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Survey and evaluation of modified oxygen delivery devices used for suspected severe acute respiratory syndrome and other high-risk patients in Hong Kong

Key Messages

1. Covering facemasks or nasal cannulae with surgical facemasks generally improved percentage of inspired oxygen (FiO_2) but at a risk of increased CO_2 rebreathing when a low oxygen flow rate was used.
2. We recommend that at least 5 L/min of oxygen be used for nasal cannula and at least 6 L/min of oxygen be used for facemask when these devices are covered with a surgical facemask.
3. Using a combination of several oxygen delivery devices is unlikely to increase the FiO_2 significantly.
4. All the modifications described did not introduce any significant increase in airway resistance.

Introduction

The severe acute respiratory syndrome (SARS) outbreak at the Prince of Wales Hospital was attributed to an index patient using a nebuliser with an open oxygen facemask, while a later outbreak at another hospital implicated the use of high oxygen flow rates with an open type of oxygen facemask. Although controversial, oxygen delivery devices (ODDs) are thought to facilitate the spread of infective organisms into the environment from air expired by infected patients.[1,2] However, the ability to improve oxygenation is one of the most important factors in determining patient well-being during respiratory infections. Consequently, various modifications to ODDs were introduced in order to supplement oxygen delivery whilst also minimising the risk of cross infection.

Some modifications included using a nasal cannula covered with a surgical mask or N95 facemask, while others involved simultaneously using a nasal cannula and an oxygen mask, covered with a surgical mask or N95 facemask. Because of these rather haphazard modifications to ODDs, physicians were unclear as to the amount of oxygen being provided to the patient. It was during the SARS epidemic that these modifications were hastily introduced, but their performance had never been investigated and described.

The aims of this study were to (1) summarise the modifications made to ODDs used in Hong Kong public hospitals during the SARS epidemic, and (2) evaluate the performance of each modification using a high-fidelity human patient simulator.[3]

Methods

This study was conducted from March 2005 to September 2005.

Survey

Approval from the Survey and Behavioral Research Ethics Committee of The Chinese University of Hong Kong was obtained before the study. The survey was conducted by a research associate and a medical student, using a format consisting of site visits and a direct face-to-face semi-structured interview, using both closed and open-ended questions.[4]

A manikin head together with various ODDs and masks were used for demonstration and digital pictures taken for the record. We surveyed intensive care units (ICUs), high dependency units, respiratory disease wards, and isolation units in all public hospitals taking acute admissions.

Evaluation of masks

All studies were performed on the simulator (Medical Education Technologies Inc [METI], Sarasota, Florida, US). After preliminary testing, we substituted the simulator manikin with an airway management trainer (Laerdal Medical Corp,

Hong Kong Med J 2008;14(Suppl 5):S27-31

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RFCID project number: 02040482

