used,^{3,5-7} whereas in the critical care setting, resuscitation bags are often used.^{10,11}

A new system designed specifically for preoxygenation has gained popularity in Europe (NasOral; LogoMed GmbH, Windhagen, Germany). The NasOral system (not yet available in the United States) delivers oxygen from a 3.3-l reservoir bag to a small nasal mask, with exhalation occurring *via* the oral route by means of a mouthpiece.

One-way valves in the nasal mask and the mouthpiece ensure unidirectional flow (fig. 1). Fresh gas flow (FGF) is adjusted to the individual's ventilation to maintain an inflated reservoir bag.

Reports have described the effectiveness of the NasOral system as providing "optimal preoxygenation" in 1–3 min,^{8,9} but there have been no studies to date comparing this system with other systems in the same subjects. The current investigation was undertaken in normal subjects to compare the effectiveness of various breathing systems in achieving preoxygenation using tidal volume breathing.

Materials and Methods

After obtaining institutional review board approval, a total of 20 consenting, healthy volunteers, American Society of Anesthesiologists physical status I (14 men



Fig. 1. The NasOral system uses a small nasal mask for inspiration of oxygen from a reservoir bag. Exhalation occurs via a mouthpiece. One-way valves in the nasal mask and the mouthpiece ensure unidirectional flow.

and 6 women, with a mean age \pm SD of 35 ± 7 yr and a mean weight of 70 ± 14 kg), without history of lung or cardiac disease, were studied. The subjects were non-bearded, nonsmoking, and recruited from operating room personnel without inducement. The volunteers were allowed a light breakfast on the day of the studies. The volunteers were allowed ample time to familiarize themselves with the various systems and with mask breathing while maintaining a tight seal.

In the supine position, the subjects were asked to breathe at normal tidal volume for 5-min periods using the following systems: (1) circle absorber system; (2) NasOral system; and (3) five different resuscitation bags. All volunteers were studied using each system in a randomized order using a computer-generated random assignment table. A tight-fitting facemask was used with all the systems, with the exception of the NasOral system with which a tight-fitting nasal mask and mouthpiece were used (fig. 1). Data were collected during room-air tidal volume breathing (baseline) and at 30-s intervals during oxygenation. Fifteen-minute periods of room-air tidal volume breathing were allowed between each test period with the various breathing systems.

Measured parameters, in volume percent, included inspired oxygen (O_2), end-tidal oxygen (ET_{O_2}), end-tidal nitrogen (ET_{N_2}), end-tidal carbon dioxide (ET_{CO_2}), and respiratory rate. Measurements were performed with use of a Perkin-Elmer Model MGA 1100A mass spectrometer (Advantage 2000, Marquette Electronics Inc., Milwaukee, WI). Side-stream respiratory gases were sampled at a rate of 240 ml/min from a sampling port interposed between the filter and the anesthetic circuit or resuscitation bags. With the NasOral system, end-tidal gases were sampled from an adapter inserted between the mouthpiece and a 60-cm length of corrugated hose used as a reservoir (fig. 1). Calibration with known gas mixtures was conducted according to the manufacturer's specifications before commencement of the study. This calibration included ratio and summing correction factors for dry inspired gases and end-tidal gases saturated with water vapor.

A single anesthesia machine (model 210 Excel; Datex-Ohmeda, Madison, WI) was used throughout the studies. When the circle absorber system was evaluated, an Ohmeda GMS absorber was used with barium hydroxide lime, USP (Baralyme, Chemetron Medical Division, St. Louis, MO) absorbent, disposable, 152-cm corrugated breathing tubes and a 3-l capacity natural latex breathing bag (King Systems, Noblesville, IN) and an FGF of 7 l/min. When the NasOral system was tested, the oxygen supply

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tubing was attached to the common gas outlet of the anesthesia machine, and FGF was adjusted according to the subject's ventilation while maintaining an inflated reservoir bag. The reservoir bags of the circle absorber and NasOral systems were fully inflated using the oxygen flush and partially occluding the masks, immediately before the beginning of oxygenation.

The adult resuscitation bags evaluated were the Capniflo (Kirk Specialty Systems, Carrollton, TX), the Silicone Resuscitator (Laerdal Medical Corp., Wappingers Falls, NY), a Ruben non-rebreathing valve (Anesthesia Associates, San Marcos, CA) mounted on an Ambu black rubber bag (Ambu International, Hanover, MD), the 1st Response (Sims-Intertech, Ft. Myers, FL), and the Code Blue (Vital Signs, Totowa, NJ). When resuscitation bags were evaluated, oxygen 15 l/min, supplied from a side-port oxygen regulator on the anesthesia machine, was delivered to the resuscitation bags.

