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ORIGINAL CONTRIBUTION

Assessment of Common Preoxygenation Strategies Outside of the Operating Room Environment

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Abstract

Objectives: Preoxygenation prior to intubation aims to increase the duration of safe apnea by causing denitrogenation of the functional residual capacity, replacing this volume with a reservoir of oxygen. In the operating room (OR) the criterion standard for preoxygenation is an anesthetic circuit and well-fitting face mask, which provide a high fractional inspired oxygen concentration (FiO_2). Outside of the OR, various strategies exist to provide preoxygenation. The objective was to evaluate the effectiveness of commonly used preoxygenation strategies outside of the OR environment.

Methods: This was a prospective randomized unblinded study of 30 healthy staff volunteers from a major trauma center emergency department (ED) in Sydney, Australia. The main outcome measure is fractional expired oxygen concentration (FeO_2) measured after a 3-minute period of tidal volume breathing with seven different preoxygenation strategies.

Results: The mean FeO_2 achieved with the anesthetic circuit was 81.0% (95% confidence interval [CI] = 78.3% to 83.6%), bag-valve-mask (BVM) 80.1% (95% CI = 76.5% to 83.6%), BVM with nasal cannula (NC) 74.8% (95% CI = 72.0% to 77.6%), BVM with positive end-expiratory pressure valve (PEEP) 78.9% (95% CI = 75.4% to 82.3%), BVM + NC + PEEP 75.5% (95% CI = 72.2% to 78.9%), nonrebreather mask (NRM) 51.6% (95% CI = 48.8% to 54.4%), and NRM + NC 57.1% (95% CI = 52.9% to 61.2%). Preoxygenation efficacy with BVM strategies was significantly greater than NRM strategies ($p < 0.01$) and noninferior to the anesthetic circuit.

Conclusions: In healthy volunteers, the effectiveness of BVM preoxygenation was comparable to the anesthetic circuit (criterion standard) and superior to preoxygenation with NRM. The addition of NC oxygen, PEEP, or both did not improve the efficacy of the BVM device.

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Preoxygenation before induction of anesthesia for intubation is undertaken to provide a reservoir of oxygen within the lungs, which can delay desaturation during the period of apnea associated with induction.[1] By breathing a high fractional inspired oxygen concentration (FiO_2), the lung volume is denitrogenated: the approximately 79% nitrogen from room air ventilation is replaced with a higher percentage of oxygen.

The majority of intubations occur in an operating room with preoxygenation achieved using an anesthetic circuit, providing this high FiO_2. Furthermore, the efficacy of preoxygenation may be continuously assessed by estimating the degree of denitrogenation using a gas analyzer to determine the fractional expired oxygen concentration (FeO_2).[2]

Contrast this with emergent intubations that may occur in the emergency department (ED), in the intensive care unit (ICU), or in the prehospital setting. These intubations are more likely to involve nonfasted patients, and those with associated respiratory or circulatory compromise. Airway management in the ED and ICU has also been shown to be associated with greater adverse incidents.[3] Effective preoxygenation would

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seem to be even more important in this setting, yet it may be suboptimal for a number of reasons. There is no standard preoxygenation method in the ED, ICU, or prehospital setting, and there is no way of assessing the degree of denitrogenation achieved prior to induction of anesthesia.

Commonly used methods of preoxygenation involve tidal volume breathing from high oxygen concentration sources through a well-fitting mask for 3 minutes. The high FiO_2 source may be: 1) an anesthetic circuit that prevents rebreathing of CO_2, 2) a nonrebreather mask (NRM), or 3) a bag-valve-mask (BVM) device.

