CARBON DIOXIDE HOMEOSTASIS DURING ANESTHESIA
I. INSTRUMENTATION * † ‡

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UNTIL recently, continuous monitoring of ventilation and of respired carbon dioxide concentrations has not been subject to convenient techniques (1). The development of the rapid carbon dioxide analyzers (2–4) and the pneumotachograph (5, 6) provides the opportunity to monitor the several ventilatory parameters concerned with carbon dioxide homeostasis. The purpose of this paper is to describe the rapid, infrared carbon dioxide analyzer, to report the techniques of total sampling of respired air with this instrument and the pneumotachograph in anesthetized or conscious patients, and to define useful criteria for interpretation of the recorded carbon dioxide curves.

CARBON DIOXIDE ANALYZER

This instrument is designed specifically for continuous measurement of respired carbon dioxide concentration (Liston-Becker, Model 16). The basis of its operation is the specific infrared absorption bands of carbon dioxide (4). The analyzer is divided into a "pick-up box" and an electronic section. This arrangement reduces the space required at the patient's head and permits pneumatic seal of the pick-up to reduce explosion hazards. The pick-up (fig. 1) contains two infra-red sources (IR) and a detection system. A metal enclosure confines these components and may be pressured with air or nitrogen (5 pounds per inch ^{2}) to prevent an inward leak of flammable agents should a defect occur in the seal of the pick-up. An aneroid manometer mounted on the pick-up indicates the failure of this seal.

A sampling tube extends through the pick-up box. Three sampling tubes are available; standard, low resistance, and microcatheter sampling tubes. The standard and low resistance tubes have a diameter of $7/8$ inch. A segment in the center of these sampling tubes is flattened and quartz windows are mounted plane-parallel to provide transmission of infrared energy across the path of gas within the sampling tube (fig. 1). The standard sampling tube has a total volume of 50 cc.

and a resistance of 2 cm. of water at 50 LPM (liters per minute). The low resistance sampling tube has an increased cross sectional area over the flattened segment, a total volume of 64 cc. and a resistance of 1.5 mm. of water at 50 LPM. The microcatheter sampling tube has a diameter of 0.8 mm., a smaller streamlined cell at the flattened segment, a total volume of 0.5 cc. and a resistance of 20 mm. of mercury at 500 cc. per minute.

Infrared energy from one of the sources is transmitted through the sampling tube and then passes into a detector cell which consists of a sealed chamber covered with a quartz window (fig. 1). Infrared
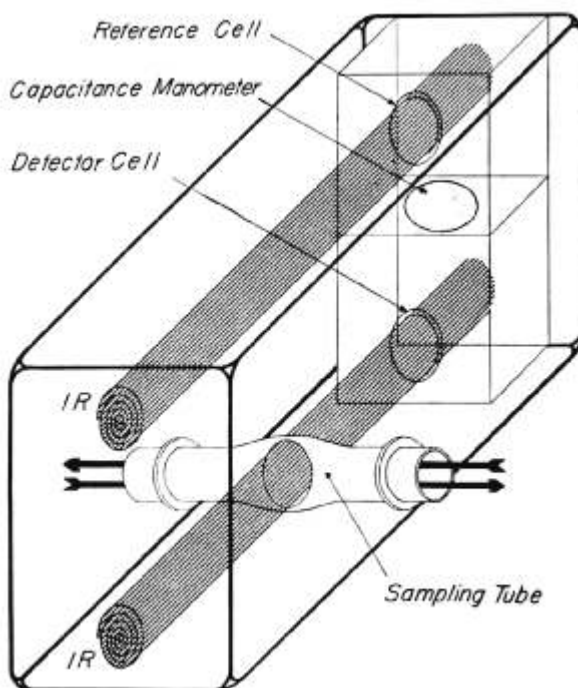

FIG. 1. Schema of pick-up box of rapid infrared carbon dioxide analyzer. Gas flowing through sampling tube traverses one infrared path, causing pressure difference between carbon dioxide filled detector and reference cells.