Survival statistics were applied to ET_{O_2} versus time curves to determine statistically significant differences (overall and pairwise) between circuits in reaching a target ET_{O_2} of approximately 90%. The Wilcoxon (Gehan) statistic and two-tailed probabilities were calculated. Statistical significance was accepted at $P < 0.05$. A two-way repeated-measures analysis of variance was used to detect statistical differences in the variables studied between the various systems tested and at 30-s time intervals over the 5-min test period. After determining the time point at which ET_{O_2} reached a plateau in all breathing systems, the Student-Newman-Keuls test was applied to a selected time period to identify significant differences between circuits at plateau. Statistical significance was accepted at $P < 0.05$. Values are reported as mean \pm SD.

Results

Figure 2 compares ET_{O_2} and ET_{N_2} data during 5-min periods of oxygenation with the circle absorber and the NasOral systems. Between 30 s and 2 min of oxygenation, ET_{O_2} increased rapidly and significantly with both systems as compared with room air. At 2.5 min, ET_{O_2} plateaued at 88.1 ± 4.8 and $89.3 \pm 6.4\%$ for circle and NasOral, respectively. The ET_{N_2} had rapidly decreased from 78.0 ± 0.1 to 10.8 ± 7.7 and $6.7 \pm 5.9\%$ by 2 min of oxygenation, for the circle and NasOral systems, respectively. At 2.5 min, ET_{N_2} plateaued at 6.7 ± 4.5 and

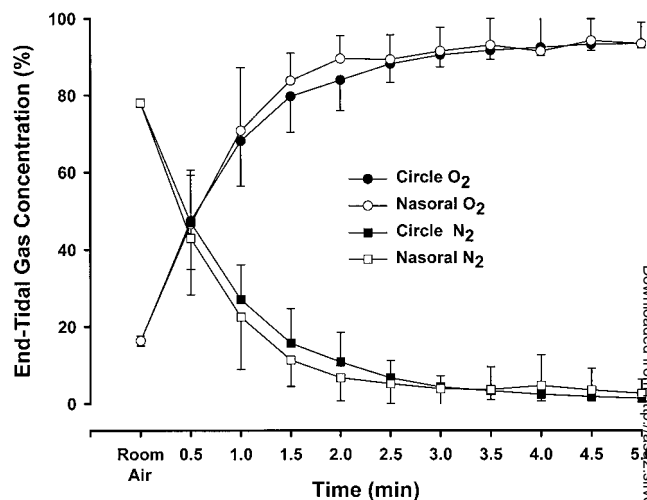


Fig. 2. Comparison of mean end-tidal oxygen and nitrogen concentrations obtained at 30-s intervals during 5-min period of spontaneous tidal volume oxygenation using the circle absorber and NasOral systems in 20 volunteers. Data shown as mean \pm SD.

$5.1 \pm 5.1\%$ for the circle and NasOral systems, respectively, and there was no further significant change between 2.5 and 5 min. Pairwise survival analysis demonstrated that the NasOral system resulted in significantly faster oxygenation, *i.e.*, more volunteers reached a target ET_{O_2} of approximately 90% faster in comparison with the circle absorber system. However, once reaching the plateau, the ET_{O_2} did not differ between the two systems.

Three of the resuscitation bags (the Kirk, the Ruben valve, and the Laerdal) delivered inspired O_2 more than 90%. inspired O_2 with the bag incorporating the Ruben valve ranged between 91.0 ± 4.5 and $98.2 \pm 3.5\%$, the Laerdal bag ranged between 90.1 ± 4.1 and $91.4 \pm 2.7\%$ and the Kirk bag ranged between 97.2 ± 1.3 and $98.4 \pm 1.6\%$. Over the entire 5-min period, the Kirk and Ruben valve bags delivered statistically ($P < 0.0001$) higher inspired O_2 than the Laerdal bag. Tidal volume breathing with the Vital Signs and the Sims bags resulted in significantly lower inspired O_2 than the Laerdal, Kirk, and Ruben valve bags. During the 5-min period, the inspired O_2 for these two bags never exceeded 40%.

When using the Ruben valve, Laerdal, and Kirk resuscitation bags, ET_{O_2} increased rapidly and plateaued at 77%, 84%, and 89%, respectively, at 2 min (fig. 3). The ET_{O_2} values at plateau were significantly different from each other. In addition, the Kirk bag resulted in significantly faster oxygenation (*i.e.*, more volunteers reached

|| Additional data are available from the authors by request.

