Cardiothoracic Anesthesia, Respiration and Airway

When a leak is unavoidable, preoxygenation is equally ineffective with vital capacity or tidal volume breathing

[Quand une fuite est inévitable, la préoxygénation n'est pas plus efficace avec des manoeuvres de capacité vitale qu'avec une respiration normale]

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Purpose: Ideally, preoxygenation is performed using a tight fitting mask either by breathing normally for three to five minutes or with four to eight vital capacity (VC) breaths in 0.5 to one minute, but in practice leaks are frequent and sometimes unavoidable. This study was designed to determine which breathing method provided the best oxygenation in the presence of leak.

Methods: Twenty volunteers were instructed to breathe from a circle circuit supplied with 6 L·min^{-1} of fresh oxygen. Each subject was tested under four situations selected in random order: 1) normal breathing for three minutes without leak; 2) normal breathing for three minutes with a leak; 3) four VCs in 30 sec without a leak; and 4) four VCs in 30 sec with a leak. The leak was created by a piece of size 18 French nasogastric tube, 5 cm long, taped under the face mask. Inspired and expired O_2 and CO_2 were sampled at the nostrils.

Results: In the absence of a leak, the end-tidal oxygen fraction (F_{EO2}) was greater after three minutes of tidal breathing (89 ± 3%; mean ± SD) in comparison with the response to four VCs (76 ± 7%; $P < 0.001$). Introduction of a leak decreased the F_{EO2} significantly ($P < 0.001$). With a leak, the F_{EO2} was similar with normal breathing (61 ± 8%) and after four VCs (59 ± 11%).

Conclusion: Preoxygenation with tidal volume breathing for three minutes yields higher F_{EO2} in comparison to four VCs. If a small leak (4 mm internal diameter) is introduced, the F_{EO2} decreases significantly with both breathing methods to approximately 60%.

***Objectif** : Idéalement la préoxygénation est effectuée avec un masque étanche selon deux techniques; soit en respirant normalement pendant trois à cinq minutes ou en prenant quatre à huit respirations à capacité vitale (CV) en 0,5 à une minute. En pratique, les fuites sont fréquentes et quelquefois incontournables. Cette étude fut réalisée pour déterminer quelle méthode produit la meilleure préoxygénation en présence de fuite.*

***Méthode** : Vingt volontaires ont respiré dans un circuit en cercle fournissant 6 L·min^{-1} d'oxygène frais. Chaque sujet fut soumis à quatre situations sélectionnées de façon aléatoire: 1) respiration normale pour trois minutes sans fuite; 2) respiration normale pour trois minutes avec fuite; 3) quatre CV en 30 sec sans fuite; 4) quatre CV en 30 sec avec fuite. La fuite a été créée avec un segment de tube nasogastrique de taille 18, long de 5 cm, fixé sous le masque. Les fractions inspirées et expirées d'O_2 et de CO_2 ont été mesurées aux narines.*

***Résultats** : En l'absence de fuite, la fraction expirée d'oxygène (F_{EO2}) est plus grande avec trois minutes de respiration normale (89 ± 3% ; moyenne ± ET) qu'avec quatre CV (76 ± 7%, $P <$ 0,001). Avec une fuite, la F_{EO2} diminue significativement ($P <$ 0,001). En présence d'une fuite, la F_{EO2} est la même avec respiration normale (61 ± 8%) qu'avec quatre respirations profondes (59 ± 11%).*

***Conclusion** : Une préoxygénation avec respiration normale pour trois minutes donne une F_{EO2} plus élevée qu'avec quatre CV. Si une petite fuite (4 mm de diamètre interne) est présente, la F_{EO2} s'abaisse de façon significative à environ 60 % avec les deux méthodes de préoxygénation.*

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This study was supported by internal departmental funds. Presented at the 78th IARS congress in Tampa Bay, March 27-31, 2004.

Accepted for publication March 29, 2005.

Revision accepted August 23, 2005.

