INSPIRED GAS, REBREATHING AND APPARATUS DEADSPACE

J. F. NUNN* AND H. C. NEWMAN†
Research Department of Anaesthetics, Royal College of Surgeons, London

SUMMARY

The relationships between mixed inspired gas, rebreathing and apparatus deadspace have been considered in relation to the conditions which may exist during anaesthesia. Different fractions of expired air may be re-inhaled according to the gas circuit employed, and it may be necessary to distinguish the gas drawn into the respiratory tract from the gas which actually enters the alveoli and so influences gas exchange. The effects of various degrees and patterns of rebreathing upon gas exchange may be determined by the use of a mixing equation analogous to Bohr's equation or by the use of a volume/concentration diagram. The effective mean concentration of a gas in mixed inspired air can only be derived when the instantaneous concentration is considered in relation to the volume inhaled rather than in relation to the time during which it is inhaled.

The composition of the inspired air normally remains constant throughout the life of the individual. However, during anaesthesia, the composition of the inspired gas may be varied widely according to the whim of the anaesthetist. By this means the arterial oxygen level can be controlled and the tension of anaesthetic gases in the arterial blood can be raised or lowered as required. The arterial $P_{CO_2}$ may be raised by adding carbon dioxide to the inspired gas.

For any gas ($x$) the alveolar concentration ($F_{AX}$) is related to the inspired concentration ($F_{IX}$) according to the general equation:

$$F_{AX} = F_{IX} - \frac{V_x}{V_A}$$

where $V_x$ (the symbol for the exchange of the gas “x”) is of positive sign for uptake and negative sign for elimination. $V_A$ is the alveolar ventilation. $F_{IX}$ represents the gaseous environment of the individual with regard to the gas “x”. It will be seen that the alveolar concentration of a gas will equal its concentration in the gaseous environment if its exchange ($V_x$) becomes zero or the alveolar ventilation ($V_A$) infinite.

With non-rebreathing circuits and negligible apparatus deadspace, the inspired gas is identical to the fresh gas mixture delivered from flowmeters and vaporizers. Its composition may be derived with sufficient accuracy from Rotameters and calibrated vaporizers. However, it is not unusual for anaesthetists to use more complicated circuits which cause the fresh gas to be contaminated with previously expired gas. The effect of this upon the exchange of carbon dioxide can be eliminated by absorption with soda lime but, unfortunately, there is no comparable method for preventing its effect upon the exchange of oxygen and anaesthetic gases.

Control of the gaseous environment is fundamental to inhalation anaesthesia and is of particular importance in studies of gaseous exchange under these conditions. Increasing familiarity with the subject has served only to make us more aware of its complexity. Over the years certain aspects of the subject have become clearer to us and form the basis of this paper since they have not found expression elsewhere.

TYPES OF REBREATHING

Gas circuits may be devised to impose almost any pattern of rebreathing on anaesthetized patients. Many apparently simple circuits result in a pattern of such complexity that they almost defy analysis. Nevertheless certain types of rebreathing predominate and may be conveniently listed.

Simple apparatus deadspace ($V_{DAP}$).

This constitutes a simple extension of the patient's anatomical deadspace ($V_{DAN}$). Familiar

Throughout this paper certain simplifying assumptions have been made. We have assumed that the inspired and expired tidal volumes are equal. Secondly, we have assumed that the composition of the alveolar gas is constant during expiration and that the composition of the re-inhaled gas is also constant during the period over which it is re-inhaled.
examples are facepieces, masks, endotracheal tubes and their connections. The pattern of rebreathing is a retracing of the previous expiration until fresh gas is reached. The contamination is thus by end-expiratory gas in volume equal to the functional volume of the apparatus deadspace. This may be less than, but cannot exceed, the volume of the apparatus deadspace as measured by water displacement.

It is quite usual to consider simple apparatus deadspace as an extension of the patient's respiratory tract. Thus solution of Bohr's equation for physiological deadspace yields a volume which always includes the apparatus deadspace. Measurement of anatomical deadspace by the technique of Fowler (1948) includes apparatus deadspace if the sampling point lies between the apparatus deadspace and the fresh gas supply. Apparatus deadspace is not included if the sampling point lies between the apparatus deadspace and the patient's respiratory tract (e.g. at the lower end of the endotracheal tube).

Contamination with mixed expired gas.

A number of anaesthetic gas circuits result in the contamination of fresh gas with mixed expired gas. In the case of circle systems, carbon dioxide absorption is usual, but with to-and-fro systems the canister is frequently omitted to leave the simple bag-and-mask described as circuit C by Mapleson (1954). With the latter circuit, during early inspiration, the inspired gas consists largely of mixed expired gas until the inspiratory flow rate falls when the proportion of fresh gas rises.

Contamination with gas exhaled from the patient's anatomical deadspace.

