REMOTE MONITORING BY MASS SPECTROMETRY DURING ANAESTHESIA

Evaluation of a suitable inlet system

G. GORDON, T. BOYD AND R. F. SALAMONSEN

SUMMARY

We describe a three-stage mass spectrometer inlet system suitable for use in operating theatres and evidence of its performance in delay and response times to step changes in oxygen and halothane concentrations. At 55 m and a sampled gas flow of 100 ml/min, the inlet imposed a delay of 21 s and prolonged the 10-90% response to 310 ms for oxygen and 510 ms for halothane. A linear relationship between inlet length and 10-90% response time at constant sampled gas flow was demonstrated for halothane but not for oxygen. Our results compared with those of other workers support the chosen compromise between practical flexibility and convenience versus maximum speed of response that was adopted in this system design.

Respiratory mass spectrometry is becoming more widely used clinically and although still mainly a research tool, it is able to provide valuable information for patient monitoring. In a busy ward or theatre suite there may be little space and it would be an advantage to place the mass spectrometer (MS) system some distance from the patient. This requires long inlet systems, but permits sequential monitoring of more than one patient.

We have designed an inlet system which conducts sampled gas from the patient's breathing circuit to the analyser in three stages (fig. 1): first stage = a disposable p.t.f.e. sampling cannula (6-mm bore; 1 m long); second stage = a micro-needle valve (S.G.E., Melbourne); third stage = a stainless steel capillary tube (1.54-mm bore; variable length).

An increase in length of the third stage may be expected to prolong the time for the gas front to pass through the inlet system (delay time) and also to establish itself in the ionization chamber (response time). An increase in the sampled gas flow rate would have the opposite effect. The interaction of these two factors has been evaluated in the laboratory and we present the results of this study.

METHODS

Step changes in oxygen and halothane concentrations were presented to a sampling probe by a gas switch (see Appendix) which was controlled and timed by a computer. This directed the probe into either of two gas streams which had different concentrations of the two agents, then automatically switched the probe back and forth to produce step changes in gas concentration.

All stainless steel components used for the study were prepared by exposure of internal surfaces to 10% phosphoric acid in methanol, 100% methanol and 100% acetone in sequence and subsequently air dried.

By varying the length of the stainless steel capillary tubing and the sampled gas flow we were able to study their effects on the step to 10% delay and the 10-90% response times (as defined in figure 2) of the gases monitored. Using zero
deadspace connectors (S.G.E., Melbourne) the stainless steel capillary tubing was lengthened in increments of 11 m to a maximum of 55 m. The sampled gas flow, measured by a high precision rotameter, was increased by adjustment of the inlet needle valve in steps of approximately 25 ml min$^{-1}$ from approximately 10–200 ml min$^{-1}$. At each length and sampled gas flow, inlet response to step increases and decreases in concentrations were measured and the results averaged.

Two ancillary studies were conducted to determine the relative contribution of the micro-needle valve and the p.t.f.e. cannula to inlet response times. First, the response time of the needle valve alone when applied directly to the mass spectrometer was compared with the standard 1-m Centronic capillary tube at 30 ml min$^{-1}$ (flow rate obtained with the latter). Second, the response of the needle valve alone and of the needle valve with p.t.f.e. cannula was measured at sampled gas flows from 10 to 200 ml min$^{-1}$.

All measurements were made with an eight-channel mass spectrometer (M.G.A. Centronics, U.K.) interfaced to a Minc 11 microcomputer (Digital Equipment Corporation). Oxygen concentrations were monitored on a single channel but, because of its lower signal to noise ratio, five channels were used for halothane and the results averaged. All channel outputs were modified by the automatic stability control (a facility which expresses the partial pressure of each component as a fraction of the total) to minimize viscosity-induced artefacts in step responses. Delay and response times were then calculated and recorded by the computer.

Statistics. Linear and second-degree polynomial regressions were performed to examine the linearity of relationships between inlet length and 10–90% response time (at constant sampled gas flow) for both halothane and oxygen.

The criterion for linearity was a significant improvement in fit of the data points to the regression line when the quadratic term was added. The significance of the improvement was tested by an analysis of variance as detailed by Snedecor and Cochran (1980). The same approach was used to determine whether capillary tube length or square of length was more linearly related to delay time.

RESULTS

Differences in the response of the MS to step increases and decreases in oxygen concentration

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**FIG 2. Mass spectrometer response to step changes in gas concentration** The exponential increase applies to short and the sigmoid response to long versions of the inlet. In both cases, response can be assessed in terms of the step-10% delay and 10-90% response times.
EVALUATION OF MASS SPECTROMETER INLET

Flow/time relations. Figures 3 and 4 display the 10–90% response times for oxygen and halothane against sampled gas flow rate for various lengths of inlet. Despite the increased variability in the results, the 10–90% response times for halothane are invariably longer than for oxygen. By contrast, delay times for oxygen and halothane were more similar. Although those for halothane were always longer, the differences were not statistically significant. Accordingly, only the results for oxygen are graphed (fig. 5).

