CONCERNING THE CONCENTRATION OF INHALED GASES IN SEMICLOSED ANESTHESIA SYSTEMS

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The literature on anesthesia commonly contains statements such as: the patient was given a gas mixture containing 4 liters of nitrous oxide (or another gas) and 1 liter of oxygen. Obviously, it is implied that the gas mixture received by the patient has "about" the same percentage composition as is delivered by the machine, which means in the example cited, 20 per cent oxygen. The reservation which is being made (the word "about") apparently depends on the unreliability of the flowmeters. An attempt has been made to evaluate the validity of this supposition and to determine to what extent the percentage of any given gas in a mixture may be modified by the particular anesthetic system. These considerations apply in their full extent only to anesthetic technics employing continuous flow with semiclosed systems.

It must be quite evident that if the patient is to inhale the gas mixture from the machine in the same proportion as it is delivered, the anesthesiologist must make sure that the patient is inhaling only these gases. Therefore every addition, either from the exhalations of the patient or from the ambient atmosphere, must be avoided because it always results in a change in the mixture. In other words, the dead space in the apparatus must not be increased, and it should be airtight from the outside to prevent dilution with air (but, of course, not in the direction outward because an exhalation valve is necessary). Even if carbon dioxide absorption is accomplished, rebreathing due to any increase in dead space or to faulty valves will appreciably modify the percentage of the gas which reaches the alveoli.

How great a flow of gases is necessary to avoid rebreathing? If no flow of gases was added from the machine, there would be rebreathing of all the exhaled gases, that is all of the respiratory volume per minute (RMV). With increasing flow from the machine the amount of air rebreathed will be decreased. For example, with a flow of 2 liters per minute from the machine, rebreathing will be diminished by almost 2 liters and therefore, it will be approximately the respiratory volume per minute less 2 liters. On continuing this line of thought it will be found that the flow must be of a magnitude comparable with the

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respiratory volume per minute if no rebreathing is to take place. However, at the start of an exhalation, the rebreathing bag will not be full if the gas flow from the machine is the same as the respiratory volume per minute and therefore part of the exhaled gases will flow against the bag. Because of this, part of the exhaled gases may be inhaled together with the fresh gases at the start of the next inspiration. How much and how significant this will be depends on the completeness with which the bag fills at the start of an exhalation, and this again depends on the relation between the respiratory volume per minute and the magnitude of the flow from the machine. Thus it is necessary to have flows higher than the respiratory volume per minute to avoid "contamination" of the fresh gases by the exhaled air.

According to Molyneux and Pask (1950) (1), for a tidal volume of 500 cm.³ and a respiratory rate of 25 per minute (that is, RMV = 12 ½ liters) a flow of gases of 14 liters per minute is needed to reduce the flow of exhaled gases back toward the bag to 150 cm.³ at each inhalation. In accordance with these views, the maximal percentage of gas a patient inhales when a certain percentage of gas is delivered from the machine at different total rates of flow has been calculated. If

\[ I_x = \text{percentage of gas } x \text{ in the inhaled air}, \]
\[ F = \text{flow of gas } x \text{ from the machine in liters per minute}, \]
\[ E = \text{percentage of gas } x \text{ in the exhaled air (expressed as decimal)}, \]
\[ F_l = \text{total flow of gas mixture from the machine in liters per minute}, \]
\[ \text{RMV} = \text{respiratory minute volume}, \]

then it can be shown, that

\[ I_x = \left( \frac{F + [\text{RMV} - F_l] \times E}{\text{RMV}} \times 100 \right), \]

which is applicable for flows up to the respiratory volume per minute.

