

THE COLLISION BROADENING EFFECT OF NITROUS OXIDE UPON INFRARED ANALYSIS OF CARBON DIOXIDE DURING ANESTHESIA

NORMAN A. BERGMAN, M.D., HERBERT RACKOW, M.D.
M. JACK FRUMIN, M.D.

INFRARED spectroscopy of respired gases for carbon dioxide concentration is now being carried on more and more frequently during anesthesia. However, apparently little consideration has been given to the effect of the volatile anesthetic agents upon the accuracy of the analysis (1). Even though infrared spectroscopy is a highly selective and specific analytical technique, it is possible that the volatile anesthetic agents or other respired gases may significantly affect the values for carbon dioxide which are obtained if both carbon dioxide and the anesthetic agents absorb some energy in the same regions of the infrared spectrum. This relationship has been termed the "crossover" effect and is exhibited to a very slight degree by carbon dioxide and nitrous oxide.

Nevertheless, Ramwell (1), Stow (2), Göpfert and Henneberg (3) and Collier *et al.* (4) reported systematic errors in carbon dioxide analysis due to various proportions of oxygen and nitrogen in the analyzed mixture. This finding cannot be the result of any crossover effect since oxygen and nitrogen are homoatomic gases and only heteroatomic gases absorb infrared energy. It appears probable, as Ramwell pointed out, that this finding can be explained on the basis of another phenomenon which occurs in infrared and other types of spectroscopy called "pressure broadening" or more properly "collision broadening."

It will be shown that nitrous oxide does cause a significant increase in infrared absorption by carbon dioxide because of this phenomenon when measurements are made with a widely used commercially available instrument. It was therefore thought desirable to point out this effect of nitrous oxide, to discuss the expected activity of other agents on this basis, and to present a practical solution for minimizing the effects of this phenomenon by appropriate instrumentation.

METHODS

A commercially available * infrared carbon dioxide analyzer based upon the Luft principle (fig. 1) was used, with a cuvette light path of

Received from the Department of Anesthesiology, Columbia University, College of Physicians and Surgeons, and the Anesthesiology Service, The Presbyterian Hospital, New York 32, New York. Accepted for publication August 13, 1957.

* Model 16 Gas Analyzer, Liston-Becker Division, Beckman Instruments Company, Springfield, Connecticut.

1.0 mm. The detector cell was charged to an absolute pressure of 50 mm. of mercury, with either carbon dioxide or a mixture of carbon dioxide and argon. In the latter instance, the carbon dioxide tension was 10 mm. of mercury and the argon tension was 40 mm. of mercury.† At the start of each experiment, the case of the detector assembly containing the light sources, cuvettes and detector cells was flushed with nitrous oxide. This was done in order to remove any carbon dioxide which may have been liberated within the detector case by the heating of hydrocarbons such as paint or bearing grease, since this would decrease the sensitivity of the system to carbon dioxide. The case was then charged to 3 pounds per square inch above atmosphere with nitrous oxide to prevent any carbon dioxide from entering the case from the ambient atmosphere. By this maneuver all of the energy in the nitrous oxide regions of the infrared spectrum is absorbed in the light path between the sources of infrared energy and the cuvette so that none remains for absorption by the nitrous oxide in the cuvette. This,

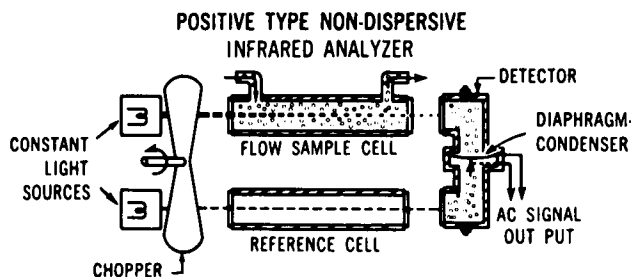


FIG. 1. Schema of the detector assembly of the Liston-Becker infrared analyzer.

therefore, eliminates even the small crossover effect which nitrous oxide in the mixture exerts upon the carbon dioxide analysis.