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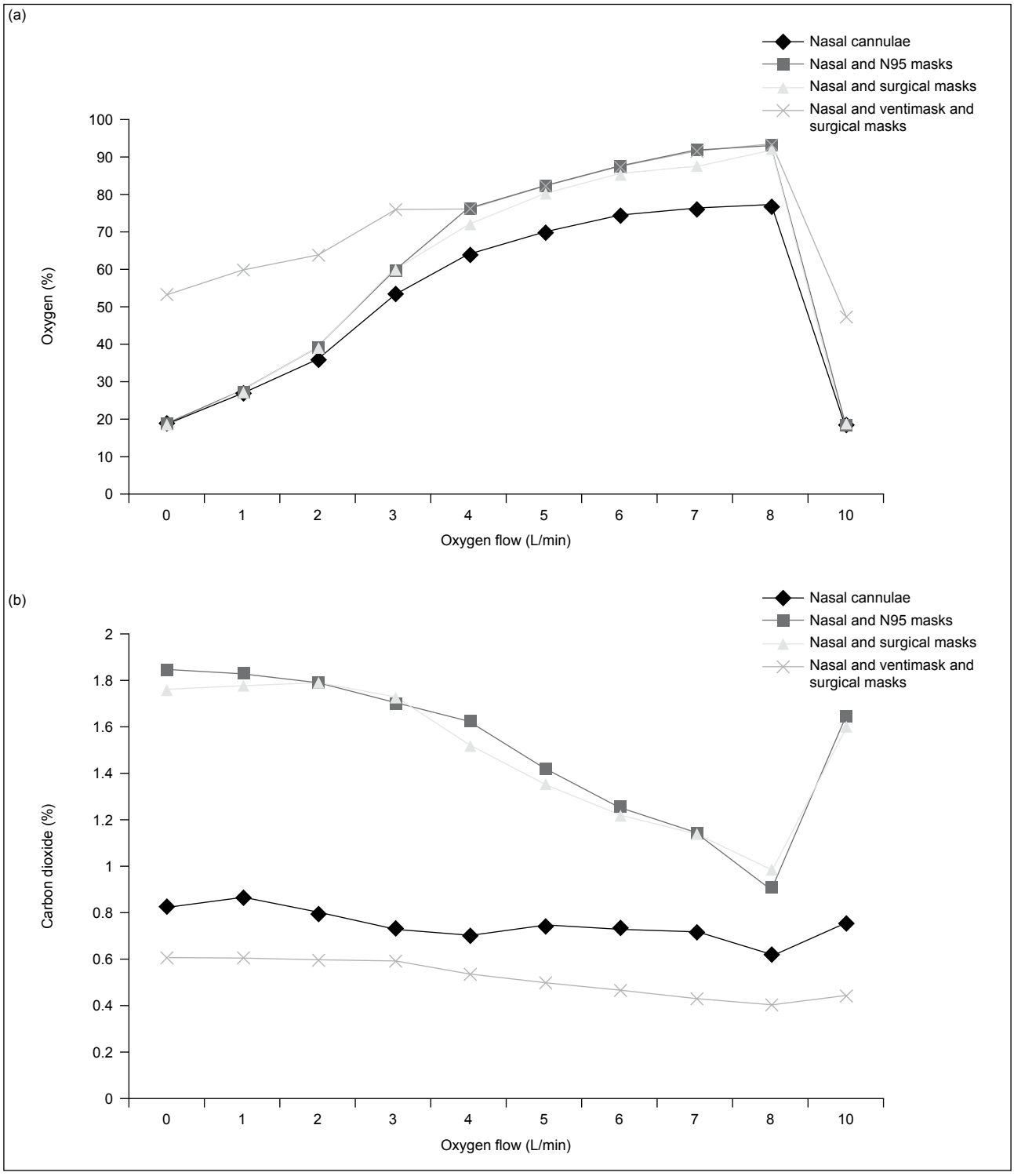

Fig 1. Nasal cannulae modifications
Plot of oxygen flow rate vs (a) inspiratory oxygen percentage and (b) carbon dioxide percentage

New York, US). Using the modified Bohr equation, the dead space ratio of this model was estimated to be 0.30 of the tidal volume, which agreed closely with the published geometric value of 0.33.[5] We connected a paediatric spirometer (AS3, Datex Ohmeda Corporation, Helsinki, Finland) probe to the lower trachea for real-time gas sampling.

After calibration using a portable spirometer (MedGraphics CPFS/D, St Paul, Minnesota, US), the simulator was set to breathe room air for 15 minutes as baseline. Then an ODD with the selected oxygen flow rate to be tested, was placed on the manikin. Data were recorded for 5 minutes for each flow setting. A washout period of at least 3 minutes was used between each setting. For each flow setting, the data collection process was repeated four times. Gas, spirometric and pressure measurements from

