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A PORTABLE MASS SPECTROMETER FOR CONTINUOUS ALVEOLAR GAS ANALYSIS: CERTAIN TECHNICAL CONSIDERATIONS INHERENT IN ITS USE *

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A CURRENT awareness of the physiologic rather than the technical concepts guiding the maintenance of surgical anesthesia has awakened renewed interest in analysis of respiratory gases. Many ingenious and detailed devices have been developed for this purpose, among them the Beckman oxygen analyzer (1), the acoustic gas analyzer (2), and the infra-red gas analyzer (3). The majority of such instruments have marked practical limitations. Some are seriously hampered by the presence of anesthetic gases. In 1950, Miller *et al.* (4) reported the development of a portable mass spectrometer adapted to gas analysis and capable of continuously analyzing the composition of a mixture containing five different gases. These authors have described the basic principles of this method of gas analysis and subsequently have briefly alluded to modifications in the sampling technic to permit the analysis of a single gas of rapidly fluctuating concentration, that is, carbon dioxide. It is the purpose in this paper to outline in detail the procedures devised to secure accurate results in the clinical application of this valuable investigative tool under these conditions.

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In the original sampling method (4), a small bore polyethylene tube was threaded down the cuffed endotracheal tube to the vicinity of the carina. Through this small tube a relatively large volume of respiratory gases was continuously withdrawn for the analysis. The sample thus obtained was composed of a mixture of inspiratory and expiratory gases. Because this volume of gases had to be moved through a comparatively large sampling system, a 90 second lag occurred between the instant the sample was picked up at the carina and its ultimate analysis within the spectrometer. Likewise, because of the large volume, all gases not ultilized in the analysis had to be returned to the anesthetic system in order not to hamper seriously the conduction of satisfactory narcosis.

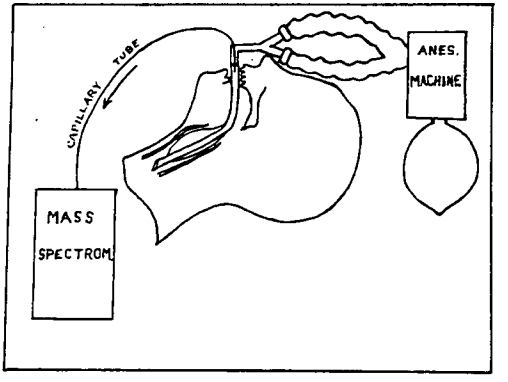

FIG. 1. Schematic illustration of the present sampling system showing the capillary sampling tube located at the upper end of the endotracheal tube; a continuous sample is withdrawn from this site and conveyed to the spectrometer for analysis.

In recent months, several innovations in sampling technic have been devised. A long capillary gas sampling tube (fig. 1) with an internal diameter of 0.009 inch has been substituted for the previously mentioned polyethylene system, resulting in marked improvement in analysis. Because of the minute caliber of the new sampling tube, mixing is almost completely eliminated. This will be discussed in detail. Likewise, the use of the capillary tube has reduced the lag time from 90 to 26 seconds, and since only about 1 cc. of sample gas per minute is withdrawn from the anesthetic system, it becomes unnecessary to return the excess gas to the circuit.

Despite the application of the improvements in design just outlined, several distinct limitations in the use of the instrument were encountered. These restrictions were the result both of physiologic variables

and mechanical and physical properties inherent in the spectrometer and the recording system as they exist today. A description of these problems and the methods by which they were resolved follows.

"Mixing" within the Capillary Tube.—In order that this machine might be employed with safety in the operating room in the study of patients anesthetized with explosive gases, it became mandatory that the main chassis, bearing the electronic circuits and vacuum tubes, be located at a reasonable distance from the operative area. Hence, the 40 foot copper capillary tube described above was devised as a means of conducting the sample of gas from the endotracheal tube within the

