TRICHLOROETHYLENE CONCENTRATION FROM A “BOYLE” TYPE ANAESTHETIC APPARATUS

BY

W. W. MAPLESON

Department of Anaesthetics, Welsh National School of Medicine, Cardiff

INTRODUCTION

GILCHRIST and Goldsmith (1956) have recently criticized the trichloroethylene vaporizing unit of the Boyle type anaesthetic apparatus on the grounds that it can deliver “dangerously high” concentrations. They made a plea for the replacement of the present unit by a calibrated and standardized vaporizer.

In order to assess the value of such a proposal it seems essential to have a good knowledge of the performance of the present unit. Although Conn, Dyer and Ferguson (1955) have made some measurements of the concentrations obtained from a Marrett head on an Airmed apparatus, no detailed investigation of the Boyle apparatus appears to have yet been established.

METHOD

A British Oxygen Gases Ltd. Model H Boyle apparatus was used for the experiments. The trichloroethylene vaporizing unit of this apparatus is shown semidiagrammatically in figure 1.

Ports AA and BB are controlled by the rotation of a barrel tap: with the tap in the “off” position ports AA are closed and BB open so that the gas bypasses the vaporizing bottle. As the tap is opened ports AA gradually open and BB gradually close, thereby gradually increasing the proportion of gas passed through the bottle until, with the tap full on, ports AA are fully open and BB closed so that all the gas passes through the bottle.

A further control of concentration of trichloroethylene is provided by the plunger. By pushing this down the incoming gases are deflected to flow closer to the trichloroethylene surface and so produce more rapid vaporization.

The concentrations of trichloroethylene were determined by means of an infrared gas analyser through which a continuous sampling flow was drawn. In some experiments sampling was from the outlet of the vaporizing unit: this will be called “proximal sampling”—proximal as referred to the vaporizing unit. In other experiments the sample was drawn after the gas had passed through an anaesthetic system; usually the reservoir bag and corrugated tube of the Magill attachment.
BRITISH JOURNAL OF ANAESTHESIA

(System A, Mapleson, 1955). This will be referred to as “distal sampling”.

In the distal sampling experiments the aim was to determine the concentration inhaled by the patient. As expected, this was generally less than that emerging from the vaporizing unit because the rubber of the anaesthetic system absorbs, or is porous to, the vapour. The inhaled concentration can be reliably determined without recourse to intermittent sampling provided that the concentration at the sampling point remains steady throughout inspiration and expiration. Clearly this will not be so if the sample is drawn near the expiratory valve with the system connected to a patient because of the vapour absorbed in the patient’s lungs. The same was true in these experiments. An “artificial patient” was used consisting of a piston pump adjustable for rate and tidal volume and lubricated with an oil which absorbed trichloroethylene to a marked extent.

The problem was solved by using the arrangement shown in figure 2 in which a tube of glass (which does not absorb trichloroethylene) whose volume was greater than the largest tidal volume used, separated the sampling point from the expiratory valve and pump. By displaying the quick response output of the analyser on an oscilloscope (Bracken, 1955) it was found that, after the first few breaths, the fluctuation within each respiratory cycle was only 5 per cent of the mean concentration and rapidly fell to only 2 per cent.*

Thus the error in determining the inhaled concentration arising from the use of a continuous sample flow was generally only about 1 per cent of the measured concentration.

A further error can arise from absorption of vapour between the sampling point and the analyser. This was avoided by using polytetrafluoroethylene tubing to make this connection.

In each experiment the concentration was noted at intervals for a predetermined period after turning on the trichloroethylene tap. The zero and sensitivity of the analyser were checked at suitably short intervals. Total errors of measurement are generally less than 0.05 per cent trichloroethylene and rarely exceed 0.1 per cent trichloroethylene.

The results given below can be regarded as typical of this type of vaporizing unit but some variation must be expected between individual units. For instance: some recent experiments, in which four of these units were calibrated for use with Fluothane, showed that, although the general pattern of results was similar in all cases, the concentration obtained for any given condition varied by up to ± 20 per cent from the mean.

RESULTS

Some preliminary experiments showed that the factors which may affect the concentration of trichloroethylene inhaled by the patient are as follows:

1. Distance from bottom of plunger to trichloroethylene surface.
2. Tap setting.
3. Gas flow.
4. Degree of eccentricity of plunger and U-tube.
5. Room temperature.
6. Volume of trichloroethylene in bottle.
7. Type of anaesthetic system connected to vaporizing unit.