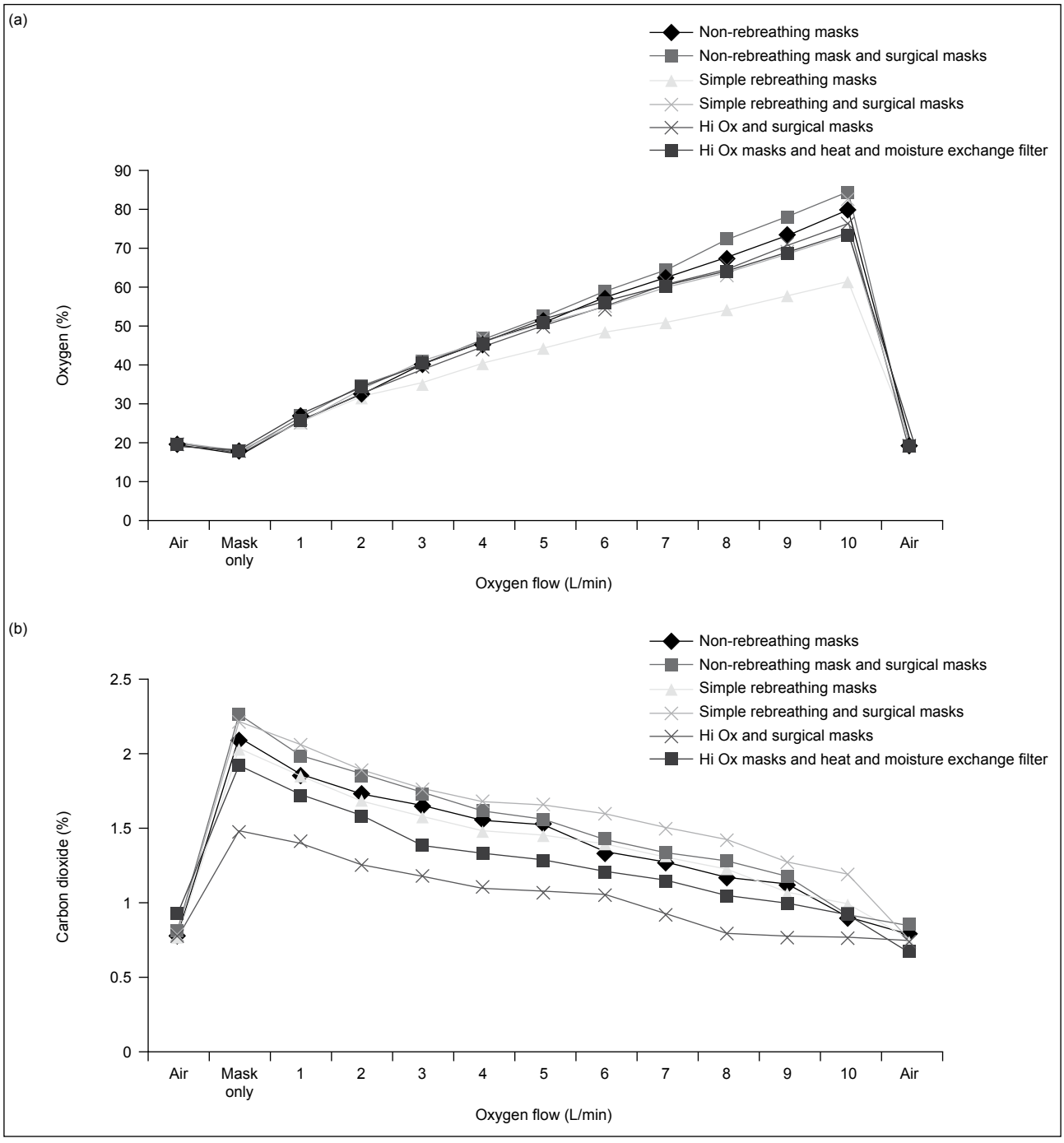

Fig 2. Oxygen facemask
Plot of oxygen flow rate vs (a) inspiratory oxygen percentage and (b) carbon dioxide percentage

the monitors were captured on a computer using an in-house program for analysis of the inspired oxygen percentage, the extent of carbon dioxide (CO_2) rebreathing, and the resistance to gas flow and work of breathing.