Length/time relations. Table I shows that the relationship between inlet length and 10–90% response time is significantly alinear for oxygen but not for halothane over the range of flows tested. Our results (table II) also indicate that, in our inlet system, the step-10% delay does not increase linearly with either inlet length or square (rise and fall times) were slight: usually within 5%, and within 9% in all cases. Greater differences existed for halothane, the fall times being always longer than rise times to a maximum of 18%. The detailed results which follow are reported as the means of individual rise and fall times.
of inlet length, although the alinearity is less with the latter.

**Effect of first and second stages.** The micro-needle valve and p.t.f.e. cannula (stages 1 and 2 of the inlet) prolong inlet response times. At 30 ml min\(^{-1}\) sampled gas flow, the needle valve alone increases 10–90% response from 65 ms (measured with the standard Centronic 1-m capillary tube) to 85 ms. The p.t.f.e. cannula (fig. 6) slows response further, particularly at sampled gas flows of less than 80 ml min\(^{-1}\).

**DISCUSSION**

With good electronic and vacuum system design, the inlet characteristics largely determine the effective response time of the MS to partial pressure changes of a component in the gas mixture sampled (Buckingham, 1979). During passage through the inlet, the partial pressure gradient of the component is reduced by dispersal into neighbouring gas (Fowler, 1969), absorption into inlet materials (Gillibe, Heneghan and Branthwaite, 1981) or, as for water vapour, adsorption on to cold internal metal surfaces (Fowler, 1958; Stout, Wessel and Paul, 1974).

Dispersion of a component in surrounding gas occurs in areas of deadspace (particularly if at high pressure), but also during passage down capillary tubes. The latter becomes significant with inlets longer than 4–5 m and relatively more important as inlet lengthens. Goodwin (1979) has given theoretical justification and experimental verification for a lengthening of response time with increasing viscosity of the sampled mixture, decreasing interdiffusion coefficient for the selected component in the mixture and increasing length (but not radius) of the capillary inlet. He also states that the delay time should increase as the square of inlet length.

Our findings are in partial agreement with Goodwin. We found that to a fair approximation, the delay time increases as the square of inlet length. Although a linear relationship was demonstrated between 10–90% response time and inlet length for halothane, this was not the case for oxygen. A possible reason for the discrepancies between the two studies is the more complex geometry of our three-stage inlet as compared with uniform bore of Goodwin’s capillary tubes.

Variations in inlet diameters and associated inlet conductances are known to complicate the inlet response to step changes in gas composition (Buckingham, 1979).

The 10–90% response time for halothane agrees with the low diffusion coefficient of organic
vapours, but is unlikely to be caused by absorption into inlet materials in our system. Solubility in p.t.f.e. is very low (Fielding, 1978) and is negligible in stainless steel. Adsorption (as for water vapour) remains an alternative explanation. It is possible that surface effects might also account for the more linear relationship between halothane response times and inlet length compared with oxygen.

Stout, Wessel and Paul (1974) suggested a terminal resistance (needle valve) together with a relatively wide-bore tube (1–2 mm) as an alternative to the inlet capillary. Advantages claimed were shorter response and delay times, reduced sensitivity both to water vapour and viscosity changes in sampled gas and greater ease of cleaning. This design concept has been favourably by Glaister and Farncombe (1979) who used either needle valves or minute holes in metal discs for terminal resistances and by Gothard and others (1980) and Gilbe, Heneghan and Branthwaite (1981) who substituted short lengths of narrow-bore capillary tubing at the distal end to achieve a similar effect.

Our approach has been to combine a micro-needle valve with a p.t.f.e. capillary tube at the patient end of the inlet. The adjustable needle valve which is mounted on the anaesthetic machine ensures that sampling flow rates can be adjusted for the individual patient irrespective of inlet length. The disposable p.t.f.e. capillary (1 m) makes a clean, convenient and electrically safe connection with the patient circuit. Disadvantages are the complicated geometry of the inlet and the risk of high pressure deadspace distal to the needle which prolong response time as indicated in figure 6. However, the graph also indicates the reduction that can be achieved with faster sampling flows. The clinical importance of these effects is difficult to determine but should assume greater importance as the inlet lengthens and overall response time increases.