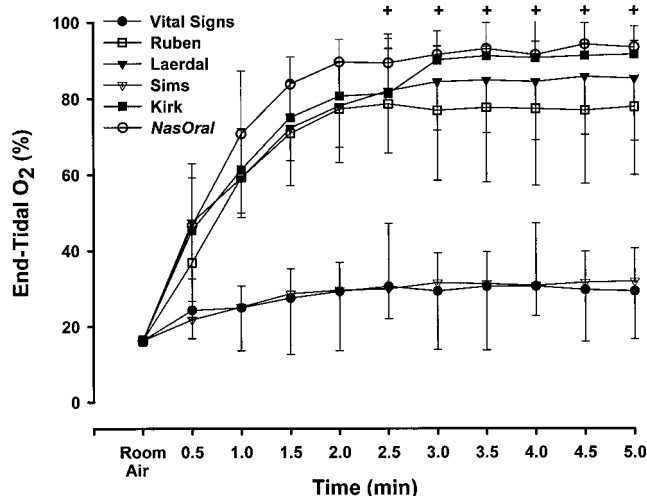


Fig. 3. Comparison of mean end-tidal oxygen concentrations obtained at 30-s intervals during 5-min periods of spontaneous tidal volume oxygenation using the NasOral system and five resuscitation bags in 20 volunteers. Data shown as mean \pm SD. + = significant difference between bags.

a ET_{O_2} 90% or more faster) than either the Ruben valve or the Laerdal bags.

The values for ET_{O_2} ranged from 24.4 ± 3.9 to $30.6 \pm 6.5\%$ for the Vital Signs bag and 21.8 ± 5.0 to $31.9 \pm 8.7\%$ for the Sims bag during the 5-min period of oxygenation. These variables did not change significantly over the remainder of the study period. The mean ET_{O_2} (fig. 3) or ET_{N_2} values during the use of these two bags did not differ statistically from each other.

In comparison with the three resuscitation bags that delivered high inspired O_2 (the Ruben valve, Laerdal bags, and Kirk bags), the NasOral system resulted in a significantly faster oxygenation and higher ET_{O_2} plateau. Between 2 and 5 min, the four systems plateaued at significantly different ET_{O_2} levels (the NasOral between 92 ± 1.5 and $95.6 \pm 1.4\%$; the Kirk between 90.1 ± 1.1 and $91.5 \pm 1.1\%$; the Laerdal between 84.4 ± 3.0 and $85.7 \pm 3.9\%$; and the Ruben valve between 76.9 ± 4.9 and $77.9 \pm 4.8\%$).

Mean ET_{CO_2} and respiratory rate did not significantly change throughout the study period.

Discussion

Previous studies on preoxygenation have been directed toward measurements of indices reflecting its efficacy and efficiency.¹² Measurements of alveolar oxygenation,¹³⁻¹⁵ alveolar denitrogenation,⁷ or the partial

pressure of arterial oxygen^{16,17} have been used as indices of the efficacy of preoxygenation, whereas the decline of hemoglobin saturation during apnea^{3,6,18,19} reflects its efficiency. Maximal preoxygenation is achieved when the alveolar, arterial, tissue, and venous compartments are all filled with oxygen.^{12,20} Failure to breathe a high inspired O_2 through the system used, insufficient time of preoxygenation,^{12,13} and the presence of leak under the mask^{3,5,15,21} can result in submaximal alveolar oxygenation.¹² Because many confounding variables can result in faster hemoglobin desaturation during apnea, the need to maximally preoxygenate before tracheal intubation is important, especially in patients with oxygen transport limitations and those in whom difficulty in airway management is anticipated.^{12,22,23}

In the current investigation, the FGs that were chosen reflect current clinical practice. The volunteers received training in breathing through these systems beforehand so as to avoid leaks, which are known to influence inspired O_2 ,^{3,5,15,21} and to avoid abnormal breathing which could influence ET_{CO_2} .²⁴ By avoiding these factors, the changes in inspired O_2 , ET_{O_2} , and ET_{N_2} can be attributed to the system tested.