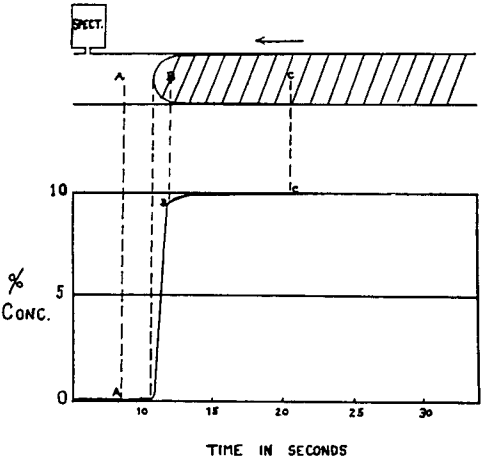

FIG. 2. *Upper,* Schematic illustration of the streamlined flow of sample gases within the capillary tube, showing the cone-shaped interface between the samples. *Lower,* Graphic representation of the recording of this gas flow.

patient to the spectrometer. In spite of the minute caliber of this tube, a phenomenon best described as "mixing" occurs within the lumen each time the gas concentration is altered sharply. This is due to the fact that when one gas displaces another from a tube, the interface between the two is not a plane surface. On the contrary, the displacing gas advances in the form of a cone, leaving a layer of the displaced gas clinging to the walls of the tube (fig. 2, upper). This results in an initial rapid rise in the concentration of the displacing gas as the stream advances, from 0 per cent at point A to about 95 per cent at point B. It will be noted that from point B to point C the increase in concentration is very gradual, until finally 100 per cent new gas is flowing past the

point of analysis. Consequently, the curve of a recording of this process (fig. 2, lower) must display an initial steep rise to 95 per cent, followed by a slowly stabilizing plateau until finally the full value of the displacing gas concentration is recorded. Only one second is required to reach this initial 95 per cent value, but ten to fifteen seconds must elapse before the full value is attained. In the normal respiratory cycle, a concentration of 0.04 per cent carbon dioxide exists in the inspired air and about 5.5 per cent carbon dioxide is present in the expired gas. These concentrations are alternately present about sixteen times per minute or once every three to four seconds. Therefore, since ten to fifteen seconds is required for complete displacement of the preceding gas, total displacement can never be accomplished and, consequently, the maximal potential reading is never attained. Instead, only the

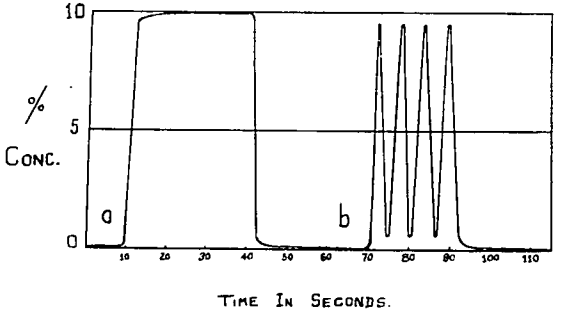

FIG. 3. Graphic illustration of curves: (a) Recorded when a continuous flow of 10 per cent carbon dioxide is used to calibrate the spectrometer. Note the length of time (about 10 seconds) required to attain full value. (b) Recorded when respiratory gas alternately containing 0.04 per cent carbon dioxide and 10 per cent carbon dioxide is then analyzed. Note the failure of the peaks to attain full value due to mixing within the tube.

initial rapid rise in concentration is recorded before the level once again falls rapidly toward zero. For the same reason, the minimal reading (0.04 per cent) is never completely attained before the carbon dioxide concentration again rises sharply. This chain of events results in a series of waves whose peaks reach about 95 per cent of the true level (fig. 3).

We have been able to resolve this problem by a maneuver which we have termed "sweep calibration." Since it is our intent to record accurately the *maximal* concentrations of carbon dioxide present in the respiratory tree, we have forfeited any attempt to attain accuracy in the minimal or trough readings. Therefore, we now calibrate the instrument with a gas mixture of known concentration (usually 10 per cent carbon dioxide in 90 per cent oxygen). This mixture is alternately

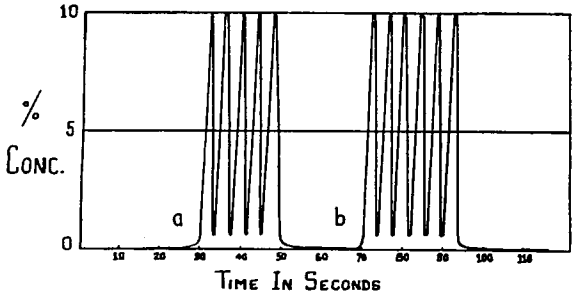

FIG. 4. Graphic illustration of curves: (a) Recorded when an intermittent flow of 10 per cent carbon dioxide is used to calibrate the spectrometer. This is the "sweep calibration" described in the text. (b) Recorded when the respiratory gas alternately containing 0.04 per cent carbon dioxide and 10 per cent carbon dioxide is then analyzed. Note the accuracy of recording of the peak concentrations.