The breathing mode of the simulator was set to provide tidal volumes ranging from 320 to 600 mL, and respiratory rates ranging from 10 to 16 cycles per minute. The controlling computer of the simulator responded dynamically to CO_2 rebreathing, and automatically adjusted the minute volume by increasing the tidal volume and respiratory rate. For the purpose of this study, significant rebreathing of CO_2 was defined as present when the percentage of inspiratory CO_2 exceeded 1.5%, and triggered an automatic 10% increase in the minute ventilation of the simulator.[6]

Data were summarised by simple descriptive statistics as numbers and percentages or means and standard deviations, and displayed as plots of oxygen flow against the inspired oxygen and CO_2 percentages. Comparisons of the gas parameters were made using analysis of variance for repeated measures, and a correlation analysis was performed

Table. Minimum oxygen flow for modified oxygen delivery devices to prevent carbon dioxide (CO_2) rebreathing and percentage of oxygen (O_2) provided at that flow rate

O_2 device	Barrier or filter	Minimum O_2 flow required to prevent CO_2 rebreathing (L/min)	O_2 % at minimum flow Median (range)
Nasal cannulae	Surgical mask	5	80 (68-83)
	N95 mask	5	85 (69-87)
Simple rebreathing facemask	Surgical mask	6	48 (46-61)
Non-rebreathing facemask	Surgical mask	8	72 (65-79)
Hi Ox device	Heat and moisture exchange filter	4	46 (43-53)
	Surgical mask	3	37 (32-46)

to investigate the relationships between the ventilatory and other relevant respiratory parameters. Statistical analysis was made using the Statistical Package for the Social Sciences (Windows version 11.0; SPSS Inc, Chicago [Illinois], US), with the level of significance set at $P<0.05$.

Results

Survey

We visited 12 hospitals throughout Hong Kong and collected data from 29 wards, 22 intensive care and high-dependency units, by directly interviewing medical or nursing staff in each unit.

General wards

There were marked variations in modifications to the ODDs in different hospitals, as well as between individual wards within the same hospital. All the modifications described are listed in Figures 1 and 2, and were made with the objective of (a) preventing expired infected droplets from reaching the surroundings and (b) increasing the percentage of inspired oxygen (FiO_2).

For the purpose of containment of infected droplets and secretions, most of these facilities used surgical facemasks rather than N95 facemasks, as availability was an issue. The two most common modifications were the use of nasal cannulae covered with a surgical or N95 facemask.

Intensive care units

Most units used a nasal cannula covered with a surgical facemask or N95 mask, but two ICUs described using biphasic positive airway pressure (BiPAP), facemasks together with a heat and moisture exchange filter.

Evaluation of masks

We were able to test all the mask modifications described except for the BiPAP masks, which required a dedicated non-invasive ventilator. Overall, 11 types of modifications to ODDs, involving nasal cannula, rebreathing masks, non-rebreathing masks, ventimasks, and Hi Ox devices were tested. The corresponding results are illustrated in Figures 1 and 2 and summarised in the Table.

Except for the ventimask, CO_2 rebreathing was greater in all ODDs covered with a surgical mask. This was particularly significant when a low fresh oxygen flow rate was used with nasal cannulae, and covered with a surgical or N95 mask. Modifications using a surgical facemask or N95 facemask required a minimum flow of 6 L/min of fresh oxygen to prevent CO_2 rebreathing. Covering the ventimask with a surgical mask did not change the FiO_2 or the extent of CO_2 rebreathing. Using the Hi Ox device and nasal cannulae together did not result in any further increase in FiO_2 compared to using the individual device alone.

Variation of the breathing patterns by alterations of the I:E ratio or minute volume within the range of our study, did not alter the deadspace ratio, and the extent of CO_2 rebreathing was similar.

Discussion

In this study we evaluated the modified ODDs used in the public hospitals of Hong Kong during the SARS epidemic. Most modifications consisted of covering the ODD with a simple surgical or N95 mask. Whereas this action did not significantly change the performance of any oxygen facemask, covering nasal cannulae with a surgical mask introduced a deadspace, which markedly changed their characteristics. Modified in this manner, nasal cannulae are effectively converted into an oxygen facemask. Within the deadspace under the surgical mask, oxygen is trapped and enhances the FiO_2. However, it also traps expired air, resulting in rebreathing of CO_2 when there is a low oxygen flow rate (1-4 L/min). To prevent rebreathing and accumulation of CO_2 requires a minimum oxygen flow rate of 5 L/min for nasal cannulae, and 6 L/min for simple facemasks.