The end points of preoxygenation and denitrogenation have been defined as a ET_{O_2} of 90%^{6,13,14} and a ET_{N_2} of approximately 5%, respectively. The shape of the oxygen washin curve observed with the circle absorber and the NasOral systems is in agreement with previous studies.^{13,15} The nitrogen washout curve was also similar to that reported by Carmichael *et al.*⁷

It is evident from the current investigation that maximal alveolar preoxygenation cannot be reliably achieved with tidal volume breathing during the first minute in adults, regardless of the system used, and that a period of at least 2.5 min is required. Both the circle absorber and NasOral systems were equally effective in achieving alveolar oxygenation, despite their different characteristics. The effect of nitrogen rebreathing at 7-l FGF in the circle absorber system was of such minor importance that it had no discernible impact on the increase of ET_{O_2} . However, our findings suggest that the use of the NasOral system results in slightly faster increase but not more optimal plateau ET_{O_2} in comparison to the circle absorber system.^{8,9} Although it is not currently available in the United States, the cost of the NasOral system in Europe is approximately equal to \$35.82 US. Thus, we see little justification for the additional cost of this device in the operating room where the circle absorber system can be used for both preoxygenation and for general anesthesia.

This investigation also demonstrates that the effectiveness of various resuscitation bags in achieving preoxygenation differs markedly during spontaneous respiration. Because of their design, some resuscitation bags (the Vital Signs and Sims bags) could not deliver high inspired O_2 , despite an FGF of 15 l/min. Resuscitation bags can be categorized into two groups depending on the type of valve mechanism. Disk-type valve systems use single or multiple disks to allow fresh gas to flow to the subject (and seal the exhalation port) during inspiration. The disk returns to its former position and opens the exhalation port during exhalation. Because this disk valve function is not dependent on compression of the reservoir bag, this type of resuscitation bag functions equally well during manual and spontaneous ventilation. The Ruben disk-type resuscitation bag we tested delivered a inspired O_2 more than 90%. Disk-type resuscitation bags can deliver high inspired O_2 during spontaneous ventilation and therefore can be used effectively for preoxygenation in the critical care setting.^{11,25}

Resuscitation bags using duck-bill inspiratory valves function differently during manual *versus* spontaneous ventilation. During manual ventilation, fresh gas is forced through the valve base, opening the duck-bill valve and delivering fresh gas to the patient's lungs. This force also seals the valve base to the exhalation port. During exhalation, the valve base returns to its former position, and, thus, exhaled gases are vented to the exhalation port. The efficacy of the duck-bill type resuscitation bags in delivering high inspired O_2 during spontaneous breathing has been previously questioned. Mills *et al.*²⁵ found that duck-bill-type resuscitation bags, without one-way exhalation valve to prevent air entrainment, showed variability in delivered oxygen concentration during spontaneous ventilation. They suggested that duck-bill resuscitation bags should not be used in spontaneously breathing patients when high inspired O_2 is required.

Our findings with the duck-bill-type resuscitation bags without one-way exhalation valves confirm those of Mills *et al.*,²⁵ that they cannot deliver a high inspired O_2 in a spontaneously breathing subject, even if high FGF is used. In the absence of a one-way valve on the exhalation port, generation of sufficient negative pressure to open the duck-bill valve becomes impossible. During inspiration, the unsealed valve base allows room air to

enter through the exhalation port and mix with oxygen from a partially open duck-bill valve.

Contrary to the findings of Mills *et al.*,²⁵ the current study demonstrates that in the presence of a one-way valve on the exhalation port, duck-bill-type resuscitation bags (Laerdal and Kirk) do reliably deliver a inspired O_2 more than 90% during oxygenation with an FGF of 15 l/min. The addition of this valve seals the exhalation port during inspiration and allows the patient to generate sufficient negative pressure to open the duck-bill valve permitting oxygen to flow without dilution.#

The NasOral system has advantages over resuscitation bags when used for preoxygenation in the critical care setting. (1) It provides better preoxygenation than all the resuscitation bags tested. This is probably related to the higher inspired O_2 that is achieved with NasOral system because of its non-rebreathing characteristics, and the decreased apparatus dead space. (2) It is economical when oxygen tanks are used, since it requires a FGF comparable to the subjects minute ventilation. (3) It can provide apneic oxygenation *via* the nasal mask during laryngoscopy and orotracheal intubation, if needed. Disadvantages of the system are that it requires patient cooperation to use the mouthpiece and that it cannot be used for positive pressure ventilation.

In conclusion, the circle absorber and the NasOral systems are equally effective in achieving maximum preoxygenation during tidal volume breathing, whereas resuscitation bags differ markedly in this regard. The inability of a resuscitation bag to deliver a high inspired O_2 may have serious consequences during rapid-sequence induction and intubation in the critical care setting or during transport of the spontaneously breathing, critically ill patient. Clinicians should ascertain that the resuscitation bags used at their institution are capable of delivering a high inspired O_2 during spontaneous ventilation.

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For a diagram of these different bag-valve combinations and their behavior during spontaneous and controlled ventilation, please see the Web Enhancement to this article.

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