Despite both the NRM and the BVM devices employing a reservoir system to allow high FiO_2 gas to be inspired during peak inspiratory flow, they have both previously been shown to provide only moderate increases in FeO_2 when tested.[4] This is likely to reflect the entrainment of room air both around the mask and through the valves present on these devices.[5,6]

The addition of a spring-loaded positive end-expiratory pressure (PEEP) valve to a BVM may reduce room air entrainment through the expiratory port of some BVM devices, and the addition of PEEP has also been shown to improve arterial oxygenation.[7,8] Many authors recommend the addition of nasal cannula (NC) to facilitate ongoing oxygenation during apnea, by a process of bulk flow gas movement.[8,9] The addition of NC oxygen during the preoxygenation period provides a higher oxygen flow rate overall and in combination with a BVM and a PEEP valve may provide continuous positive airway pressure, which has been shown to increase duration of apnea without desaturation.[10]

To evaluate the efficacy of preoxygenation in healthy volunteers, and to assess the adjuncts described, we compared the above three methods with four additional techniques: 4) NRM with NC oxygen, 5) BVM with NC oxygen, 6) BVM with PEEP valve, and 7) BVM with PEEP valve and NC oxygen.

METHODS

Study Design

This was an observational noninvasive study of human physiology. Before data collection, approval for the study was granted by the South Western Sydney Local Health District Human Research Ethics Committee (HREC Reference LNR/14/LPOOL/289).

Study Setting and Population

A convenience sample of 30 healthy volunteers were recruited from ED staff. Volunteers with respiratory disease, such as a history of asthma, or pregnancy were excluded; however, bearded subjects ($n = 1$) were included. There were no edentulous subjects in our sample. Informed consent was obtained from all participants. Volunteers did not have intellectual investment in this study.

Study Protocol

Preoxygenation sessions consisted of 3 minutes of spontaneous tidal volume breathing with each technique (Table 1). The order of techniques was determined in advance by computer randomization, resulting in a different sequence of techniques for each subject.

Table 1
Summary of Preoxygenation Techniques, Oxygen Flow Rates, and Equipment Used

1. Anesthesia machine[a] + anesthetic circuit[b] + facemask[c]* (O_2 15 L/min)
2. BVM[d] (O_2 15 L/min)
3. BVM (O_2 15 L/min) + NC[e] (O_2 5 L/min)
4. BVM (O_2 15 L/min) + PEEP valve[f] (5 cmH_2O)
5. BVM (O_2 15 L/min) + PEEP valve (5 cm H_2O) + NC (O_2 5 L/min)
6. NRM[g] (O_2 15 L/min)
7. NRM (O_2 15 L/min) + NC (O_2 5 L/min)

*The same air-cushioned facemask was used in preoxygenation techniques 1–5.
Product references:
[a]Datex-Ohmeda Aestiva 5, GE Healthcare, Little Chalfont, UK.
[b]ConnectEZY anaesthesia breathing circuit CEB51418020DNC (72 inch), Endovations, NSW, Australia.
[c]Ambu Ultraseal II disposable facemask (252084 = small adult; 252085 = medium adult; 252086 = large adult), Ambu Australia Pty Ltd, NSW, Australia.
[d]Resus-EZY adult resuscitator HP-9511FL3, Endovations, NSW, Australia.
[e]SMHC 2021, Mayo Healthcare, Mascot, NSW, Australia.
[f]Laerdal disposable PEEP valve assembly 845040, Laerdal Medical AS, Stavanger, Norway.
[g]SMHC 2035, Mayo Healthcare, Mascot, NSW, Australia.
BVM = bag-valve-mask; NC = nasal cannula; NRM = nonrebreather mask; PEEP = positive end-expiratory pressure.

For the anesthetic circuit technique, a Datex Ohmeda Aestiva 5 anesthesia machine (GE Healthcare) with a semiclosed circle breathing system was used, consisting of 72-inch lengths of corrugated tubing and a 2 L bag. The oxygen flow rate was set at 15 L/min with the adjustable pressure limiting valve fully open. The circuit was primed with oxygen before use. An air-cushioned facemask was used for both the anesthetic circuit and BVM techniques, sized appropriately for each subject. The mask was held firmly in position by the same investigator (CWC) throughout the experiment, without assisting ventilation. A BVM with a built-in one-way valve on its expiratory port was used (ResusEzy, Endovations, Australia). For the NRM techniques the mask position was optimized by the investigator with adjustment of the elasticated headband and nose clip. Oxygen from standard hospital wall flowmeters was used to provide oxygen supply to the BVM, NRM, and NC.