The peculiar virtue of the Magill attachment is that, when rebreathing occurs, the gas most likely to be re-inhaled is that which has been exhaled from the patient's anatomical deadspace and is therefore identical to fresh gas. In terms of gas volumes, rebreathing has occurred, but it is without effect on gaseous exchange.

Contamination late in inspiration.

If it is allowed to occur, the pattern of rebreathing with Ayre's T-piece is exceedingly complex (Mapleson, 1958). Contamination is most likely to occur towards the end of inspiration since fresh gas accumulates in the proximal part of the open limb at the end of expiration. This gas may be available during early inspiration. Gas which is inhaled at the end of inspiration may never reach the alveoli but come to rest in the patient's deadspace where it can have no effect upon gaseous exchange. As in the previous case, rebreathing has occurred in terms of gas volumes but not in terms of gaseous exchange. This important aspect of rebreathing influences most of our discussion below.

DEFINITIONS AND SYMBOLS

The symbols are in accord with the recommendations of the Committee for the Standardization of Definitions and Symbols in Respiratory Physiology (Pappenheimer et al., 1950).

Fresh gas refers to the gas delivered from Rotameters and vaporizers before it is contaminated with the expired air of the patient. We have used the symbol \( i \) signifying "ideal" or "intended" inspired gas.

Mixed inspired gas refers to the mixture of fresh gas and previously exhaled gas which is inhaled by the patient. It carries the symbol \( I \). Unfortunately two separate interpretations may be required. The first relates to the gas actually drawn into the respiratory tract and may be specified by the symbol \( I^* \) (the letter "t" signifying "total" or "tidal"). This definition is applicable in measurements of gaseous exchange from the difference between inspired and expired concentrations. Alternatively it may be necessary to consider only that part of the inspired gas which enters the alveoli and actually influences gaseous exchange. This fraction of the inspired gas may be specified by the symbol \( I^a \) (the letter "a" signifying "alveolar").

This distinction is only relevant in the presence of rebreathing, particularly when contamination occurs towards the end of inspiration. It will be shown below, however, that there is still a difference between the two definitions of mixed inspired gas even with the simple form of apparatus deadspace.

Mean inspired concentration may also be defined in two ways corresponding to the two possible definitions of mixed inspired gas mentioned above. The first (\( F_{I^x} \)) is the total volume of the gas "\( x \)" inhaled divided by the total inspired volume. It is applicable in the following general equation for the determination of exchange of any gas "\( x \)":

\[
V_{I^x} = V_I \cdot F_{I^x} - V_E \cdot F_{E^x} \quad \ldots \quad (ii)
\]

(\( F_{E^x} \) is the mixed expired concentration of the gas "\( x \)", correspondingly defined.)

The second definition (\( F_{I^ax} \)) is the volume of the gas "\( x \)" inhaled into the alveoli, divided by the total volume inhaled into the alveoli. We may
now rewrite the general alveolar air equation (i) in more precise form:

\[ F_{AX} = F_{ix} - \frac{V_X}{V_A} \text{ (iii)} \]

It should be noted that, in both cases, the mean concentration is determined in relation to volume and not time as in the case of mean arterial blood pressure, mean intrathoracic pressure, etc. Thus the mean inspired or expired concentration of a gas cannot be determined solely from a plot of instantaneous gas concentration against time (as is displayed on a pen oscillograph). A disproportionate amount of the trace will relate to the time when the flow of gas past the sampling point is slow, as during the post-expiratory pause. The determination of the mean inspired concentration is, in fact, difficult and is considered in some detail below.

**Apparatus deadspace** \((V_{DAP})\) is the volume of expired gas which is re-inhaled. The gas which is actually re-inhaled may be fresh gas \(i^1\), mixed expired gas \(E\), end-expiratory gas \(E'\) or any mixture of these.

**Rebreathing ratio** \((\gamma)\). At first sight it might appear reasonable to consider the rebreathing ratio as the apparatus deadspace divided by the inspired tidal volume. However, since the final part of an inspiration neither enters the alveoli nor takes part in gas exchange, rebreathing is in fact complete when the apparatus deadspace equals the inspired tidal volume minus the patient's anatomical deadspace (assuming contamination occurs during the early part of inspiration). It is therefore more useful to define the rebreathing ratio as:

\[ \gamma = \frac{V_{DAP}}{V_I - V_{DAn}} \text{ (iv)} \]

The rebreathing ratio may be used to rewrite the general alveolar air equation in the following form:

\[ F_{AX} = F_{ix} - \frac{V_X}{V_A (1 - \gamma)} \text{ (v)} \]

This equation may be used to derive alveolar gas concentrations from the composition of the fresh gas supply, the gaseous exchange, the alveolar ventilation and the rebreathing ratio. It will indicate the effect of rebreathing and the amount by which fresh gas composition or alveolar ventilation must be altered to compensate for rebreathing. This equation is applicable only to situations in which rebreathing of end-expiratory gas occurs at the beginning of inspiration. In rebreathing systems which depend upon the flushing effect of fresh gas flow \(V_{I^1}\) to expel expired gas:

\[ \gamma \geq 1 - \frac{V_{I^1}}{V_A} \text{ (vi)} \]

where \(V_{I^1}\) does not exceed \(V_A\). The two sides of the equation will be equal in a maximal efficiency system (e.g. the Magill system) but the lefthand side will be greater than the right in less efficient systems.