energy from the other source follows a similar path but does not pass through the sampling tube. It passes into a reference cell which is adjacent to the detector cell and of similar construction. Both detector and reference cells are charged with carbon dioxide. The absorption of infrared energy within the cells, therefore, is restricted to the absorption bands which are characteristic of carbon dioxide. Hence the presence of carbon dioxide in the sample tube reduces the amount of absorbable infrared energy reaching the detector cell. This reduces the gas temperature and pressure in this cell as compared with the reference cell. A differential capacitance manometer meas-

ures the difference in pressure between the detector cell and reference cell. With constant intensity of the infrared sources, the pressure difference between the detector and reference cells is a specific function of the number of carbon dioxide molecules in the transparent section of the sampling tube. Hence the instrument may be calibrated to measure the partial pressure or concentration of carbon dioxide.

The signal from the pick-up is carried by a 20 foot cable to the electronic section, which is not designed for use near flammable agents.

The panel meter on the electronic section of the carbon dioxide analyzer does not respond sufficiently rapidly to follow accurately the changing carbon dioxide concentrations in respired air. Therefore, such measurements require recording the signal by means of a direct writing oscillograph. This arrangement results in a 90 per cent response time of 0.05 second for the Model 16 carbon dioxide analyzer and a 90 per cent response time of 0.3 second for the Model 11 carbon dioxide analyzer. The latter response is not satisfactory with respiratory rates exceeding 20 per minute. Response time is determined by introducing an opaque card into the sampling tube to occlude partially the infrared path and rapidly withdrawing the card. A Sanborn DC amplifier, Model 64–300A, is employed between the analyzer and the oscillograph. To obtain optimal response time with this amplifier, the output of the electronic section of the carbon dioxide analyzer is shunted with 100,000 ohm resistors. The output of the amplifier is recorded on one channel of a two-channel direct-writing oscillograph (Sanborn, Model 60–1300). Other electrocardiograph units which have DC input terminals may be used to record the carbon dioxide analyzer signal. Impedance matching of the output of the analyzer to the input of the electrocardiograph may be necessary.

Prior to and following the measurement of respired carbon dioxide concentrations the analyzer should be calibrated with: (1) Gas containing zero or negligible carbon dioxide (ambient air or oxygen). (2) Gas mixtures with carbon dioxide concentrations which bracket alveolar concentrations (4.0 and 6.0 per cent approximately). (3) Gas mixture with carbon dioxide concentration of approximately 1.0 to 2.0 per cent. This mixture is unnecessary unless there is significant elevation in the patient's inspired carbon dioxide concentration.

The calibrating mixtures §were obtained in G cylinders and repeatedly analyzed over a six month period by the Henderson-Haldane gasometric method. Reproducibility of the gasometric analyses was ± 0.01 per cent carbon dioxide. For convenience, the gas mixtures were transfilled from G cylinders to small cylinders (lecture bottles) which may accompany the analyzer.

A simple method of calibrating the carbon dioxide analyzer, providing direct recording of the calibration curve, has been devised by

§ We are grateful to Dr. John Gilroy and the Ohio Chemical and Surgical Equipment Co. for supplying these gas mixtures.

Clements (7). Two rubber bags, partially air filled, are placed over the ends of the sampling tube. A slow and constant stream of carbon dioxide is introduced into one bag and is mixed with the gas in the closed system by manual rapid compressions of the two bags alternately. As the carbon dioxide concentration rises slowly, a record is taken. By using the response obtained with one known gas mixture and the time required to reach this concentration, the remaining points on the entire calibration curve may be determined by assuming a linear relation between time and carbon dioxide concentration. This affords sufficient accuracy for clinical use.

The concentration of oxygen in carbon dioxide-oxygen-nitrogen mixtures has an appreciable effect on the infrared absorption by carbon dioxide, as reported by Stow (8). The magnitude of this effect is of the order of several millimeters at normal alveolar carbon dioxide tensions. Therefore, calibrations of the carbon dioxide analyzer for measurements in patients were made with gas mixtures of oxygen and nitrogen composition comparable to that of alveolar air. Reproducibility of carbon dioxide analyzer measurements of the same gas mixture at different times is ± 0.03 per cent carbon dioxide.