PREOXYGENATION with 100% oxygen is performed routinely before induction of anesthesia.[1,2] Its goal is to increase the body's oxygen stores by replacing nitrogen in the lungs by an equivalent volume of oxygen, thus delaying the onset of arterial desaturation and hypoxemia during the apneic period following induction of anesthesia.[3]

Preoxygenation was described and shown to be effective as early as 1955,[4] and several techniques have been used since. Most often, the patient is required to breathe 100% oxygen for three to five minutes.[2,3,5,6] To shorten preoxygenation time, a technique where the patient is asked to take four vital capacity breaths (VC) in 30 sec has been proposed, and claimed to be as effective as normal breathing for three to five minutes.[7,8] However, these preoxygenation techniques require a tightly fitting face mask, and do not account for the leaks that occur frequently in practice.[9–12] Leaks have been reported in 10 to 11.5% of subjects with no facial anomalies and normal dentition.[13,14] In real life, leaks probably occur even more frequently since we often preoxygenate patients who are edentulous, wear beards or mustaches, have a nasogastric tube in place, or cooperate poorly. When a leak is unavoidable, an imperfect preoxygenation is presumably better than none at all, but it is unclear which breathing method then yields the best results.

A leak is expected to allow air entrainment into the circuit and dilute the oxygen present. The flow through a leak is turbulent and depends upon the square root of the pressure difference across it.[15] Therefore, the relative importance of the leak is expected to decrease when a large pressure, created by a VC maneuver, is generated. However, a leak might cause the reservoir bag of the circuit to empty partially, limiting the amount of oxygen available for a VC breath. It is unclear which of these two opposing effects predominates. Therefore, the purpose of the study was to compare the effectiveness of preoxygenation using tidal volume breathing *vs* VC breathing, with and without a leak.

Methods

The study was approved by the Research Ethics Committee of the Maisonneuve-Rosemont Hospital, and informed consent was obtained from all volunteers prior to their enrollment in the study. Twenty healthy volunteers of both sexes were recruited. They were between the ages of 18 and 65 yr. All subjects were within ± 30% of ideal body weight. None of the subjects had a history of lung disease or any active airway infection. Subjects were not recruited if they had a mustache or a beard, if they were edentulous, or if they had a known allergy to latex.

The same Modulus II Ohmeda (Ohmeda, Madison, WI, USA) anesthesia machine was used throughout the study. The circle system consisted of an absorber with baralyme 1.5-L, two disposable 72-inch corrugated breathing tubes and a 2-L capacity breathing bag. Gases were analyzed with the Siemens MultiGas+ system (Siemens Medical Systems, Danvers, MA, USA) and calibration with known gas mixtures (air, 95% O_2 and 5% CO_2) was carried out according to the manufacturer's specifications.

After being informed of the different steps in the study, subjects were asked to lie in a supine position on a stretcher. They were instructed to breathe through their nose at all times. A pulse oximeter was applied to a finger tip to measure oxygen saturation and heart rate. A nasal cannula was fixed at the nostrils to sample expired gases at a rate of 200 $mL \cdot min^{-1}$. The cannula exited the circuit through a sealed connector between the mask and the circuit and was connected to the gas analyzer (Figure 1). Inspired and end-tidal oxygen concentrations were measured. End-tidal carbon dioxide concentrations were also recorded. To create a standardized leak, a 5-cm long piece of #18 nasogastric tube (Levin type) was fixed to the upper crux of the facemask, so it lay on the bridge of the nose. A Rush facemask (#2, #3 or #4) was chosen to achieve the best fit for each subject. Each subject acted as his/her own control by going through each of the different phases in a random order, separated by rest periods of at least five minutes breathing room air.

Randomization was achieved by the use of sealed envelopes. Before each step, the reservoir bag was fully inflated with 100% oxygen, using the oxygen flush while occluding the mask. The reservoir bag was emptied three times to expel the air and replace it with 100% oxygen. Preoxygenation was performed with 100% oxygen using a fresh gas flow of 6 $L \cdot min^{-1}$. There were four different techniques, all using 100% oxygen: 1) tidal volume breathing for three minutes with no leak; 2) tidal volume breathing for three minutes with leak; 3) four VC breaths in 30 sec with no leak; 4) four VC breaths in 30 sec with leak.

Data were recorded by taking a picture of the anesthesia monitor with a digital camera every 7.5 sec for the first 30 sec, then every 15 sec for three minutes. The primary outcome measurement in this study was the end-expiratory oxygen fraction (F_{EO2}) reached at the end of each intervention technique. Comparisons were made at the end of the preoxygenation period between the tidal volume breathing method and the four VCs in 30 sec. Similar comparisons were made

TABLE I Demographic data

	Age *(yr)*	*Gender* *(F/M)*	*Weight* *(kg)*	*Height* *(cm)*	*Body mass index* *($kg \cdot m^{-2}$)*
Mean	35.6	14 F : 6 M	66.7	168.8	23.3
SD	11.5		11.6	7.1	3.2
Range	21–56		49–90	157–183	18.6–29.3

F = female; M = male; SD = standard deviation.