Carbon dioxide-oxygen mixtures were obtained commercially ‡ and their carbon dioxide tensions were determined by the Scholander technique (5). One hundred per cent carbon dioxide, oxygen, nitrogen, and nitrous oxide were also obtained from these sources. A glass gas train (fig. 2) was then constructed to permit the preparation of a highly reproducible mixture of carbon dioxide in these diluent gases. The entire system was first filled with mercury. Chamber A was then filled with carbon dioxide to a fixed mark on the capillary tubing between the chamber and the mercury reservoir, and the system then allowed to come to atmospheric pressure. Chamber B was then filled to a calibrating mark with the diluent gas and also allowed to come to atmospheric pressure. The carbon dioxide was then driven over mercury into chamber B. Repeated transfers of the gas mixture between cham-

† Dr. Max Liston of Beckman Instruments Company suggested and fabricated the detector cells charged with carbon dioxide tension of 10 mm. of mercury.

‡ Ohio Chemical & Surgical Equipment Co., New York, New York.

bers B and C insured complete mixing. Precautions were taken to prevent the entry of room air into the system while the pressures were being adjusted to atmosphere. The reproducibility of the mixtures produced in the gas train was assessed by generating carbon dioxide-oxygen mixtures in quadruplicate and analyzing each mixtures in duplicate in the infrared analyzer.

The analyzer was calibrated initially with commercially prepared carbon dioxide-oxygen mixtures and the sensitivity adjusted so that one scale division on the meter of the analyzer corresponded to approximately 1 mm. of mercury of carbon dioxide in the region of 40 mm. of mercury of carbon dioxide. The stability and the sensitivity of the analyzer was checked before each single analysis of the carbon dioxide-diluent mixtures by noting the deflection produced by fixed carbon dioxide mixtures and correcting for any drift in the instrument.

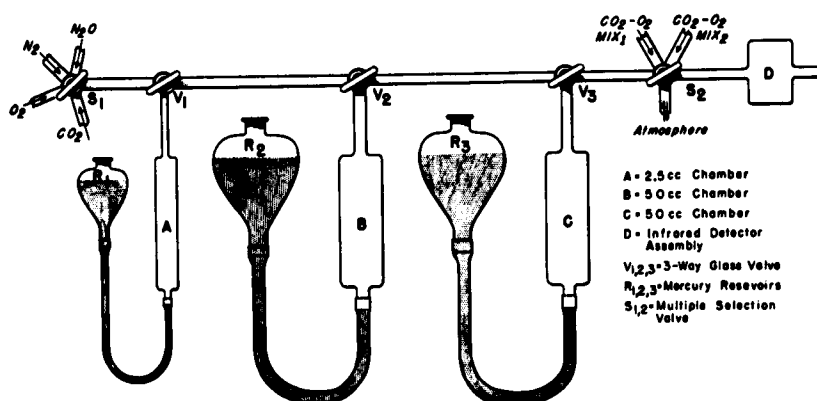


Fig. 2. Gas train used for producing reproducible mixtures of carbon dioxide in diluent gases.

The "crossover" relationship of nitrous oxide and carbon dioxide was tested by charging the case of the detector assembly with room air, filling the cuvette with oxygen or nitrogen and then noting the meter deflection. The detector cell in this instance was charged with 25 mm. of mercury of carbon dioxide and of argon. The meter was adjusted to read zero and the sensitivity adjusted as before so that 40 mm. of mercury of carbon dioxide in oxygen read 70. The cuvette was then filled alternately with nitrous oxide and oxygen.

In some experiments, attempts were made to remove any carbon dioxide which might have been present in the diluent gases before mixing with the predetermined volume of carbon dioxide. However, passage of the gases through concentrated sodium hydroxide solution produced no apparent changes in carbon dioxide tension. In other experiments, attempts were made to remove the effects of any water vapor present in the diluent gases before producing the mixture of carbon dioxide. However, drying the gases by passage over Dririte

agent, or by passage through a concentrated sulfuric acid solution, did not change the apparent carbon dioxide tension of the diluent.