The thermal equilibration of the carbon dioxide analyzer pick-up is quite slow and baseline drift may be encountered for as long as eighteen hours after the instrument is turned on. For this reason the analyzer was left on continuously in the same ambient temperature as the operating room.

The pick-up was found to be position-sensitive. Therefore, to avoid baseline or sensitivity shift, the pick-up should be positioned for measurements in patients before calibration with the gas mixtures. Should it become necessary to readjust the position of the pick-up, calibration should be repeated. Using these precautions, baseline shift has been less than 0.1 per cent carbon dioxide concentration over periods of six hours. Following warm-up sensitivity shift has not been encountered.

Since a grounding connection is provided in the cable between pick-up and electronic section of the carbon dioxide analyzer and in the coupling cable to the Sanborn unit, grounding of the latter prevents accumulation of static electricity on the carbon dioxide analyzer. When flammable agents are in use, the electronic section of the carbon dioxide analyzer, amplifiers, and two-channel oscillograph are placed in an adjacent room or corridor.

PNEUMOTACHOGRAPH

The differential pneumotachograph consists of a 400 mesh Monel screen placed in the path of the air flow and manifolds for measuring the pressure drop across the screen. The pressure drop across the 1 inch diameter screen is linear between 0 and 100 LPM. The resistance of the unit employed in these studies is 5.0 mm. of water per

10 LPM. Pressure drop across the screen is detected by a differential manometer; the diaphragm of the manometer activates a linear differential transformer (Schaevitz, No. 020–LC). The differential transformer is coupled to a strain gauge amplifier (Sanborn, Model 54–500A) and recorded on one channel of a two channel direct-writing oscillograph (Sanborn, Model 60–1300). The pneumotachograph is similar to the designs of Silverman (5) and of Mead (6).

Condensation of water vapor on the screen, which occurs when the pneumotachograph is placed in the closed system, increases the resistance and produces significant error in the flow measurements. To avoid this effect the screen must be heated. Current from a 6 volt transformer or storage battery may be used. Mounting of the Schaevitz transformer manifold within a heavy lucite housing provides satisfactory thermal stability. Following several hours of warm-up, baseline drift becomes negligible. Various sizes of screens are unnecessary since adjustable sensitivity may be attained with the strain gauge amplifier.

The 90 per cent response time of the pneumotachograph is 0.01 second. The external dead space imposed upon the patient by the screen manifold is 60 cc. The pneumotachograph record is calibrated before and after flow measurements in patients by means of a rotameter at flow rates of 30, 40 and 50 LPM.

SAMPLING PROCEDURES

Total sampling of respired air with the rapid infrared carbon dioxide analyzer involves a leak-free coupling of the standard or low resistance sampling tube directly to the patient's upper airway. All of the inspired and expired gas traverses the sampling tube.

The carbon dioxide analyzer pick-up is suspended on a wheeled frame (fig. 2). The width of the frame permits maneuvering of the pick-up to any desired position at the head of the operating table without encumbrance to anesthetist or surgeon. A bracket for mounting the pneumotachograph unit (differential manometer) is also attached to the frame.

A flexible metal adapter is used to couple one end of the sampling tube of the carbon dioxide analyzer to the endotracheal tube or rubber mouthpiece. At the other end of the sampling tube the pneumotachograph screen is mounted. The Y-piece of the circle system or a to-and-fro canister is attached to the pneumotachograph screen.

The attachment of the endotracheal tube to the standard sampling cell of the carbon dioxide analyzer and pneumotachograph screen results in an external dead space of 110 cc. Resistance of the pneumotachograph screen and the sampling tube of the analyzer, through which passes all the patient's inspiration and expiration, is 9.0 mm. of water per 10 LPM. The volume of the sampling cell from the endotracheal tube attachment to the windows in the pick-up (site of

measurement of carbon dioxide) is 25 cc. This volume requires 65 cc. for complete wash out to obtain 100 per cent response to a change in carbon dioxide concentration.