TABLE II Number (percentage) of patients with end F_{EO2} > 90, 85, 80%

	F_{EO2} at 3 min Tidal volume No leak	*F_{EO2} at 3 min Tidal volume With leak*	*F_{EO2} at 30 sec Vital capacity No leak*	*F_{EO2} at 30 sec Vital capacity With leak*
$F_{EO2} > 90\%$	11 (55%)	0 (0%)	0 (0%)	0 (0%)
$F_{EO2} > 85\%$	18 (90%)	0 (0%)	0 (0%)	0 (0%)
$F_{EO2} > 80\%$	19 (95%)	0 (0%)	8 (40%)	0 (0%)

F_{EO2}= end-expiratory oxygen fraction.

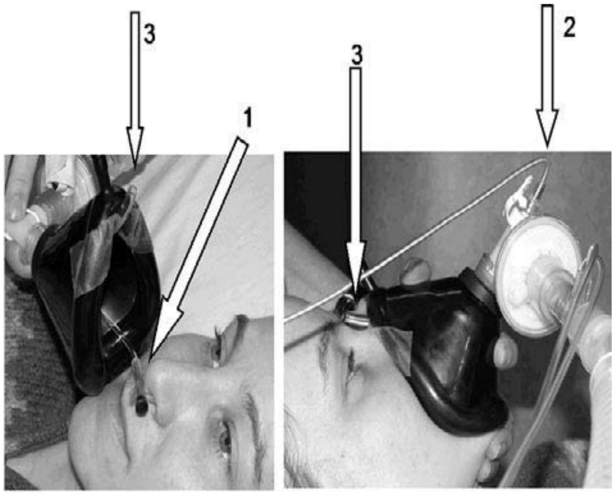

FIGURE 1 Experimental setup. Expiratory gases were sampled via a nasal cannula (arrow 1). The tubing went through the inside of mask, out through the circuit connector (arrow 2), and was connected to the gas analyzer. On the right, the sealed connection between the gas analyzer and the nasal cannula (arrow 2) is shown. In both pictures the leak (arrow 3) was created with a #18 piece of nasogastric tube, 5 cm in length.

between end-expiratory values using the same breathing techniques, with or without leaks. A student t test with four Bonferroni corrections for multiple comparisons was used with a *P* value of < 0.05/4 = 0.0125 indicating a significant difference. Statistical analysis was performed using the S-plus statistical software, version 4.5 (Insightful, Seattle, WA, USA). The number of subjects (20) was chosen to detect a 10% difference in end-tidal oxygen values between techniques, with a two-sided test, assuming a type I (α) error of 0.05 and a power (ß) of 0.8. A 10% difference was considered to be of clinical significance. The standard deviation with a leak was expected to be 10%, based on the results of McGowan *et al.*[12]

Results

All volunteers were non smokers. Their demographic data are presented in Table I. Each volunteer completed all steps in the study.

In the absence of a leak, inspired oxygen fraction (F_{IO2}) increased rapidly within 30 sec, irrespective of the breathing method (Figure 2). The F_{IO2} at the end of the preoxygenation period was significantly greater ($P = 0.004$) with tidal volume breathing (mean 97 ± 2%, range: 89–98%) compared with values at the end of VC breathing (mean 88 ± 13%, range: 57–98%), (Figure 2, Panels A and B).

In the absence of a leak, the F_{EO2} for tidal volume breathing for three minutes was greater (89 ± 3%; range 79–91%) than with four VCs (76 ± 7%; range 55–84%); $P < 0.001$ (Figure 2, Panels C and D). An F_{EO2} > 85% was reached in 90% of subjects with tidal volume breathing, while this was achieved in none of the subjects breathing deeply four times (Table II).

In the presence of a leak, the F_{IO2} reached a plateau within 0.5 min with both breathing techniques. The F_{IO2} reached 61 ± 14% (range 36–89%) with tidal volume breathing and 65 ± 17% (range 31–98%) with VC breathing (Figure 2, Panels A–D).

In the presence of a leak, there was no significant difference in F_{EO2} values between the two breathing methods 61 ± 8% (range 39–78%) for tidal volume and 59 ± 11% (range 34–77%) for VC breaths.