Each subject's baseline FeO_2 was measured prior to the start of preoxygenation. Subjects were positioned supine for the periods of preoxygenation but were allowed to mobilize between techniques to avoid atelectasis. In between each technique, FeO_2 was again measured to ensure return to baseline.

Measurements

FeO_2 measurements were made with a calibrated gas analyzer (Datex-Ohmeda E-CAiO Gas Module, GE Healthcare). The final FeO_2 result for each technique was determined by the volunteer exhaling continuously at the end of the 3-minute period into a separate reservoir attached to the gas analyzer, after a brief breathhold. This was done to avoid artificially high FeO_2 readings from the continuous addition of O_2 from the preoxygenation device.

Data Analysis

Statistical analysis was carried out using SPSS version 22. Mean FeO_2 values calculated for each method with 95% confidence intervals (CIs). Based on the ideal endpoint of FeO_2 90% as an indicator of optimal preoxygenation,[2] we estimated that a minimum of 16 participants would be required to determine a difference of more than 10% with an alpha of 0.05 and a power of 80% in a single paired comparison. We chose 10% as this difference was deemed to be clinically important among the investigating clinicians. We recruited 30 participants as the sample size estimate was not based on multiple comparisons and by having a larger subject pool we aimed to produce more precise point estimates for each method of preoxygenation and to allow for multiple comparisons.

Overall differences in FeO_2 between methods were determined using a repeated-measures analysis of variance. We then performed a post hoc analysis with a Bonferroni correction to examine the differences between individual methods allowing for multiple comparisons, using the anesthetic circuit as the control.

RESULTS

The volunteer characteristics are summarized in Table 2. Baseline FeO_2 was the same between all groups. Mean FeO_2 for the seven techniques measured after a 3-minute period of preoxygenation, are shown in Figure 1.

Overall there was a significant difference in the FeO_2 achieved between the seven techniques ($p < 0.01$). Compared to the anesthetic circuit, the BVM device with or without PEEP produced very similar FeO_2 levels of approximately 80% ($p = 1.0$), while the addition of NC with or without PEEP showed a nonsignificant trend toward a lower FeO_2 ($p = 0.4$ and $p = 0.2$, respectively). The NRM with or without NC produced significantly lower FeO_2 readings ($p < 0.001$).

DISCUSSION

Effective preoxygenation provides a safety margin for emergent intubation by denitrogenating the functional residual capacity of the lungs, prolonging the duration of apnea without desaturation. In the operating room, an anesthetic circuit is used to provide a high FiO_2. Moreover, the degree of denitrogenation may be assessed by measuring the FeO_2 throughout the preoxygenation period. With an approximate carbon dioxide concentration of 5%, an FeO_2 of 90% corresponds to an approximate alveolar nitrogen concentration of 5%.[11] This has been used as a clinical indicator and endpoint of complete preoxygenation.[2] Continuous assessment of FeO_2 also allows anesthetists to rapidly identify occasions when preoxygenation is suboptimal, for example, with a poor mask seal, prompting adjustments in technique.

Outside the operating room environment, critical care physicians rely on a standard 3-minute period of preoxygenation, traditionally by breathing from a presumed high FiO_2 source in the form of a BVM or NRM system. This study assessed these methods for efficacy of denitrogenation in cooperative healthy volunteers. Noninvasive ventilation strategies are also used for preoxygenation; however, these were not assessed in the current study as these devices are not universally available prior to emergent intubation, particularly in the prehospital setting.[12]

Robinson and Ercole[4] showed comparable FeO_2 achieved by preoxygenating with BVM and NRM devices. Both, however, have been found to significantly underperform traditional anesthetic circuits.[4,13] Conversely, we found that preoxygenation with this particular BVM model achieved a mean FeO_2 that was comparable to the anesthetic circuit and significantly better than the NRM. Previous authors have found that in spontaneously breathing patients, the FiO_2 delivered by BVMs without one-way expiratory valves was significantly lower than those with one built in.[14,15] The BVM used in this study has a dedicated expiratory valve that prevents entrainment of room air. We postulate that the different models of BVM used, and the inclusion of expiratory valves, may contribute to the differences observed in efficacy of preoxygenation, as demonstrated by prior authors.[6,14]