Inspiratory or expiratory sampling requires a valving arrangement between the patient and the sampling tube. Unless the valve system has low dead space this type of sampling does not yield accurate values of alveolar carbon dioxide concentration. Especially when an anesthesia circle system is in use, oxygen and anesthetic gases should be delivered directly into the reservoir bag; otherwise these gases dilute the air expired into the analyzer sampling tube. Since total sampling
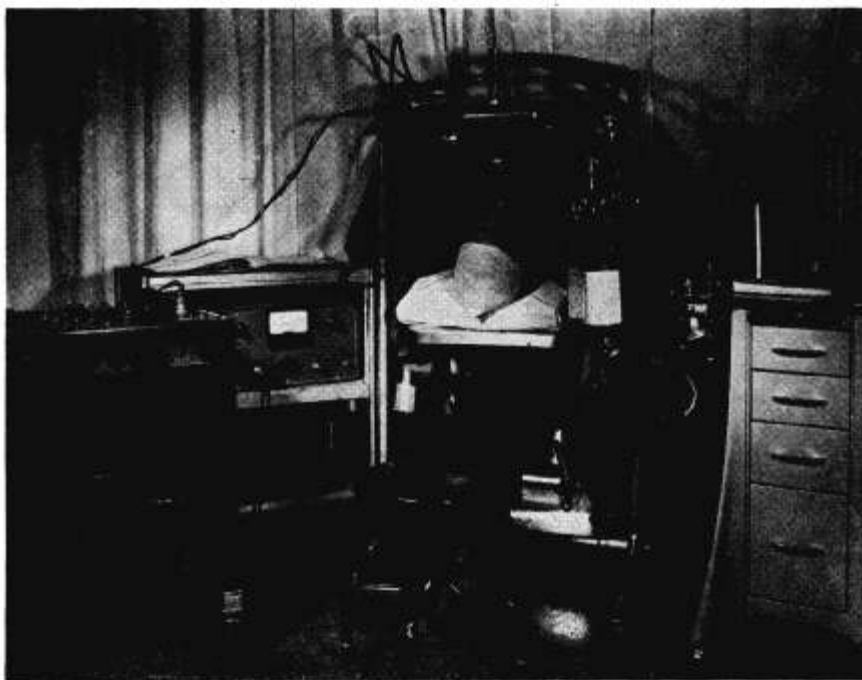

FIG. 2. Total sampling of respired gas with carbon dioxide analyzer and pneumotachograph during anesthesia.

yields both the inspired and alveolar carbon dioxide concentrations, inspiratory or expiratory sampling is infrequently employed.

Fractional sampling involves a continuous withdrawal of respired gas from the airway through the microcatheter sampling tube by means of a pump. The technique required for accurate use of fractional sampling is described by Collier, Affeldt and Farr (9).

INTERPRETATION OF RECORDS

Continuous monitoring of the record provides a convenient assay of ventilation and carbon dioxide elimination. Although simultaneous

measurement of ventilation is desirable, the record of carbon dioxide alone yields useful clinical information.

Alveolar Plateau Value. These values represent, for practical purposes, the patient's alveolar carbon dioxide concentration. It is apparent that the plateau value is not flat but has an appreciable slope (fig. 3). This gradual increase in the alveolar carbon dioxide concentration during expiration is the result of continued transfer of carbon dioxide from blood to alveoli while the lung volume is diminishing as expiration proceeds. This slope almost disappears in the curve following breath holding.