Both the F_{IO2} and the F_{EO2} had a similar time course whether or not a leak was present, but reached a lower plateau with a leak (Figure 2). After three minutes of tidal volume breathing with a leak the mean F_{EO2} was 61%, a 28% decrease compared with no leak (F_{EO2} = 89%), ($P < 0.001$). A leak also produced a decrease in F_{EO2} with the four VC breath technique ($P < 0.001$), but the difference was only 17%, from 76 to 59%.

The end expiratory carbon dioxide tension was similar in the presence or absence of a leak. When a leak was present it was 33 ± 3 mmHg (range 29–38) after four VCs, compared with 42 ± 4 mmHg (range:

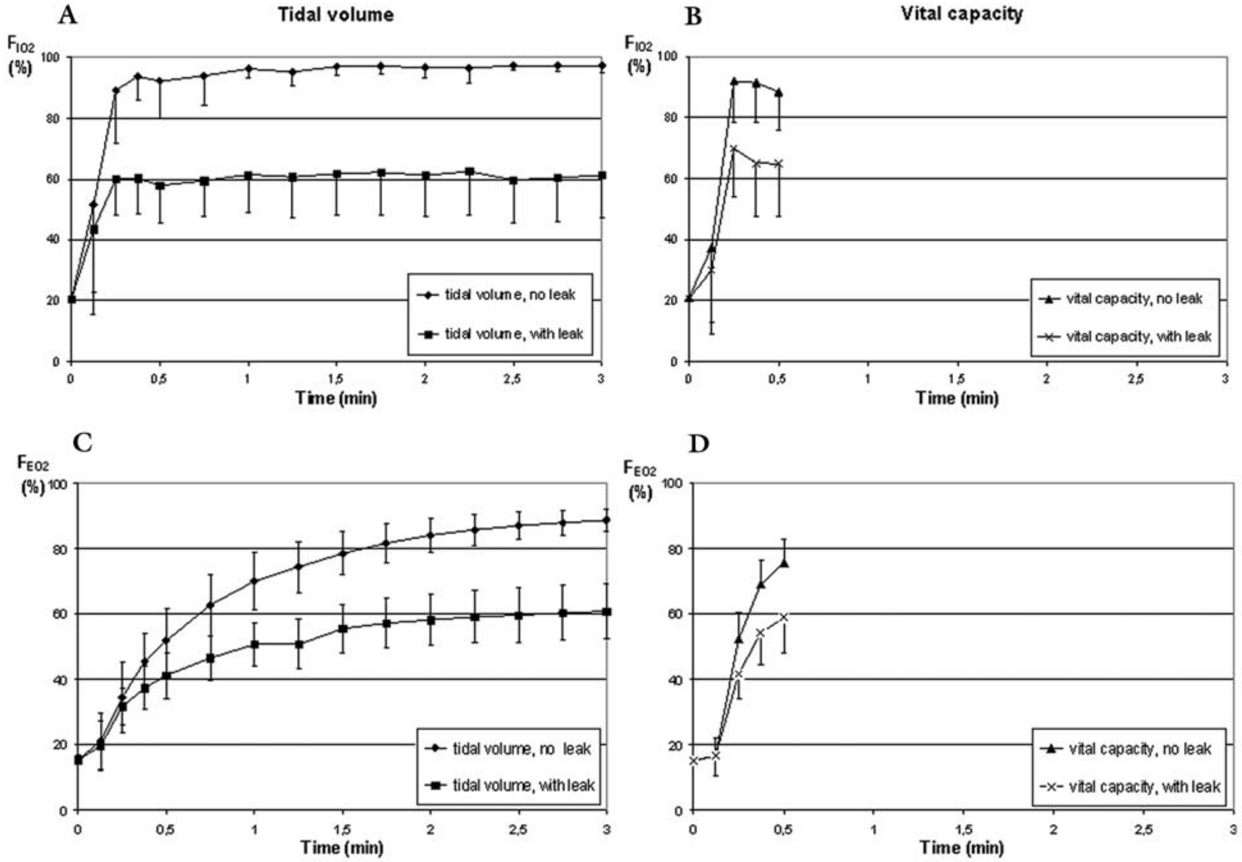

FIGURE 2 (Panel A) Inspired fraction of oxygen (F_{IO2}) during tidal volume breathing preoxygenation for three minutes, with or without leak *vs* time. (Panel B) F_{IO2} during vital capacity breathing preoxygenation for 0.5 min, with or without leak *vs* time. (Panel C) End tidal fraction of oxygen (F_{EO2}) during tidal volume breathing preoxygenation for three minutes, with or without leak *vs* time. (Panel D) F_{EO2} during vital capacity breathing preoxygenation for 0.5 min, with or without leak *vs* time. At the end of the measurement period, F_{IO2} and F_{EO2} are statistically less in all panels with a leak than without a leak ($P < 0.001$). There is a statistically significant difference between Panel A and Panel B ($P < 0.01$) for no leak. There is no difference between Panel A and Panel B (NS) with the leak present. Similarly, differences between Panel C and Panel D are observed for no leak only ($P < 0.01$), but not for leak present (NS).

36–50) after three minutes of tidal breathing.

Discussion

The present study shows that during preoxygenation, if a leak is unavoidable, breathing normally for three minutes or taking four rapid VC breaths will yield similar, but suboptimal, F_{EO2} values. However, without a leak, normal breathing for three minutes provides better oxygenation than four VC breaths.

The few studies which have examined the effect of a leak on preoxygenation used several different techniques to create a leak. We used a nasogastric tube #18, which has an internal diameter of 4 mm, and placed it between the face mask and the bridge of the nose. Others created a leak by cutting a 9.5-mm diameter hole in the mask,[1] which we thought to be too large to go undetected. McGowan *et al.*[12] chose to either hold the mask over the subject's face by gravity alone, or to place it over two small 1-cm^3 cubes inserted between the mask and the face. The leak created by a nasogastric tube in the present study is likely to be more reproducible, uniform, and less sensitive to slight changes in pressure applied by the holder of the mask. Whether all the air went through the lumen of the tube, or some of it escaped through leaks on the outside is of little practical importance, as the same method was used to produce a leak in all subjects. The F_{EO2} obtained in this study after tidal volume breathing (61%) is comparable to that measured while leaving the mask on the face by gravity alone (70%) or putting it 1 cm away from the face (55%).[12] Thus, the nasogastric tube is likely to simulate the situation created by a poorly fitting mask.