RESULTS

The limits of reproducibility of mixtures produced in the gas train are shown in table 1 and were 1 mm. of mercury, the reading error of the meter scale of the analyzer. Mixtures of carbon dioxide in oxygen,

TABLE 1
REPRODUCIBILITY OF MIXTURES OF CARBON DIOXIDE IN OXYGEN

Sample Number	Apparent Carbon Dioxide Tensions
1	37
2	36
3	36
4	37

nitrogen or nitrous oxide were then prepared in duplicate in the gas train and were analyzed with the detector cell charged with 50 mm. of mercury of carbon dioxide. As shown in table 2, the results with oxygen and nitrogen differed from each other by only the reproducibility error, while with nitrous oxide, the carbon dioxide tension apparently rose 4 mm. of mercury or 16 per cent.

Subsequently, the detector cell charged with 50 mm. of mercury of carbon dioxide was replaced with one charged with 10 mm. of mercury of carbon dioxide and 40 mm. of mercury of argon. Mixtures of car-

TABLE 2
COMPARISON OF CARBON DIOXIDE-OXYGEN MIXTURES USING DETECTOR CELLS CHARGED WITH 50 MM. OR 10 MM. OF MERCURY OF CARBON DIOXIDE

Mixture	50-mm. Cell		10-mm. Cell	
	Apparent $p\text{CO}_2$	Per Cent Difference from CO_2 in O_2	Apparent $p\text{CO}_2$	Per Cent Difference from CO_2 in O_2
CO_2 in O_2	36	—	33	—
CO_2 in N_2	37	3	33	0
CO_2 in N_2O	41	16	33	0

bon dioxide in oxygen, nitrogen or nitrous oxide were again prepared in duplicate in the gas train and analyzed. Now the apparent carbon dioxide tension in all mixtures was identical (table 2).§

It should be noted that the carbon dioxide tensions in the mixtures of this latter set of analyses differed from that obtained in the earlier set when the 50 mm. of mercury of carbon dioxide detector cell was

§ Essentially similar results were obtained by Dr. Max Liston who carried out a similar set of determinations based upon reproducible mixtures of carbon dioxide in diluent gases produced by pressure measurements rather than volume measurements.

used. This difference could be accounted for by the slightly different volumes in the gas train in the two sets of determinations. However, since the carbon dioxide values within each set carried out with a fixed carbon dioxide detector charge were similar when oxygen and nitrogen were used as diluents, it was clearly evident that the reproducibility of the system was the same in both instances.

When the case of the detector assembly was charged with room air and the cuvette contents were changed from oxygen to nitrous oxide, the meter of the analyzer was deflected from zero to three and one-half scale divisions. This corresponds to less than 1 mm. of mercury, an amount hardly detectable in a useful biological range.

DISCUSSION

The physical basis for infrared gas analysis is the absorption of radiation at frequencies of 10^{13} to 10^{14} cycles per second, that is, in the infrared portion of the electromagnetic spectrum, by atoms which also vibrate at these frequencies (6). Infrared spectroscopy is therefore a measure of the vibrational frequency of atoms within the molecule. This mode of vibration is a function, among other things, of spatial arrangement, valence forces, intermolecular forces and collision between molecules, all of which may alter the character of the intramolecular vibrations. The infrared spectrum of carbon dioxide consists of a number of principal bands which are related to the translational movements of atoms within the molecule and of a number of other bands which are related to the rotation of the molecule as a whole. These latter bands are usually smaller and are called side bands or rotational bands. Collisions between molecules affect this latter rotational movement, and hence also the energy absorption at the corresponding wave lengths. This process is commonly called collision broadening or an increase of these otherwise smaller side bands. In other words, the collision broadening effect is the increase in the amount of energy absorbed at these wave lengths in the rotational bands of carbon dioxide. This is the process which occurs in the cuvette containing the carbon dioxide and diluent gas.