We had anticipated that the addition of NC oxygen would improve the denitrogenation achieved. This was true for the NRM groups (51.6% vs. 57.1%). However, for the BVM groups, addition of NC oxygen actually slightly reduced the FeO_2 achieved for both the BVM (80.1% vs. 74.8%) and the BVM + PEEP (78.9% vs. 75.5%) groups. We observed a higher frequency of clinically detectable leak when using NC concurrently with the BVM. We postulate that the efficacy of preoxygenation is dependent on the quality of the seal achieved, which was probably adversely affected by the inclusion of NC tubing. Interestingly, Gagnon and colleagues[16] demonstrated a significantly reduced efficacy of preoxygenation when they deliberately created a leak using nasogastric tubing beneath the mask.

Addition of a PEEP valve to the BVM was also expected to increase the FeO_2 achieved as previous studies had shown improved preoxygenation with PEEP.[10] The addition of a spring-loaded PEEP valve to a disposable BVM may also reduce the entrainment of room air around the expiratory valve on these devices. Our study found a nonsignificant reduction in FeO_2 with PEEP (80.2% vs. 78.9%). This may be because the

Table 2
Participant Characteristics

Volunteer Characteristics	Range	Mean
Age (yr)	20–48	33
Weight (kg)	50–98	69
Height (m)	1.5–2.0	1.7
BMI (kg/m^2)	19–31	24
Sex	14 male, 16 female	