*In this paper a variation or change in concentration is given as a percentage of the concentration existing under some specified condition and not as an actual percentage concentration. For actual concentrations the term “percent trichloroethylene” is used, implying per cent trichloroethylene (v/v) in some gas. Although oxygen was used here the results would be the same for any mixture of perfect gases such as oxygen, nitrous oxide and air.
TRICHLOROETHYLENE CONCENTRATION

(8) Type of rubber used in anaesthetic system.
(9) Type of breathing.
(10) Time from turning on trichloroethylene.

In the laboratory factors 5, 6 and 10 can be replaced by a single factor: the temperature of the trichloroethylene. However, since a thermometer is not normally fitted in the vaporizing unit, it was felt the results could be more easily applied in clinical practice if presented in terms of the ten factors listed above.

If an average of only three different values were used for each of the first nine of these factors, then, to cover all combinations, a total of some $3^9 = 19,683$ experiments would be needed, each lasting an hour or more. However, the preliminary experiments indicated the general trend of the results and led to the selection of seventeen experiments, each lasting twenty minutes. The majority of these were designed to show, by proximal sampling, the influence of the first six factors on the concentration emerging from the vaporizing unit and the remainder, by distal sampling, how this concentration was modified, on its way to the patient, by factors 7 to 9.

From the results of this main sequence, together with some information from the preliminary experiments, it is possible to estimate the inhaled concentration for most reasonable combinations of values with tolerable accuracy.

A few important results from the preliminary experiments will be considered first.

Preliminary Experiments

Variation of concentration with time. As would be expected from a consideration of the physical principles involved (Macintosh and Mushin, 1947) the trichloroethylene concentration, immediately after turning on the tap, was relatively high and fell with time—rapidly at first and then more and more slowly. In particular, with the plunger down, in the period from 20 to 60 minutes after turning on the tap, the concentration fell by only 10 per cent of the value at 20 minutes. With the plunger up the equivalent figure was 5 per cent. The fall was rather greater when gas was bubbled through the trichloroethylene, but this condition was not included in the main sequence of experiments. In one experiment observations were continued for two hours, with the plunger down, and in the second hour the concentration fell by 5 per cent of the value at 20 minutes.

Thus the experiments in the main sequence could be terminated after 20 minutes in the knowledge that the concentration-time curves could be extrapolated to two hours in accordance with the above figures.

Variation with degree of eccentricity of plunger and U-tube. In the vaporizing unit used for these experiments, as with many similar units, slackness in the sleeve bearing which guided the plunger allowed considerable play in the latter. Thus the plunger could be set so that it was not concentric with the U-tube. It was found that with a gas flow of 6 l./min and the plunger halfway down, moving the plunger from the concentric position to a position such that the inside of the plunger touched the outside of the U-tube at one point increased the trichloroethylene concentration by 20 per cent. In extreme conditions—at a flow of 2 l./min with the plunger up—such a manoeuvre can as much as double the concentration.

The undesirable nature of this feature is considered later. For the moment it is sufficient to say that in the main sequence of experiments this variable was eliminated by always setting the plunger concentric with the U-tube.

Variation with volume of trichloroethylene in bottle. Most of the preliminary experiments were conducted with 50 ml of trichloroethylene in the bottle at the start, but in a few 75 ml were used. The rate of fall of concentration was a little less in the latter cases because the trichloroethylene cooled more slowly but the effect was small. Therefore a volume of 50 ml was used throughout the main sequence of experiments. This gave a depth of liquid of a little over 2 cm and is of the same order as that commonly used in clinical practice.

“Standard” Conditions in the Main Sequence of Experiments

In describing the results of the main sequence of experiments it is convenient to state an artificial “standard” set of conditions involving one particular value for each of the factors listed at the beginning of the results section. Then each experiment shows the effect on the concentration
of varying one or more of these factors.

The standard set of conditions, then, was as follows:

1) Distance from bottom of plunger to trichloroethylene surface at start of experiment: 70 mm.
2) Tap setting: full on.
3) Gas flow: 7 l./min.
4) Plunger and U-tube: concentric.
5) Room temperature: 24°C (75°F).
6) Volume of trichloroethylene in bottle at start of experiment: 50 ml.
7) Type of anaesthetic system: reservoir bag and corrugated tube (Magill attachment).
8) Type of rubber: antistatic.
9) Type of breathing: 330 ml tidal volume at 33 respirations per minute (to simulate the commonly occurring tachypnoea).

Items 7 to 9, of course, do not apply to the experiments with proximal sampling.

The effect of different values of each factor, except those already dealt with, will now be considered in detail, taking the experiments with proximal sampling first.