Substituting equation (vi) in equation (v):

\[ F_{AX} \geq F_{ix} - \frac{V_X}{V_{I^1}} \text{ (vii)} \]

in which it is seen that, under the conditions of rebreathing, the fresh gas flow rate takes the place of the alveolar ventilation in the general alveolar air equation. This conclusion has already been propounded by Mapleson (1958). Under these circumstances hyperventilation cannot alter the alveolar gas composition which is determined by gas exchange and by the flow rate and composition of fresh gas.

**INSPIRED GAS MIXING EQUATIONS**

It is possible to construct a mixing equation for the constituents of inspired gas, analogous to Bohr's equation which relates the constituents of expired gas. Solving this equation for apparatus deadspace:

\[ V_{DAP} = V_I \left( \frac{F_{ix} - F_{ip}x}{F_{ix} - F_{iap}x} \right) \text{ (viii)} \]

This equation is the basis for the measurement of the functional volume of the apparatus deadspace. The equation may alternatively be solved to indicate the mean concentration of gas "x" in the inspired tidal volume:

\[ F_{ix} = \frac{V_{DAP} \cdot F_{iap}x + (V_I - V_{DAP})F_{ix}}{V_I} \text{ (ix)} \]

A slightly more complicated form of the equation indicates the mean concentration of the gas "x" actually inhaled into the alveoli:

\[ F_{ix} = \frac{V_{DAP} \cdot F_{iap}x + (V_I - V_{DAn} - V_{DAP})F_{ix}}{V_I - V_{DAn}} \text{ (x)} \]

**THE VOLUME/CONCENTRATION DIAGRAM**

Figure 1 shows a plot of the instantaneous concentration of a gas "x", sampled at the mouth, plotted against lung volume. The righthand end of
Plot of instantaneous concentration of any gas "x", sampled at the mouth, against lung volume during one respiratory cycle. End-expiratory gas is re-inhaled during the first part of inspiration (D-E). The form shown is typical of carbon dioxide but could apply to any gas with appropriate re-arrangement of the Y axis.

The abscissa represents the end-expiratory lung volume and the lefthand end the end-inspiratory lung volume. Thus inspiration is traced by a point moving to the left and expiration by a point moving to the right. Figure 1 is, in fact, typical of carbon dioxide, but there is no reason why it should not represent any gas provided that the ordinate is inverted for gases which are taken up rather than eliminated.

The situation in figure 1 represents respiration through simple apparatus deadspace. Contamination is by end-expiratory gas and takes place at the beginning of inspiration.Expiration (continuous line) commences with the gas at the sampling point having a concentration of "x" equal to the concentration in fresh gas (\(F_{Rx}\)). This is shown on the graph by the part of the curve from A to B. After the patient’s anatomical deadspace is flushed out, the concentration of “x” at the mouth rises rapidly to a relatively constant alveolar plateau value (\(F_{Ex}\)) shown by the line CD.

During inspiration (broken line) the first gas to pass the sampling point is from the apparatus deadspace and the concentration of the gas “x” retraces the expiratory curve from D to E. At E, the apparatus deadspace is flushed out and the concentration of “x” falls to the level in the fresh gas, shown by the part of the curve from F to A. If there were no apparatus deadspace, the part of the curve from E to F would be displaced to the right to lie below D.

The tidal volume is broken into three parts: on the left the patient’s anatomical deadspace, on the right the apparatus deadspace, and in between the effective volume of tidal exchange. The area BCEF represents the volume of the gas “x” which is exchanged in a single breath. If BC were coincident with EF, the patient’s anatomical deadspace together with the apparatus deadspace would together equal the whole of the inspired tidal volume and none of the gas “x” would be exchanged. Rebreathing would be total according to our preferred definition (equation (iv)).

The mean concentration of the gas “x” in the gas inspired into the patient’s respiratory tract (\(F_{Rx}\)) is indicated by the height of a rectangle, of area equal to that under the whole of the inspiratory curve (DEFBA) and length equal to \(Vr\) (fig. 2). The shaded areas are equal.
The mean concentration of the gas "x" in the gas inspired into the patient's alveoli (FPx) is indicated by the height of a rectangle of area equal to that under the part of the inspiratory curve from D to B and length equal to $V_A$ (fig. 3). The shaded areas are equal.