As an example, if the percentage of oxygen inhaled is calculated when different flows from the machine containing 20 per cent of oxygen are delivered to patients having respiratory minute volumes of 8 and 12 liters, the results shown in figure 1 are obtained. (The percentage, E, of oxygen in the exhaled air appears in all of the calculations chosen as 16.3.) However, it must be assumed that in most cases the oxygen content which is inhaled is less than the value here calculated, partly because the backflow is greater than calculated and also because of the dead space (discussed later). Similar calculations using the formula given above can be made with other percentages of oxygen in the gas

* The following assumptions are made: (1) The system works at a constant pressure. (2) No change in the concentration of the exhaled gases takes place during the calculation minute. (3) The flow from the machine is not greater than the respiratory minute volume. (4) In a semiclosed system the amount of gases rebreathed equals or is more than the respiratory minute volume less the total flow of gases from the machine, that is, \( \text{RMV} - F_l \). From assumption (4) the absolute amount of gas rebreathed thus is equal to \( \text{RMV} - F_l \times E \).
flow from the machine. On the other hand, if the flow containing the 20 per cent of oxygen is kept constant at 2½ liters per minute, the curve in figure 2 shows the effect of an increasing respiratory minute volume on the inhaled oxygen content.

Consequently the oxygen percentage necessary in the flow to provide the patient with a gas mixture containing 20 per cent of oxygen depends on the respiratory minute volume.

If it is assumed that the backflow to the machine is only the deficit between the respiratory minute volume and the flow, which as mentioned is frequently not sufficient, then the required oxygen percentage in the flow can be calculated (with varying respiratory minute volumes and different flows). An example is given in figure 3, which shows

![Diagram](image)

the curve obtained with a flow of 2½ liters per minute. It may be seen that the respiratory minute volume is directly proportional to the necessary oxygen percentage in different flows which are less than the respiratory volume per minute. For example, if the respiratory minute volume is increased because of stimulation for some reason (for example, increased carbon dioxide), then it will be necessary to increase the oxygen percentage in the mixture if the anesthetist believes that the patient should inhale the same oxygen percentage as before the increase in the respiratory minute volume.

In all the calculations given above, the mechanical dead space (that is, in the apparatus) has not been considered. This, however, usually is of some importance, especially when face masks are used. The rebreathing caused by this extension of the physiologic dead space
will also influence the proportions of the inhaled gas mixture, the composition of which will vary even more from that of the flow.

For example, if a patient is given a mixture containing 20 per cent oxygen, and the mechanical dead space is 150 cm.\(^2\), which is not uncommon with the usual face masks and connections, then the following calculations can be made. Let us suppose that the tidal volume and the respiratory rate are unchanged. With this added dead space of 150 cm.\(^2\), the patient is given only about 16 per cent oxygen (the oxygen percentage of the expired air) instead of the intended 20 per cent, which means

\[
\frac{150 (20 - 16)}{100} = 6 \text{ cm}^2.
\]

oxygen less with each inhalation. To provide the same amount of oxygen in centimeter\(^3\) per breath, that is the same average percentage

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Highest possible O\(_2\) % in inhaled mixture after fixed 2.5 l gasflow containing 20% O\(_2\) with varying R\(_{\text{VM}}\)}
\end{figure}

of oxygen as without the increased dead space, the percentage of oxygen from the machine must be increased.

With the tidal volume of 500 cm.\(^3\), the volume of gases which will come in contact with the alveoli will be:

Tidal volume — (physiologic + mechanical dead spaces)
i.e.: \(500 - (150 + 150)\) cm.\(^3\) = 200 cm.\(^3\)

This volume will contain 20 per cent of oxygen or 40 cm.\(^3\). To increase the oxygen content in this effectively inhaled air by 6 cm.\(^3\), the oxygen content per 200 cm.\(^3\) must be increased from 40 to 46 cm.\(^3\). That again
means that the oxygen inhaled must be increased from 20 to 23 per cent. When this is included in our former calculation methods, the usual case can be analyzed as follows:

The patient has a respiratory minute volume of 12 liters and the apparatus has a dead space of 150 cm$^3$. The flow of gases is stated to be 5 liters per minute, with an oxygen content of 20 per cent. It can then be estimated that at the start, including the dead space in the calculation, the mixture contains at the most 17.8 per cent of oxygen. After mixture with the air in the mechanical dead space, the air at the patient's mouth will contain an average of less than 16.9 per cent of oxygen which is, in fact, only slightly greater than the oxygen content of the exhaled air (16.3 per cent). For this reason the oxygen percentage (oxygen tension) of the alveolar air will decrease and