**Proximal Sampling**

*Variation of concentration with distance from plunger to trichloroethylene surface.* Besides the standard value of 70 mm (plunger fully up) values of 0 and 35 mm (plunger down and halfway respectively) were used. These were the distances at the beginnings of the experiments and consequently they gradually increased as the trichloroethylene evaporated. Figure 3 shows that the concentration is highest and falls most rapidly with the plunger down. The brief initial peak with the plunger up is attributed to saturated gas displaced from the bottle by the first few hundred ml of fresh gas after turning on the tap.

Gas was not bubbled through the trichloroethylene in the main sequence of experiments but the preliminary experiments showed that with otherwise standard conditions such a procedure would give from 5 to 3 per cent trichloroethylene for the first few minutes.

*Variation with tap setting.* In January, 1946, British Oxygen Gases Ltd. introduced a new design of tap. Although there was no change in the external features, the internal modification considerably altered the way in which the concentration varied with tap setting. The unit used for the main sequence of experiments happened to contain an old style tap, so a few supplementary experiments were made with a unit incorporating a new style tap.

In both the old and new styles the “scale” beside the tap comprises four horizontal lines separating the words “off” and “on”. With both units experiments were made with the tap at each mark and at “on”, with otherwise standard conditions. For the unit with the old style tap it was found that with the tap at the 1st (adjacent to “off”) and 2nd marks no trichloroethylene vapour was obtained. With the tap at the fourth mark the concentration was the same as with it fully on. With the tap at the third mark the concentration at 20 minutes was about one-third of that with it fully on (see fig. 4). For the unit with the new style tap the results are shown in figure 5. It will be seen that here trichloroethylene vapour begins to appear when the tap is between
Fig. 4
Variation of concentration with tap setting—old style tap.

Fig. 5
Variation of concentration with tap setting—new style tap.

Fig. 6
Variation of concentration with gas flow—at two plunger-to-surface distances.

Fig. 7
Variation of concentration with room temperature—at two rates of vaporization.
the first and second marks and the concentration at 20 minutes then increases nearly linearly with 
tap setting up to the fourth mark.

Variation with gas flow. In two experiments an 
increased gas flow of 10.5 l./min was used. In 
one of these the conditions were otherwise stan-
dard, while in the other the plunger to surface 
distance was 0 mm. Figure 6 shows that increas-
ing the flow has decreased the concentration by 15 
to 20 per cent, of that at 7 l./min, with the 
plunger down and 10 to 15 per cent with the 
plunger up.

Variation with room temperature. For two 
experiments the room temperature was reduced 
to 20.5°C (69°F). In one of these the conditions 
were otherwise standard; in the other rapid 
vaporization was obtained by using a gas flow of 
10.5 l./min with the plunger down. Figure 7 
shows that in both cases reducing the room tem-
perature reduced the initial concentration by 10 
to 15 per cent and the concentration at 20 minutes 
by 5 to 10 per cent.

Distal Sampling

The effect of distal sampling. As mentioned 
elier, rubber either absorbs or is porous to tri-
chloroethylene vapour. It is to be expected, there-fore, that the inhaled concentration will be less 
than that emerging from the vaporizing unit, par-
ticularly just after turning on the trichloro-
ethylene. Figure 8 confirms this. Three pairs of 
curves show proximal and distal concentrations, 
all with standard distal conditions but with three 
different sets of proximal conditions covering a 
wide range of vaporization rates. It will be seen 
that the initial peaks in the proximal concentra-
tions have been very much flattened in the 
corresponding distal concentrations. Also, the 
distal concentration gradually approaches the 
proximal concentration.

Variation with type of anaesthetic circuit and 
breathing. In addition to the reservoir bag and 
tube the T-piece and Cardiff perforated connector 
(Picken, 1950) systems were considered. In the 
first of these the gas is fed to the patient through 
a length of narrow bore tubing and a T-piece. 
Expiration and spillage of gas occurs through the 
free limb of the T-piece which may have a length of 
tubing attached to it. In the second system

the T-piece is replaced by a short straight tube 
with a number of holes perforated in its wall. 
In both these systems, provided the gas flow is 
sufficient to eliminate rebreathing or the dilution 
of the anaesthetic with air, the breathing pattern 
cannot affect the inhaled concentration of 
vapour; since there is no reservoir bag the flow 
through the narrow bore tubing is constant and 
determined solely by the controls on the anaes-
thetic apparatus. Thus in these experiments the 
performance of both these systems could be 
examined merely by sampling from the end of 
a length of narrow bore rubber tubing without 
using the breathing pump. The particular tube 
used was 1.5 m long with a 6 mm bore. With 
the reservoir bag and corrugated tube, on the 
other hand, the breathing pattern will influence 
the flow in the rubber tubing and bag and hence 
affect the inhaled concentration. Accordingly, in 
addition to the “standard” respiratory pattern of 
33 respirations per minute and 330 ml tidal 
volume, chosen to simulate the tachypnoea of 
established trichloroethylene anaesthesia, one 
experiment was done with 19 respirations per 
minute and 500 ml tidal volume—a pattern more 
characteristic of the induction stage.