introduced and withdrawn from the sampling tip at a rate approximating the respiratory rate of the subject under study. In this manner, only the segment of the analysis curve containing the rapid rise is used for calibration. Thus, the situation which will obtain in the breathing patient is simulated (fig. 4). Experimentation has shown that, using this calibrating technic, a linear response is obtained with gas concentrations ranging from 5 to 30 per cent (figs. 5A and 5B).

Mechanical Lag of the Recorder.—The recorder employed with this analyzer is a standard commercial single-point pen-writing potentiometer such as is commonly used in industry. The instrument requires 8 seconds for a full scale excursion and the subsequent return to the baseline. Fortunately, even in the most extreme cases of respiratory acidosis seen clinically, carbon dioxide concentrations requiring full-scale excursion are not encountered, since if such concentrations did

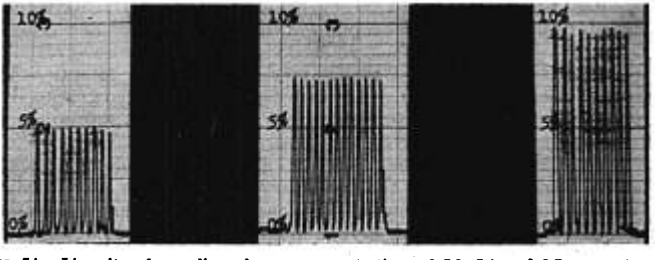

FIG. 5A. Linearity of recording when gas concentrations of 5.0, 7.4, and 9.7 per cent are introduced intermittently at a rate of 28 to 30 per minute.

exist, this recorder could follow accurately fluctuations occurring not more often than once every 8 seconds, or 7.5 times per minute. Usually we are dealing with concentrations which require only 1.2 seconds (10 per cent carbon dioxide concentration) to 2.0 seconds (15 per cent carbon dioxide concentration) to record the complete wave. Hence, rates of fluctuation of fifty and thirty times per minute, respectively, can be recorded with fidelity. It is fortunate that we are rarely called upon to deal with respiratory rates more rapid than those just cited. Figure 6 shows the accuracy obtained through a wide range of respiratory rates. If in an extreme case the concentration of carbon dioxide is found to exceed the values already noted and the accuracy of the recording is consequently impaired owing to the recorder lag, the sensitivity of the spectrometer amplifier can be attenuated; a smaller signal is thereby produced, requiring a smaller excursion of the recorder.

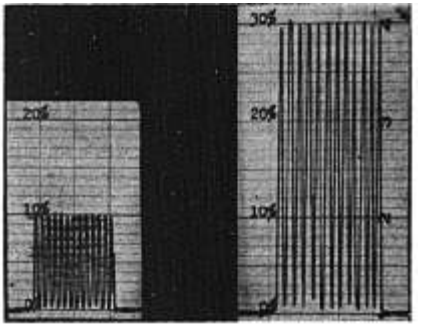

FIG. 5B. Illustrates linearity of recording when gas concentrations of 10 per cent and 30 per cent are introduced.

To summarize these data, we can expect fidelity in recording alveolar concentrations of carbon dioxide of from 5.5 to 15 per cent with respiratory rates up to about 50 per minute in the former value, and up to 30 per minute in the latter. When an accumulation of 20 per cent alveolar carbon dioxide is reached, a respiratory rate of 23 per minute is the maximum compatible with accuracy. For higher concentrations or faster rates, the amplifier sensitivity can be reduced to retain a comparable accuracy.