A leak as small as 4 mm in diameter (nasogastric tube #18) was large enough to prevent high F_{EO2} values to be obtained, and hence, hindered preoxygenation significantly. The results show a similar F_{EO2} after both methods with a leak present. However, when compared with a perfect seal, introducing a leak had more effect with tidal volume breathing (a 28% decrease, from 89 to 61%), than with a VC technique (a 17% change, from 76 to 59%). It was expected that VC breathing might have two opposite effects when a leak was introduced. First, the 2-L reservoir bag could empty partially through the leak, causing air to enter the circuit if the volume remaining in the bag was insufficient during a VC maneuver. This alone would make VC breathing worse than tidal volume breathing in the presence of a leak. However, the flow through the leak is likely to be more turbulent than in the rest of the circuit. When flow is laminar, it is proportional to the pressure gradient. When it becomes turbulent, it is proportional to the square root of the pressure gradient.[15] Thus, when a large negative pressure is created, as occurs when taking a VC breath, it is expected that the flow might be proportionately less through the leak, that is, through the device that produces turbulent flow. For example, if pressure inside the circuit doubles, laminar flow (from the circuit) doubles, while turbulent flow (through the leak) increases by a factor of $\sqrt{2}$, or 1.41. This turbulent flow effect, which alone would make the leak less important with VC breaths, was probably greater than the empty reservoir bag effect, because the decrease in F_{EO2} with the introduction of a leak was less with four VC breaths (17%) than with tidal volume breathing (28%).

The fresh gas flow (FGF) in the present study was set at 6 $L \cdot min^{-1}$, as most preoxygenation studies were performed with flows in the range of 5 to 10 $L \cdot min^{-1}$.[3] The results obtained in the present study without a leak are similar to those of previous investigations. Nimmagadda *et al.*[3] measured, after three minutes of tidal volume breathing, F_{EO2} values of 86.2 and 88.1% with FGF rates of 5 and 7 $L \cdot min^{-1}$, respectively. In comparison we observed an F_{EO2} of with 88.7% in the present study at a FGF rate of 6 $L \cdot min^{-1}$. Following four VCs, mean F_{EO2} values of 75 and 77% were obtained with FGF rates of 5 and 7 $L \cdot min^{-1}$ of oxygen, respectively.[3] This compares well with the value of 76% observed in the present study, at 6 $L \cdot min^{-1}$ FGF.