Figure 9 compares the inhaled concentrations 
for these various distal conditions with the 
proximal concentration (curve A). The proximal 
conditions are the same in all cases. It will be 
seen that, unlike the reservoir bag and tube 
(curves C, D), the T-piece or perforated connector 
system (curve B) leads to only a slight flattening 
of the initial peak; the inhaled concentration is 
within 10 per cent of the proximal concentration 
after one minute. This is to be expected because 
of the smaller surface area of rubber and the 
thicker walls. (From this it can be deduced that 
the half-metre or so of narrow bore tubing some-
times inserted between the anaesthetic apparatus 
and the reservoir bag of the Magill attachment 
will have little effect on the inhaled concentra-
tion.) With the reservoir bag and tube the deeper 
slower respirations (curve D) lead to a more 
marked flattening of the peak than the “standard” 
respiratory pattern (curve C). This, also, is to be 
expected: in the extreme case of zero tidal volume 
the reservoir bag will remain distended so that 

it is effectively out of circuit, apart from diffu-
TRICHLOROETHYLENE CONCENTRATION

Effect of distal sampling with reservoir bag and tube and 33 respirations per minute of 330 ml tidal volume—three rates of vaporization.

As the tidal volume is increased the bag becomes effectively more in circuit, giving a greater area of rubber and greater absorption or diffusion of the vapour.

Variation with type of rubber. In all the experiments so far described antistatic rubber was used. One of these was repeated with a reservoir bag and tube in red rubber, but the results were identical with those obtained with antistatic rubber.

Note on the release of trichloroethylene from rubber. Since rubber absorbs trichloroethylene from the vapour stream it is to be expected that it will also release it back into the gas stream when the concentration is suddenly reduced. This was confirmed in one of the preliminary experiments by continuing distal sampling with the bag and tube after turning off the trichloroethylene. The concentration just before turning it off (60 minutes after turning it on) was 0.8 per cent trichloroethylene. This fell to 0.3 per cent trichloroethylene after one minute, to 0.1 per cent after four minutes and to 0.05 per cent after seven minutes.

Therefore, to be sure of consistent results in the distal sampling experiments, the bags and tubes were always allowed at least 24 hours “rest” from trichloroethylene before use.

DISCUSSION

The general pattern of the results is roughly what would be expected on theoretical grounds (Macintosh and Mushin, 1947), but a few points call for comment.

Firstly, in this vaporizing unit, short of bubbling gas through the liquid trichloroethylene, it is impossible to maintain concentrations much in excess of 1 per cent trichloroethylene. From informal inquiries among a small, but widely spread, group of anaesthetists it seems that this will generally be thought surprisingly low.

Another striking feature is the magnitude of the effect of vapour absorption in the reservoir bag and corrugated tube, particularly initially.
However, when this is combined with the initially high concentration emerging from the vaporizing unit the resultant inhaled concentration is remarkably steady, particularly with the relatively slow and deep respirations of curve D in figure 9. In fact the variation is not a great deal more than would be expected from an elaborate vaporizer specially designed to eliminate such variations. Indeed, the performance of a vaporizer which, in itself, was theoretically perfect would be somewhat impaired by the absorption of vapour in the anaesthetic system.

The plunger and tap are intended to regulate the concentrations and do so quite effectively with the following reservations. Firstly, the old style tap has a very unsatisfactory relation between concentration and tap position, but this has been overcome in the new design. Secondly, any play in the plunger bearing gives rise to unwanted changes of concentration, but Hillard (1957) has devised a modification to overcome this. The other factors which influence the concentration (gas flow, room temperature and volume of liquid trichloroethylene) seem to have little effect within the ranges examined in these experiments.

Thus, given the improvement in the plunger guide and a more rigid quality control in manufacture, it would be practicable to compile a simple calibration table for the vaporizing unit when used with a reservoir bag and corrugated tube. With certain reservations such a table would generally be accurate to the nearest 0.25 per cent trichloroethylene.