Variations in Tidal Volume.—It is an accepted physiologic principle that the terminal portion of the expiratory gas contains a concentration of carbon dioxide which is equal to the concentration of that gas present in the alveoli. This alveolar carbon dioxide is, in turn, in equilibrium with gas present in the blood as it leaves the respiratory unit. With the spectrometric method we are attempting to analyze accurately this

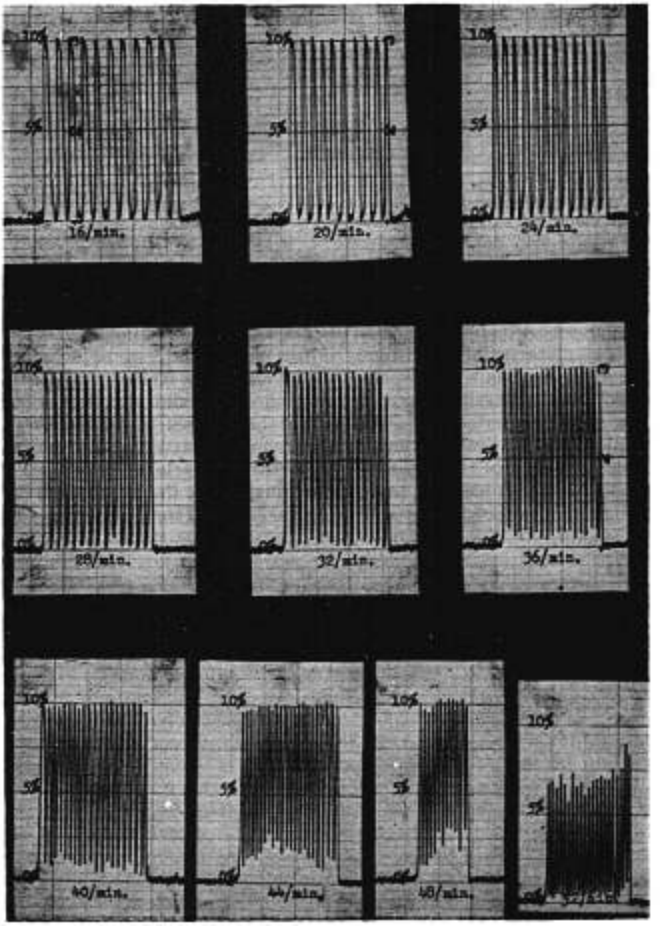

FIG. 6. Illustrates the accuracy of recording of varied respiratory rates to 50 times per minute using 10 per cent carbon dioxide as the test gas. Note the low reading when rate reaches 52 times per minute.

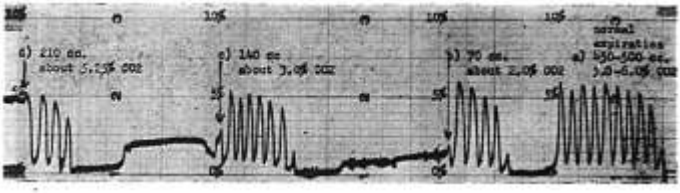

FIG. 7. (read chart from right to left) Expiratory volume-carbon dioxide correlation study using the gas meter described in the text. Tracing illustrates carbon dioxide level of 5.0 to 6.0 per cent during normal expiration (a); low values of 2.0 per cent (b), and 3.0 per cent (e), obtained when expiratory volume was depressed to 70 cc. and 140 cc. respectively; normal level again recorded when expiratory volume increased to 210 cc. (d). Note: Each titration is prefaced by four or five normal expirations in order to establish smooth gas flow in the circuit.

alveolar concentration of carbon dioxide in order to supplant the more cumbersome arterial blood analysis for pCO_2. Since it is technically difficult to cannulate an alveolus, the alveolar gas must be raised to a higher, more accessible point in the tracheobronchial tree, where sampling may be carried out. Barker (5) has shown that the pCO_2 of samples obtained from the level of the tracheal bifurcation is essentially identical to the pCO_2 of simultaneously-drawn arterial blood. That author further noted that samples obtained from the respiratory tree at about the level of the teeth have a pCO_2 about 2 mm. of mercury less

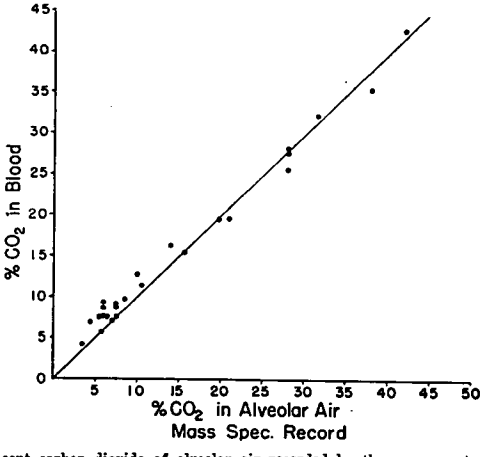

FIG. 8. Per cent carbon dioxide of alveolar air recorded by the mass spectrometer plotted against per cent carbon dioxide of simultaneously drawn arterial blood.