For comparing the alveolar carbon dioxide value of one plateau with that of another, an arbitrary reference point on the plateau must
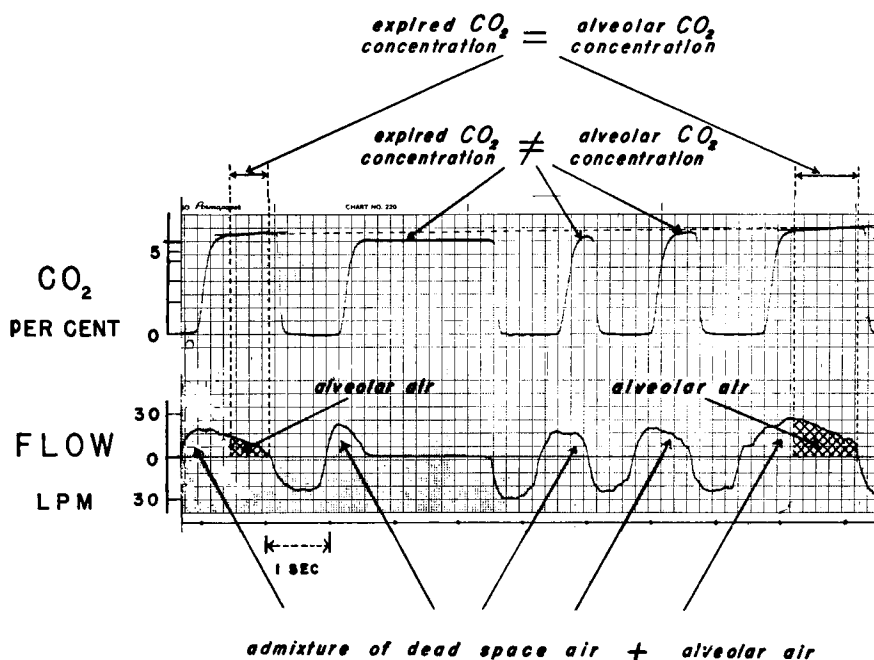

FIG. 3. Simultaneous carbon dioxide and flow curves showing criteria for reading alveolar concentration of carbon dioxide from recorded plateau.

be selected. One suitable such reference is the midpoint on the plateau.

Obviously, the expired carbon dioxide curve cannot reach the value of alveolar air unless the tidal volume is sufficient to bring undiluted alveolar air into the sampling tube of the carbon dioxide analyzer (fig. 3). In general, tidal volumes of 300 to 400 cc. are required. When undiluted alveolar air does not reach the sampling tube, the plateau is replaced by a spiked or dome-shaped excursion. An apparent plateau may be seen if the patient exhibits significant pause after expiration (fig. 3).

Simultaneous recording of flow affords reliable interpretation of the plateau values. When expired flow is noted to continue during the time the plateau is recorded, the alveolar carbon dioxide concentration may be read from midplateau. If flow is not observed during the plateau, alveolar carbon dioxide concentration cannot be estimated reliably (fig. 3).

Recognition of Hypoventilation. If tidal volume is sufficient to deliver undiluted alveolar air into the analyzer sampling tube, hypoventilation is accompanied by an elevation in the alveolar plateau value. With tidal volumes less than 300 cc., a moderately assisted inspiration (500 to 800 cc.) will yield an alveolar plateau value on the succeeding expiration. With a gradual onset of hypoventilation, a progressively increasing alveolar plateau value is observed. After appreciable accumulation of carbon dioxide, a constant elevated plateau value may persist for some time, indicating ventilation which is adequate to eliminate carbon dioxide produced by the tissues but which is not sufficient to eliminate the previously accumulated carbon dioxide.

Recognition of Hyperventilation. The carbon dioxide record shows a series of alveolar plateau values of less than 5 per cent concentration or a gradual decline in height of successive alveolar plateaus.

Elevation of Inspired Carbon Dioxide Concentration. Failure of the carbon dioxide record to return to the zero baseline during inspiration may be the result of: (1) incomplete carbon dioxide absorption; (2) direct rebreathing of expired air (*a,* incompetence of inspiratory or expiratory valves, or of both; *b,* volume change of breathing tubes, and *c,* excessive external dead space), and (3) inadequate tidal volume.