Since most patients with SARS required a very high FiO_2 to maintain blood oxygenation, the issue of CO_2 rebreathing was not a problem. However, patients with other respiratory diseases, such as during postoperative states, only a low oxygen flow rate is needed to maintain oxygenation. Thus, some of the latter patients may have been inadvertently subjected to rebreathing of CO_2 when using modified ODDs and low oxygen flow rates.

For patients with acute exacerbations of chronic obstructive pulmonary disease, controlled oxygen therapy using a ventimask preserves the patient's hypoxic drive and prevents hypercapnia. However, the use of a high gas flow rate with a ventimask was discouraged (or banned) in some

wards, as it was considered to facilitate spread of infected respiratory droplets. It was difficult to provide a low FiO_2 using a facemask (rather than a ventimask) without inducing CO_2 rebreathing and hypercapnia. Using nasal cannulae and a low oxygen flow rate of 1 L/min was an alternative. However, if covered with a surgical mask, this would lead to significant CO_2 rebreathing, and hypoventilation, thus aggravating the hypercapnia.

Later during the course of the SARS epidemic, newer ODDs were introduced such as the Hi Ox device. This device has a complicated series of valves, which channel expired air away to prevent rebreathing and can provide a high FiO_2 using a relatively low oxygen flow rate. Covering a Hi Ox facemask with a surgical mask did not significantly change breathing characteristics.

When nasal cannulae are used in combination with a ventimask (set at an FiO_2 of 0.5 L/min) and covered with a surgical mask, the FiO_2 increased and CO_2 rebreathing was virtually eliminated. However, with this combination, the net flow of gas supplied to the patient would be about 50 L/min, thus greatly increasing the risk of disease transmission. The FiO_2 provided by the Hi Ox device in combination with nasal cannulae was similar to the flow provided by the Hi Ox device alone, so there appears to be of no benefit in using the combination.

We found that all these modifications did not significantly increase airway resistance, and the work of breathing was unchanged. This finding could be a consequence of our methodology using the simulator. In our study, the simulator breathes dry gases in and out, whereas in a true clinical situation, patients breathe out humidified gases that condense on the surgical or N95 masks and progressively increase air resistance.

Although the human simulator was designed as a teaching tool, it provides an excellent platform for simulating in-vivo physiological experiments. The realistic replication of respiratory airflow and physiological consumption of oxygen and CO_2 production overcame a lot of difficulties with bench laboratory modelling of the human lung. The simulator also mimics in-vivo human responses by automatically responding to challenges such as CO_2 rebreathing by increasing minute volume or respiratory effort. Although the respiratory parameters of critically ill patients requiring oxygen therapy may differ from settings on our simulator, it was beyond the scope of this study to evaluate ODDs at such extreme respiratory parameters. We estimate that the range of respiratory parameter settings that we used in this study would have been consistent with those used in the majority of the patients in Hong Kong.

While the surgical mask was widely used to cover ODDs in many hospitals, it is unclear whether this method actually helped prevent cross-transmission of SARS virus. According to this survey, health care workers felt that they had contributed to reducing the risk of cross-infection to staff and among patients. It can only be postulated that these modifications somehow reduced the size of the infectious zone around each patient, but to answer this question requires a separate study of the actual movement of droplets in expired breaths.[2]

The capacity to isolate and prevent cross-transmission within a hospital setting is limited. Although guidelines suggest that individual isolation rooms with negative pressure ventilation should be employed, such facilities are limited and easily overwhelmed during disease outbreaks. It is likely that ODDs with these modifications will continue to be used in the foreseeable future. We hope that the data from this study will be useful for physicians when deciding what is best for their patients and their environments.

Acknowledgements

This study was supported by the Research Fund for the Control of Infectious Diseases, Food and Health Bureau, Hong Kong SAR Government (RFCID: 02040482). The authors would like to thank Mr Raymond Chung, Mr Bryan Ng, and Ms Floria Ng for their invaluable help with this project.

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