When the tension of carbon dioxide in the detector cell is low, the principal peaks of the spectrum absorb most of the energy of carbon dioxide in the detector while the side or rotational bands account for only a small proportion of the total energy absorbed. As the carbon dioxide tension rises in the detector cell the upper limit is finally reached of the absorption in the principal bands so that further increases in carbon dioxide tension in the detector can only result in further increases in the side band absorption. Hence, one practical solution to the problem of apparently increased concentration due to increased side band absorption is to reduce the tension of carbon dioxide in the detector to the lowest level compatible with the requirements of instrumentation and the biological system. This lowering

of carbon dioxide tension in the detector decreases proportionately the amount of radiation absorbed by carbon dioxide in the rotational bands and hence the effect of the gases in the mixture other than carbon dioxide. The reduction of the detector charge of carbon dioxide to 10 mm. of mercury reduced this collision broadening effect of nitrous oxide upon carbon dioxide to an insignificant level in this particular biological application. The use of such a detector eliminated the systematic discrepancy between the end-tidal carbon dioxide tension as determined with a 50 mm. of mercury of carbon dioxide detector and the arterial carbon dioxide tension as determined from the measurement of arterial hydrogen ion concentration and carbon dioxide content (7). Furthermore knowledge of this effect permitted the introduction of an appropriate correction factor when the 50 mm. of mercury of carbon dioxide detector was used.

These findings may be useful in explaining the results obtained by Ramwell, Stow and others when carbon dioxide was mixed with oxygen or nitrogen. Unfortunately, none of these authors states the tension to which the detector cells are charged with carbon dioxide, even though this value is critical in evaluating the collision broadening effect of these types of analyzers.

However, information on this point was elicited by personal communication after the experimental portion of the present paper was completed. Dr. Stow stated in his response that the carbon dioxide tension in his detector cell was 760 mm. of mercury with carbon dioxide being used as a pure gas. Dr. W. M. Pols, of Godart-Mijnhardt NV, informed us that the detector cells in the Uras-M instrument used by Göpfert were filled with a 90 per cent argon-10 per cent carbon dioxide mixture at atmospheric pressure. The carbon dioxide tension was, therefore, approximately 76 mm. of mercury. Dr. Max Liston of Beckman Instruments Co., notified us that the detector cell in the instrument used by Collier and Affeldt was charged to 100 mm. of mercury with carbon dioxide. Dr. Ramwell stated that the Model Sc analyzer of the Infra Red Development Co. which he used was filled to 50 mm. of mercury with carbon dioxide.

From such theoretical considerations, these higher tensions would be expected to magnify greatly the collision broadening effect. This would be especially true with Stow's apparatus. The fact that these "errors" were noted when the diluent gases were homoatomic, that is nitrogen and oxygen, supports this viewpoint. Homoatomic gases with only one atomic species in the molecule do not themselves absorb infrared radiation, and, therefore, could not directly produce these changes in infrared absorption of the mixture.

Presumably, the instruments commercially available more recently utilize sapphire windows both in the detector cells and the cuvettes as well as other technological improvements. These allowed for a decrease in the detector cell charge while still producing a useful signal.

Even the 50 mm. of mercury of carbon dioxide detector which has been generally available for at least two years does not exhibit any significant collision broadening effect when oxygen or nitrogen are used.

Since the collision broadening effect is a result of intermolecular collisions, it can be affected by a number of factors. These include the number, weight, size, thermal activity and dielectric constants of the molecules which collide with the molecule being measured. Molecules which are highly polar can influence molecular rotation at a distance as well as by direct collision and therefore may be expected to be very effective in producing this phenomenon (8). Although it is probable that many of the anesthetic agents such as diethyl ether, chloroform or cyclopropane can, under certain conditions, produce significant collision broadening of carbon dioxide, the concentrations at which they are used clinically are relatively so low that their effects are probably unimportant with the carbon dioxide analyzers presently available and in use in the United States. Only nitrous oxide and ethylene are used in sufficiently high concentrations to be of more than minor importance.

Infrared spectroscopy may also be used in a similar system for measuring the tension of the volatile anesthetic agents which are respired. If measurements are to be made on the exhaled gases, consideration should be given to the collision broadening effect of carbon dioxide on the apparent concentration of such compounds as chloroform and diethyl ether. However, since the concentration of carbon dioxide is almost invariably below 10 per cent and since the carbon dioxide molecule is considerably lighter than the molecule of the anesthetic agent, the error introduced by the collision broadening effect of carbon dioxide upon the analysis of the anesthetic agent would be entirely negligible.