USE OF ANALYZER DURING ANESTHESIA

The alveolar plateau values and the inspired carbon dioxide concentrations accompanying premedication and nitrous oxide-oxygen-ether anesthesia obtained in an adult patient are indicated graphically in figure 4. Prior to premedication, respired carbon dioxide concentrations were recorded for forty-five minutes. During this control period and the subsequent seventy-five minutes, to-and-fro total sampling was carried out continuously by means of a standard mouthpiece. An alveolar plateau value of 39 mm. of mercury was maintained as a basal value. Approximately eight minutes after intravenous premedication (consisting of morphine sulfate, 10 mg., and atropine sulfate, 0.4 mg.), the alveolar plateau value gradually increased and became stabilized at 40.5 mm. of mercury. During venipuncture, the patient was aroused and stimulated to hyperventilate; this resulted in a fall in the alveolar plateau value to 36 mm. of mercury. At this juncture, nitrous oxide-oxygen was started with a semiclosed circle system (10 LPM total flow). An immediate increase in

the inspired carbon dioxide concentration to 0.4 per cent appeared and persisted. Concomitantly, the patient's alveolar plateau value was gradually elevated to 41.0 mm. of mercury. Nitrous oxide was then discontinued, the oxygen flow reduced to 300 cc. per minute, the system was closed, and ether started. As soon as the system was closed, the inspired carbon dioxide concentration immediately rose to 2.0 per cent and a parallel increase in the alveolar plateau value to 46 mm. of mercury occurred. Changing the soda lime in the circle absorber, which had been used two hours previously, reversed both the inspired and alveolar carbon dioxide values. An inspired carbon dioxide concentration of 0.35 per cent persisted. As ether anesthesia progressed to
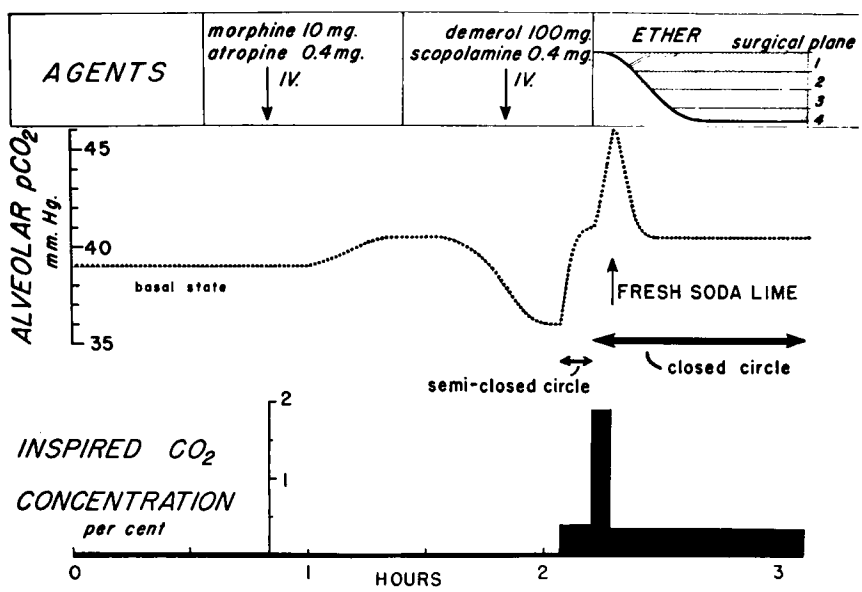

FIG. 4. Alveolar and inspired carbon dioxide measurements before and after premedication and during nitrous-oxide-oxygen-ether anesthesia. The onset of carbon dioxide accumulation coincided with closing the circle system. Changing the soda lime reversed this beginning acidosis. Carbon dioxide accumulation did not reappear after thirty-five minutes of surgical plane 3 ether anesthesia.

lower surgical plane 3 during the next twenty-five minutes, the patient maintained an alveolar plateau value of 40.5 mm. of mercury.

This study is presented to illustrate the practical utility of the carbon dioxide analyzer alone to follow continuously both the status of the carbon dioxide homeostasis of the patient and the performance of the carbon dioxide absorber. Continuous sampling of the inspired and expired volumes yields this information promptly and conveniently.

SUMMARY

The instrumentation and techniques developed for employing the rapid infrared gas analyzer and the pneumotachograph during clinical

anesthesia are described.   Sampling techniques are defined.   The basis for interpretation of records of total sampling of respired air is discussed and illustrated by positive findings during closed system ether-oxygen anesthesia.

ACKNOWLEDGMENT

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