Adequate predictions of upper limits of acceptability for inlet length are hampered by the lack of clearly defined limits for delay and response times and sampling flow in different clinical situations. Presumably any significant delay is a disadvantage when gas measurements are incorporated into alarm systems or control mechanisms, but is of much less importance for other monitoring applications provided it is constant and known. Fowler (1969) quotes a maximum 0–90% response time of less than 1 s for low resolution applications such as measurement of slope of the alveolar plateau and less than 100 ms for high-resolution studies such as measurement of cardiogenic oscillations or single-breath deadspace. Davies and Denison (1979) report that cardiogenic oscillations are demonstrated with inlets giving response times of 200–300 ms. Severinghaus (1978) reports response times of up to 700 ms as satisfactory for analysis of inspired and end-tidal concentrations, while many workers accept response times of 300–500 ms (table III). Similarly, although Fowler (1969) specified a maximum sampling flow of 1% minute volume and Davies

<table>
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<th>Study</th>
<th>Material</th>
<th>Length (m)</th>
<th>TC</th>
<th>$V_s$ (ml min$^{-1}$)</th>
<th>Test gas</th>
<th>Delay time (s)</th>
<th>Index (%)</th>
<th>Time (ms)</th>
<th>Instrument</th>
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<tr>
<td>A</td>
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<td></td>
<td></td>
<td>CO$_2$</td>
<td>9</td>
<td>0–95</td>
<td>700</td>
<td>?</td>
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<tr>
<td>B</td>
<td>P</td>
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<td>NV</td>
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<td>N$_2$</td>
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<tr>
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<td>?</td>
<td>5–95</td>
<td>375</td>
<td>MGA200</td>
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Table III. Characteristics of reported inlet systems. A = Severinghaus and Ozanne (1978); B = Glaister and Farncombe (1979); C = Gilbe, Heneghan and Branthwaite (1981); D = Gothard and others (1980); E = Davis and Spence (1979) Cap = short, narrow bore capillary tube; N = nylon; NV = needle valve, TC = terminal constriction, WB = watch bearing.
and Denison (1979) a range of 20-50 ml (both unsupported by experimental evidence), a much wider range of sampling flow rates are currently in use (table III). It thus appears that use of inlets up to 50 m or more might be feasible for breath-by-breath analysis of airway gases, but more precise functional specifications are required before definite conclusions can be reached.

APPENDIX
Symbols in text relate to figure 7.
Tubing B1 conducts 2% halothane in dry air mixture while tubing B2 conducts a mixture of 50.1% oxygen, 49.1% nitrogen and 0.8% argon. Position of tube orifices is altered relative to sampling cannula E to provide step changes in oxygen and halothane concentrations. This is achieved by rotating the assembly around the bearing C, by energizing (or de-energizing) the solenoid G. Limits D1 and D2 are adjusted to direct the gas streams to the catheter tip.

Duration of the switching event was the interval between closing of one micro switch and opening of the other under computer control. This was 5 ± 0.5 ms.

ACKNOWLEDGEMENTS
This work was supported by a grant from the Digital Equipment Corporation (U.S.A.), the Telelectronics ASA award and the Alfred Hospital Whole Time Specialist Teaching and Research Trust Fund.

REFERENCES
EVALUATION OF MASS SPECTROMETER INLET

SURVEILLANCE TELECOMMANDEE PAR SPECTROMETRIE DE MASSE EN COURS D'ANESTHESIE

Evaluation d'un système d'admission approprié

RESUME
Nous décrivons un système d'admission du spectromètre de masse à trois étapes qui est adapté pour utilisation dans les salles d'opération, ainsi que des preuves de son rendement en périodes de délai et de réponse afin de mesurer les modifications des concentrations d'oxygène et d'halothane. A 55 m et un flux de gaz échantillonné de 100 ml min⁻¹, l'admission imposait un délai de 21 s et prolongeait la réponse 10-90% jusqu'à 310 ms pour l'oxygène et à 510 ms pour l'halothane. Un rapport linéaire entre la longueur d'admission et le temps de réponse 10-90% pour un flux de gaz échantillonné constant a été démontré pour l'halothane mais pas pour l'oxygène. Nos résultats comparés avec ceux d'autres chercheurs viennent confirmer le compromis choisi entre la flexibilité pratique et la commodité vis-à-vis de la vitesse de réponse maximale qui a été adopté dans la conception de ce système.

FERNMESSUNG DURCH MASSENSPEKTROMETRIE WAHREND DER NARKOSE

Beurteilung eines geeigneten Zuflussystems

ZUSAMMENFASSUNG

VIGILANCIA REMOTA POR ESPECTROMETRIA DE MASA DURANTE LA ANESTESIA

Evaluación de un sistema de admisión apropiado

SUMARIO
Describemos un sistema de admisión de un espectrómetro de masa en tres etapas apropiado para el uso en salas de operaciones y pruebas de su rendimiento en tiempos de retardo y de respuesta en la medición de las modificaciones de concentración del oxígeno y del halotano. En 55 m y con un flujo de gas probado de 100 ml min⁻¹, la admisión impuso una demora de 21 s y extendió la respuesta 10-90% hasta 310 ms para el oxígeno y hasta 510 ms para el halotano. Una relación lineal entre el largo de admisión y el tiempo de respuesta 10-90%, con un flujo de gas probado constante, se estableció para el halotano, pero no así para el oxígeno. Nuestros resultados comparados con los de otros trabajadores apoyan el compromiso escogido entre la flexibilidad práctica y la conveniencia en comparación con la velocidad máxima de la respuesta, el que fue adoptado para el diseño del sistema.