Figure 4 shows a similar plot with the fresh gas contaminated by mixed expired gas during the early part of an inspiration.

In this case, the gas re-inhaled from the apparatus deadspace (D–E) consists of mixed expired gas. This trace is typical of that obtained for carbon dioxide with the type C circuit (Mapleson, 1954).

Figure 5 shows contamination with a mixture of fresh gas and end-expiratory gas occurring late in inspiration as will occur when Ayre's T-piece is used with inadequate fresh gas flow. During late inspiration, the concentration of the gas "x" (measured at the mouth) rises to a value intermediate between FpX and FeX. During the subsequent expiration this part of the curve is retraced and the area BCDE is unaffected. Gaseous exchange is uninfluenced provided that the contaminated part of the tidal volume is less than the patient's anatomical deadspace.

These plots may be made for concentrations of any gas which can be rapidly analyzed. It is then possible to determine by graphical means, the mean inspired concentration of the gas (either $\text{Fi}^X$ or $\text{Fp}^X$), the patient's anatomical deadspace (Fowler, 1948), the apparatus deadspace (Nunn and Hill, 1960), and the rebreathing ratio.

**PROPORTIONATE SAMPLING OF MIXED INSPIRED GAS**

Determination of the mean inspired concentration by the method described above is tedious and only applicable to gases which may be analyzed by methods with a response time of less than about 0.2 seconds. Thought has therefore been given to the problem of collecting a representative sample of mixed inspired gas which may be analyzed at leisure. Two solutions have been considered.

The first consists of allowing the patient to inhale a substitute inspired gas from the box of a box-bag system while the bag is connected in such a way that it collects the gas which the patient would normally have inhaled. This highly ingenious system was introduced by Woolmer and Lind in 1954. The gas collected in the bag will have the composition $\text{FF}^X$ but the system cannot easily be adapted to indicate $\text{FI}^X$.

An alternative system requires that gas be sampled from the mouth at a rate proportional to the rate at which the tidal flow is passing the sampling point. By this means true samples of either mixed inspired or mixed expired gas could be obtained. Again the method would indicate $\text{FI}^X$ and not $\text{Fp}^X$. Such a technique would not be simple, but a preliminary study has suggested that it is probably feasible (Smith and Bookallil, personal communication). This device would enormously simplify the measurement of gaseous exchange under the conditions of inhalational anaesthesia.

**SYMBOLS**

<table>
<thead>
<tr>
<th>Primary</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>fractional concentration.</td>
</tr>
<tr>
<td>$V$</td>
<td>gas volume.</td>
</tr>
<tr>
<td>$V$</td>
<td>rate of gas flow.</td>
</tr>
<tr>
<td>$\rho$</td>
<td>rebreathing ratio (herein defined).</td>
</tr>
</tbody>
</table>
Secondary:

A alveolar.
I inspired.
I ideal or intended inspired, fresh gas.
I mixed inspired.
I' mixed inspired as seen by the patient's respiratory tract.
I" mixed inspired as seen by the patient's alveoli.
E expired.
E' end-expiratory.
D anatomical deadspace.
Dp apparatus deadspace.
T tidal.

Specific:

x refers to any gas whose uptake (Vx) is of positive sign and whose output (Vx) is of negative sign.

ACKNOWLEDGMENT

J. F. Nunn is in receipt of a Medical Research Council Grant.

REFERENCES


BAZ INHALÉ—RÉ-ASPIRATION DU GAZ+AIR EXPIRÉ ET ESPACE MORT DES APPAREILS DE DISTRIBUTION DE GAZ

SOMMAIRE

Le rapport entre les mélanges inspirés de gaz, leur reprise lors de l'expiration et l'espace mort dans l'appareil d'anesthésie gazeuse ont été examinés par rapport aux conditions susceptibles de se présenter pendant l'anesthésie. De différentes fractions d'air expiré peuvent être ré-inhalées selon l'appareillage à circuit de gaz utilisé et il peut être nécessaire de distinguer entre les gaz entrainés dans le tractus respiratoire et celui qui pénètre effectivement dans les alvéoles en influençant ainsi les échanges gazeux. Les effets de divers degrés et types de réaspiration d'une partie des gaz peuvent être déterminés par une équation de mélange analogue à l'équation de Bohr ou par un diagramme indiquant le rapport entre volume et concentration. La concentration moyenne effective d'un gaz dans un mélange d'air inspiré ne peut être obtenue en tenant simplement compte de la concentration instantanée par rapport au volume aspiré mais par rapport au temps pendant lequel l'inhalation a lieu.

EINGEATMETES GAS, RÜCKATMUNG UND TOTRAUM DES NARKOSEAPPARATES

ZUSAMMENFASSUNG