The concentration obtained with combinations of conditions not specifically covered in these experiments can generally be estimated from a careful study of the graphs. If the conditions are changed some time after the trichloroethylene has been turned on the graph of concentration against time will jump to the curve representative of the new conditions but with some initial overshoot. For instance, if the plunger is pushed further down, the trichloroethylene temperature, and hence the emergent concentration, will be greater than if the plunger had been in the lower position from the start. However, the rate of cooling will also be greater, so that the discrepancy will gradually diminish. The reverse will occur if the plunger is raised. Absorption or release of vapour in the bag and tube will lead to these overshoots being partly smoothed out in the inhaled concentration.

Although Gilchrist and Goldsmith (1956) speak of “dangerously high” concentrations, they do not state what is the maximum concentration they would regard as safe. However, since the three figures they mention are 2.3, 1.6 and 0.9 per cent trichloroethylene, presumably 2.3 per cent would certainly be regarded by them as dangerous and perhaps also 1.6 per cent. Concentrations of these magnitudes can undoubtedly be obtained if gas is bubbled through the trichloroethylene. However, if this is avoided the maximum concentration which can be inhaled via a reservoir bag and corrugated tube is 1.5 per cent trichloroethylene and this rapidly falls to near 1 per cent.

CONCLUSION

Given the Hillard improvement of the plunger guide, the trichloroethylene vaporizing unit of the British Oxygen Gases Ltd Boyle type anaesthetic apparatus, when combined with the standard reservoir bag and corrugated tube, gives inhaled concentrations which vary remarkably little with time or, within reasonable limits, with other extraneous factors. Also, given the new style tap, the control of this concentration is reasonably satisfactory. Provided gas is not bubbled through the trichloroethylene, the concentration inhaled through a reservoir bag and corrugated tube does not exceed 1.5 per cent trichloroethylene and cannot be maintained much above 1 per cent.

SUMMARY

The concentrations of trichloroethylene emerging from the vaporizing unit of a British Oxygen Gases Ltd. Boyle type anaesthetic apparatus and the concentrations inhaled by a patient through various anaesthetic systems have been measured in the laboratory under a wide variety of conditions. It has been found that although the curve of the concentration emerging from the vaporizing unit...
unit, against time, shows an initial peak, particularly with high rates of vaporization, the effect of the absorption of vapour by rubber is to reduce or even eliminate the peak when a reservoir bag and corrugated tube are used. If a T-piece or Cardiff perforated connector system with narrow bore tubing is used absorption of vapour is much less and the inhaled concentration differs little from that emerging from the vaporizing unit. If gas is not bubbled through the liquid trichloroethylene it is impossible to maintain concentrations much above 1 per cent trichloroethylene (v/v) when the bag and corrugated tube are used.

ACKNOWLEDGMENTS

The author’s grateful thanks are due to Professor William W. Mushin for drawing attention to the problem and for his continuous encouragement; to E. K. Hillard, Esq., L.I.B.S.T., Senior Technician to this Department, for his great help in making many of the tedious observations involved; and to British Oxygen Gases Ltd, for their generosity in supplying two trichloroethylene vaporizing unit heads, and for the trouble they took to answer queries about the two styles of tap.

REFERENCES


BOOK REVIEW


With the death of Lord Horder, the 1956 edition of Medical Progress appears with Lord Cohen of Birkenhead, as editor-in-chief. In the foreword, Lord Cohen pays tribute to his predecessor whom he regards as “one of the architects of contemporary clinical medicine . . . the first physician to bring the fruits of laboratory and instrument investigation to the bedside”. As he points out, most of the arrangements for this volume were completed by Lord Horder, and the high standard set in previous issues is maintained.

On looking at the index under the heading Anaesthesia, one is referred to six abstracts which occupy about three pages of the 364-page book and these deal mainly with hypothermia. This must not be taken as indicative of the value of the book to the anaesthetist. In part II, which is devoted to Recent Advances in Pharmacology and Therapeutics, one finds an up-to-date discourse on chlorpromazine and such new drugs as methylpentynol, amiphenazole, and bemegride. With the increasing use of steroids the section on Cortisone and Related Steroids will prove extremely valuable to the clinician who has not the time to follow the numerous publications on these drugs. Likewise much valuable information can be obtained on the rauwolfia alkaloids.

New publications on hypothermia are appearing with amazing rapidity, especially in foreign journals; the time must have come for an authoritative critical survey on this subject. It is hoped that such will appear in part I of the 1957 issue of Medical Progress.

In contrast to Medical Progress, the cumulative supplement “concerns knowledge of proved value and neither controversial nor doubtful material is included”. In the absence of an index to the key numbers, it may be difficult to find Anaesthetic Trends in pages 38 and 39 (key number 34). The weakness of nitrous oxide-