than the partial pressure of the gas in the arterial blood. We have examined numerous sites to determine the optimal level from which to obtain the sample with our equipment. With the present recording system, sampling carried out with the capillary tube lying at the level of the carina failed to yield values with an accuracy greater than those secured with the sampling tip located at the upper end of the endotracheal tube. This can be explained in the light of Barker's figures, since a difference of 2 mm. of mercury in the pCO_2 would be reflected by a decrease of only 0.2 volumes per cent in the spectrometric analysis. Our present recording system permits accurate readings only to 0.5 volumes per cent. Therefore, this additional instrumentation was discarded and samples were obtained routinely from the latter location. We have been able to demonstrate a close correlation between the percentage of alveolar carbon dioxide determined spectrometrically on gas obtained in this manner and the percentage of carbon dioxide in arterial blood as calculated by means of the Henderson-Hasselbalch equation from the hydrogen ion concentration of arterial blood and Van Slyke analyses of carbon dioxide (fig. 8).

Obviously, the data are valid only when the tidal volume is sufficient to expel air in the dead space. Ordinarily, the volume of this dead space is considered to be about 150 to 175 cc. However, when an endotracheal tube ¶ is in place, this volume is considerably decreased since the 60 to 75 cc. contained in the oropharyngeal cavity is excluded as part of the dead space. Hence, if the tidal volume is in excess of 110 cc. under these conditions, samples closely approximating alveolar gas can be obtained. If, on the other hand, the exchange is less than 110 cc., the samples obtained are of considerably different composition from alveolar gas samples. We have substantiated these premises by analyzing for carbon dioxide content serial expiratory gas volumes from 35 to 210 cc. These measurements of tidal exchange were accomplished by the use of an especially adapted illuminating gas meter.# By this technic it was possible to demonstrate the relatively sharp point of transition from dead space gas to alveolar gas at between 150 to 175 cc. before intubation, and in the vicinity of 100 to 110 cc. in the intubated patient. Figure 7 shows graphically the abnormally low carbon dioxide values obtained when the volume expired was 140 cc. or less; this normal subject was conscious and was not intubated. Portion (d) of figure 7 shows the expected normal value of 5.0 to 6.0 per cent carbon dioxide in the expired sample when the volume was increased above 175 cc.

By the use of a special double circle system which will be described elsewhere, the gas meter can be incorporated into the anesthetic system, thereby providing a method of continuously observing the magnitude of the tidal exchange. The technic is accurate to about 25 cc. In this way

¶ A number 8 King endotracheal tube of 24 to 25 cm. length contains a volume of about 11 cc.

Conceived and constructed by Dr. N. K. Jensen, Clinical Assistant Professor of Surgery, University of Minnesota Medical School.

it is possible to detect depressions in tidal volume approaching the critical values previously outlined. Although it is rare that such a severe depression of respiration should occur during the conduct of an ordinary anesthesia, if such were the case, manual compression of the breathing bag would then restore the essential volume exchange and assure accurate analyses.

CONCLUSION

We believe that, when applied in accordance with the criteria described, the mass spectrometric method of alveolar carbon dioxide analysis is a dependable, accurate means through which it is possible to follow continuously the alterations occurring in respiratory gaseous exchange during the course of general anesthesia. Through its use, time-consuming arterial blood analysis requiring skillful and highly accurate technical aid is supplanted by a method offering instantaneous graphic recording of alveolar concentrations of carbon dioxide which precisely reflect the partial pressures of gases in arterial blood.

SUMMARY

A review of the original technic of respiratory carbon dioxide analysis employing the mass spectrometer and a description of recent modifications in the method are presented.

The "mixing" phenomenon is described. Its significance in this analytic technic is explained and the means by which it can be obviated are outlined.

Mechanical limitations of the recording system and methods devised to eliminate them are described.

Sample records are presented to illustrate the linearity of response to a wide range of carbon dioxide concentrations and respiratory rates.

Limitations encountered with variations in tidal volume, optimal site of gas sampling, and a method of continuously observing the volume of tidal exchange are presented.

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