In the present study, gas was sampled at the nostrils, not in the circuit. Although both sites might be considered equivalent if no leak is present, differences are likely to exist if gas can escape. We chose to sample oxygen by means of a modified nasal cannula, which allowed non-invasive collection of end-tidal gases without being altered by a leak. With this setup, nose breathing was mandatory to obtain adequate measurements, but facial morphology was not altered, and a complete seal could be obtained when needed. McGowan *et al.*[12] used mouth breathing with a Guedel airway and a nose clip in place. This setup measures end-tidal values well, but modifies the shape of the face and might increase the risk of creating an unwanted leak.

The role of a leak between the patient's face and the mask in reducing the effect of preoxygenation has been recognized since 1955.[10] Berthoud *et al.* realized that allowing even one breath contaminated with air increased end-tidal nitrogen concentration markedly.[9] Drummond *et al.*[1] studied the effect of a fixed leak on oxygen saturation after one minute of preoxygenation. They observed a significant difference in saturation at three minutes postinduction, between the group preoxygenated with (mean saturation 93.6%) and without (mean saturation 96.8%) a 9.5-mm diameter leak cut into the facial mask.[1] Leaks during preoxygenation occur in 10 to 15% of individuals with no facial anomalies and normal dentition.[14] This probably occurs more frequently in a population of unselected patients.

Several end-points have been used to evaluate the effectiveness of preoxygenation, such as time to onset of oxygen desaturation, partial pressure of oxygen in arterial blood (P_{aO2}), end-tidal nitrogen, and end-tidal oxygen. We chose F_{EO2} since it has been shown to be an accurate, continuous and non-invasive measure of alveolar oxygen.[3,13,16] Furthermore, using F_{EO2} as an endpoint value in awake volunteers allowed us to study the subjects with the different preoxygenation techniques, with each subject serving as his/her own control.

Various techniques have been advocated to accomplish preoxygenation. Tidal volume breathing of oxygen for three to five minutes is used most often.[4,10] We used three minutes of preoxygenation because extending the period to five minutes gives only a marginally greater F_{EO2}.[2,3,17,18] Gold *et al.* questioned the need for three-minute periods of tidal volume breathing by demonstrating that four VCs in 30 sec was equally effective in increasing P_{aO2}.[7] The choice of four VCs was also made to minimize preoxygenation time and to improve compliance. This technique was recognized to be effective in earlier studies in American Society of

Anesthesiologists (ASA) I–II patients,[1,7] in pregnant women[5] and in obese individuals[8] using P_{aO2} as an endpoint. However, Gambee *et al.*, in ASA I–II patients, found that it took 8.9 ± 1.0 min for patients to desaturate to 90% if preoxygenated with three minutes of tidal volume breathing compared with only 6.8 ± 1.8 min in subjects preoxygenated with four VCs.[17] Similar results were reported in the elderly, where time to desaturation was 6.75 ± 1.25 min and 3.5 ±1.5 min respectively.[6,19] Thus, it appears that, as was found in the present study, four VCs are not as effective as three minutes of normal breathing in most individuals. Possible exceptions are patients with reduced functional residual capacity, such as obese subjects and pregnant women.

A leak was associated with a smaller decrease in F_{EO2} if the four deep breath technique was used (17%) compared to three minutes of tidal volume breathing (28%). However, both techniques are equally ineffective if a leak is present because the four VC method is not optimal even without a leak. It is possible that increasing the number of VCs and/or increasing the FGF rate could correct the situation, but this hypothesis was not tested here. A more cautious recommendation is that whenever a leak is detected, everything should be done to correct it. Other alternatives have been proposed, such as delivering oxygen via a mouth piece[20] or using a very high FGF (42 $L \cdot min^{-1}$).[21] Peres has also suggested using a shortened endotracheal tube between the lips, for preoxygenation while gently pinching the patient's nose in cases of facial injuries.[22] Our study supports that any leak, even as small as 4 mm of internal diameter, significantly decreases the effectiveness of preoxygenation. Changing the preoxygenation technique does not alter the end result. In the presence of a leak, either three minutes of normal breathing or 4 VCs in 30 sec, using 6 $L \cdot min^{-1}$ of oxygen, is better than no preoxygenation, but will result in similar and suboptimal F_{EO2} values.

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