![Diagram](image)

\[Q \text{ % necessary in } 2.5 \text{ liters per minute, which ideally gives } 20\% \text{ O}_2 \text{ in the inhaled gas mixture.}

**Fig. 3.**

therefore, with the exhaled air, percentage of the inhaled oxygen will decrease further until an equilibrium is attained. To insure inhalation of 20 per cent of oxygen at the mouth it is calculated that the mixture from the machine should contain at least 29 per cent of oxygen (in other words, there should be at least 1.45 liters of oxygen in the 5 liters flow from the machine). This result is in agreement with measurements of the oxygen percentage at the mouth obtained with an oxygen analyzer (Cullen (2)) where it was found, that to have 20 per cent oxygen available at the mouth, the flow from the machine should contain 1$\frac{1}{2}$ liters of oxygen (combined, for example, with 3$\frac{1}{2}$ liters of nitrous oxide) per minute.

However, because the respiratory minute volume varies during the course of anesthesia, the oxygen percentage cannot be fixed, for
example, at 29 per cent. A decrease in the respiratory minute volume may allow a lowering of the oxygen percentage in the flow if the tidal volume is not decreased. If the tidal volume is decreased, the dead space will be of increasing importance, and may even make necessary an increase of the oxygen percentage if the respiratory minute volume decreases.

From this discussion it can be seen how important it is to be sure that the tidal volume is not too small and to know the magnitude of the respiratory minute volume. Practically, the respiratory minute volume can be evaluated by interposing a nonrebreathing valve at the mask. If, with the valve in place the volume is maintained in the rebreathing bag, the respiratory minute volume will be the same as the total flow from the machine. A decrease or increase in the size of the bag will indicate that the total flow is smaller or greater than the respiratory minute volume. By using the values of the respiratory volume per minute and the total flow, the oxygen percentage necessary in the flow to supply the desired oxygen percentage in the alveoli can be calculated. Another way to achieve the same goal is to keep the total flow from the machine above the respiratory volume per minute of the patient at all times, preferably combined with the use of a nonrebreathing valve to avoid backflow. In the last mentioned case, the inhaled oxygen percentage would be close to the percentage in the flow. It would also be possible to dispense with carbon dioxide absorption, but would be more expensive because of the high flow of gas necessary. Furthermore, even with such a high flow an increase in the oxygen delivered by the machine would still be necessary to compensate for any mechanical dead space which might be present.

The dangers or the safety of using 20 per cent oxygen in the inhaled mixture will not be discussed. The figure 20 per cent has been used because frequently in the literature it is stated that this percentage is being used. Whether the oxygen percentage is subsequently changed also is irrelevant to this discussion.

The equation is applicable to gases other than oxygen. Thus it can be shown that the percentage of nitrous oxide in the inhaled air, as is true with oxygen, will approximate the percentage of nitrous oxide in the flow only if the total flow per minute from the machine is greater than the respiratory minute volume. As with oxygen, apparatus with little mechanical dead space, that is, small rather than large masks and intubation with direct connection to the tubes, will alter the percentage delivered as little as possible.

From the discussion and calculations made it will be seen that information regarding the percentages of gases in the mixture delivered from the anesthesia machine is of very limited importance, and that the calculations do not give any information concerning the percentage supplied to the patient to inhale. It is, therefore, impossible to evaluate the effect of the inhaled gas mixture. To draw conclusions about
these conditions it is necessary that information be available concerning the absolute flow of gases, the tidal volume and the respiratory volume per minute, the last mentioned at least approximately, or continuous analyses should be carried out on the percentage of oxygen in the mixture supplied to the patient.

**Summary**

The concentration of gases inhaled in semiclosed systems is discussed. No conclusions concerning the inhalation percentages can be drawn on the basis of the percentages in the gas flow from the machine. To estimate the concentration of a gas that is inhaled it is necessary to know, not the percentages, but the absolute flow from the machine, together with the approximate respiratory minute volume and the tidal volume. Further, it is pointed out that the mechanical dead space is of significance in determining the inhaled percentages and must be taken into consideration when the effect of inhalation is evaluated.

**REFERENCES**

2. Cullen, Stuart C.: Personal communication to the author.

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