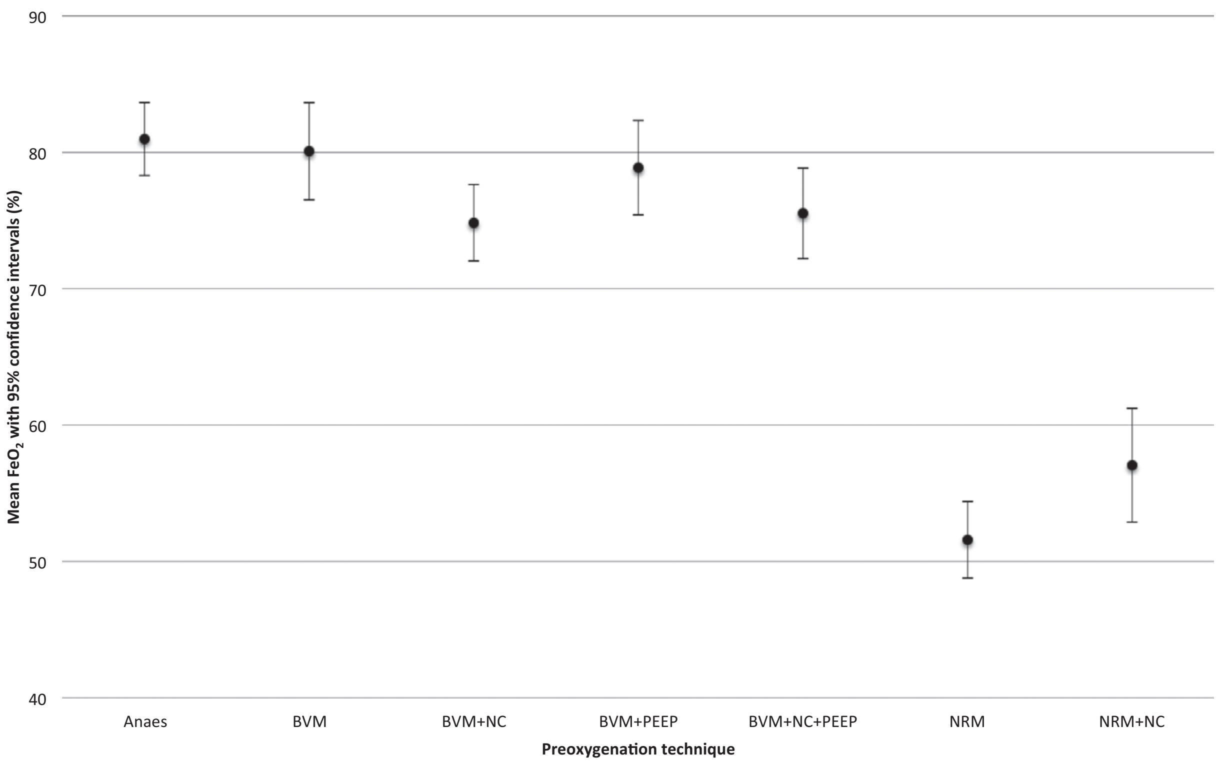

Figure 1. Comparison of mean FeO_2 achieved with each preoxygenation technique. Data are shown as mean with 95% CI. BVM = bag-valve-mask; NC = nasal cannula; NRM = nonrebreather mask; PEEP = positive end-expiratory pressure valve.

preoxygenation achieved with this BVM was near optimal and further improvements in FeO_2 in volunteers with normal lungs was not achievable. Improvements in preoxygenation may be identifiable in patients with lung disease who benefit from the alveolar recruitment and small airway splinting facilitated by PEEP.[7,8]

In our study, the mean FeO_2 achieved with the anesthetic circuit was 81.0%, with only 10% of volunteers achieving the target FeO_2 endpoint of 90%. Previous authors have shown that up to 56% of patients do not achieve FeO_2 of 90% despite preoxygenation with three minutes of tidal volume breathing using an anesthetic circuit.[17] Also, we measured FeO_2 at the end of an expiratory breath into a separate reservoir, which we believe is more accurate than continuous sampling of end-tidal gas from the facemask, which may be erroneously higher due to mixing with the device oxygen flow.

LIMITATIONS

Limitations of this study include the use of healthy volunteers who were able to breathe calmly for the full 3 minutes of preoxygenation, tolerating the mask seal achieved by the investigator. Critically unwell patients requiring emergent intubation are likely to be different in a number of ways: first, efforts to achieve a good mask seal (BVMs) can distress an already agitated patient, which is likely to greatly reduce the efficacy of preoxygenation. Volunteers consistently reported discomfort when breathing against the PEEP valve, which was set to only 5 cm H_2O. This also has implications for the tolerability of BVM + PEEP preoxygenation in agitated patients. Quiet tidal volume breathing is also unlikely to exceed the 15 L/min oxygen flow provided to the BVM. Some patients requiring emergent intubation may have a greatly increased minute volume, which would likely be accommodated by an anesthetic circuit but not by the BVM device. Conversely, patients with reduced minute volume due to an altered conscious state, for example, may not achieve optimal preoxygenation with tidal volume breathing. This would be true for all the preoxygenation methods, however, and the advantage of the anesthetic circuit and BVM techniques is the option to manually assist ventilation.

CONCLUSIONS

Preoxygenation with a nonrebreather mask was significantly less effective than the anesthetic circuit or a bag-valve-mask. The addition of NC oxygen did result in a small improvement in the denitrogenation achieved, and this combination may be an appropriate compromise in situations where it is difficult to maintain a good mask seal with a bag-valve-mask device, such as in agitated patients.

The bag-valve-mask device performed as well as the anesthetic circuit in providing maximal FeO_2 in healthy cooperative volunteers. The addition of NC oxygen, positive end-expiratory pressure, or both, did not improve the efficacy of preoxygenation with the bag-valve-mask device.

FeO_2 is a surrogate measure of the adequacy of preoxygenation. Critically ill patients may still rapidly desaturate peri-intubation, despite achievement of high FeO_2 measurements, due to underlying lung pathology, low functional residual capacity, and high basal oxygen requirements. It is in this group, however, where optimal preoxygenation is most important and, for emergency intubations outside of an operating room, strategies that achieve a high FeO_2, such as those using a bag-valve-mask, are likely to be most appropriate, whereas strategies using a nonrebreather mask, long accepted as a standard preoxygenation technique, should not be used.

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