The other major problem in infrared spectroscopy is that of cross interference. This is the result of the existence of some bands, principal or otherwise, which are shared in common by the molecule which is being measured and by the "diluent" gas. This crossover effect is of only minor importance with the common anesthetic agents when carbon dioxide is being measured. The slight effect of 100 per cent nitrous oxide in this regard (less than 1 mm. of mercury) can be eliminated entirely by charging the detector case with nitrous oxide so that all the energy in the nitrous oxide bands is completely absorbed before the infrared radiation reaches the detector cell. This procedure has unfortunately led to the difficulty that some nitrous oxide leaks into the detector cell since the latter exists at only 50 mm. of mercury absolute pressure. When this occurs the detector will act as both a nitrous oxide and a carbon dioxide analyzer and a loss of specificity naturally occurs. It is probably a safer working principle to charge the case with air rather than with nitrous oxide as was carried out in most of these experiments.

SUMMARY

Fixed mixtures of carbon dioxide in oxygen, nitrogen or nitrous oxide were prepared with a constant tension of carbon dioxide and were analyzed in an infrared carbon dioxide analyzer. When the detector cell was charged to 50 mm. of mercury with carbon dioxide, the carbon dioxide-nitrous oxide mixture showed an apparent 16 per cent rise in tension as compared with carbon dioxide in oxygen or nitrogen. When the detector cell was replaced with one charged with 10 mm. of mercury of carbon dioxide and 40 mm. of mercury of argon, the measured carbon dioxide tensions were equal in all mixtures. The basis for this apparent error in carbon dioxide analysis initially was a collision broadening effect of nitrous oxide upon the infrared spectrum of carbon dioxide which increased the amount of energy absorbed by carbon dioxide in the cuvette of the analyzer. This effect of nitrous oxide in changing the absorption in the smaller rotational or side bands of carbon dioxide could be decreased by lowering the carbon dioxide tension in the detector cell. The direct crossover effect of nitrous oxide upon the carbon dioxide analysis was studied and was found to be negligible (less than 1 mm. of mercury) when the detector is charged with carbon dioxide to 25 mm. of mercury.

This work was supported by a grant from the National Foundation for Infantile Paralysis, Inc.

REFERENCES

1. Ramwell, P. W.: Infra-Red Analysis of CO₂ During Anesthesia, *Brit. J. Anaes.* **29**: 156 (April) 1957.
2. Stow, R. W.: Systematic Error in Infrared Analysis for CO₂ in Respiratory Gas Mixtures, *Fed. Proc.* **11**: 155 (March) 1952.
3. Göpfert, H., and Henneberg, U.: Die Unmittelbare Feststellung der alveolaren CO₂-Konzentration bei normaler Atmung und nach Atemstillstand mit einem Kleinkammerigen Absorptionsschreiber, *Der Anaesthetist* **6**: 15 (Feb.) 1957.
4. Collier, C. R., Affeldt, J. E., and Farr, A. F.: Continuous Rapid Infrared Carbon Dioxide Analysis; Fractional Sampling and Accuracy in Determining Alveolar Carbon Dioxide, *J. Lab. & Clin. Med.* **45**: 526 (April) 1955.
5. Scholander, P. F.: Analyzer for Accurate Estimation of Respiratory Gases in 0.5 ml. Samples, *J. Biol. Chem.* **167**: 235 (Jan.) 1947.
6. Barnes, R. B., Gore, R. C., Liddel, U., and Williams, V. Z.: *Infrared Spectroscopy*, New York, Reinhold, 1944.
7. Frumin, M. J., Bergman, N. A., and Holaday, D. H.: Effects of Altered Expiratory Pressures or Resistances Upon Arterial Oxygen Saturations During Artificial Respiration, *Fed. Proc.* **16**: 42 (March) 1957.
8. Coggeshall, N. O., and Saier, E. L.: Pressure Broadening in Infra-Red and Optical Collision Diameters, *J. Chem. Phys.* **15**: 65 (Jan.) 1947.