CONTINUOUS MEASUREMENT OF BLOOD GASES IN VIVO BY MASS SPECTROGRAPHY*

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Abstract—The application of the mass spectrometer to the continuous monitoring of blood gases in humans is described. At the heart of the system is an intravascular catheter consisting of a cannula impermeable to gas tipped with a membrane whose special gas permeability characteristics permits accurate calibration. Expressions are presented which describe gas flow through the membrane in response to a step increase in gas concentration; characterize thermal effects on gas diffusion and illustrate the effect of the cannula and carrier tubing on steady state gas flow. The system has been successfully employed in the study of arterial nitrogen washout and the determination of human cerebral blood flow by the nitrous oxide technique.

INTRODUCTION

A KNOWLEDGE of the concentration of the various gases dissolved in the blood has become an important aid in patient evaluation and treatment. Blood oxygen and carbon dioxide partial pressure determinations are now essential during some surgical procedures and in the post-operative period, CLAUS8 et al. (1965). In addition, various pulmonary and circulatory diagnostic tests are now performed by having a patient breathe specific gas mixtures. The mixtures, for example, may include a gas not normally present in air, such as nitrous oxide. The uptake of this gas in the arterial and venous blood may then be monitored and the values obtained used to determine blood flow to the...
brain. Alternately, if nitrogen is excluded from the inspired gas mixture, its rate of disappearance from arterial blood can be used as a measure of the adequacy of pulmonary function.

The most obvious, straightforward, and sometimes still used method for determination of the quantity of any gaseous substance in the blood is chemical extraction followed by measurement by physical means. Methods of blood gas analysis based on this concept have been developed by Van Slyke and Neill (1924) and by Rough ton and Scholander (1943). These techniques can give accurate results, but they are time consuming and difficult to perform.

Modern methods for blood oxygen and carbon dioxide measurement make use of gas permeable membranes to separate the gas from the blood and an electro-chemical reaction to measure the quantity of gas. This may be accomplished by the oxygen electrode of Clark (1956), and the carbon dioxide electrode of Severinghaus and Bradley (1958). Another, more complex, technique which can be used for general blood gas analysis, is gas chromatography, Wilson and Holland (1961). Here, the gases are first evolved from the blood sample and then separated from each other by their differing rates of transit through a chromatographic column.

Both the gas electrode and gas chromatography methods require a repeated withdrawal of individual blood samples. These techniques are, therefore, limited by the amount of blood that can be safely taken from the patient. Application of gas chromatography to the study of many different gases may require complex equipment, excessive time for determination, and a difficult calibration procedure. Continuous measurement of blood gases with electrodes has been demonstrated by Gotoh et al. (1966). This technique is difficult to maintain for long periods of time and it requires heparinization of the patient to prevent clotting in the extracorporeal blood flow circuit. Furthermore, electrodes are available only for oxygen and carbon dioxide measurement.

A new method of analysis has been developed, in animals by Woltring et al. (1966) and in humans by Hass et al. (1968), which allows the continuous measurement of any gas dissolved in blood or other fluid in vivo, without drawing a sample. This system makes use of a mass spectrometer, which has previously been evaluated for its speed and versatility in the monitoring of alveolar gases by Robertson et al. (1950). The heart of the system is a gas permeable membrane. This membrane is mounted on the tip of a flexible, gas-impermeable cannula which is inserted into the blood vessel. Gases dissolved in the blood continuously diffuse across the membrane into the cannula. The cannula, under vacuum, is connected to the inlet port of a mass spectrometer. The gases are thus channeled to the mass spectrometer analysis chamber where each of the constituents can be measured. Because of the great sensitivity of the mass spectrometer, only very small amounts of gas need be collected. Rapid serial measurements of several dissolved gases are easily accomplished. The only limitations are the mass range of the mass spectrometer and the permeability characteristics of the membrane.

In the mass spectrometer analysis chamber, the molecules are ionized by electrons emitted from a heated filament whose current is continuously variable. The ions are accelerated and focused by a combination of electric and magnetic fields. The path of the ions is determined by the pattern and strength of these fields and by the mass to charge ratio of the ions. Ions of different molecular weights can thus be differentiated and their abundance measured. Ions are collected independently of their initial velocity and angle of departure. The output signal from the mass spectrometer is linear and proportional to molecular abundance, and hence to the partial pressure of each particular gas present.

The mass spectrometer system used in this study consists of two residual gas analyzers* with a 120 I sec⁻¹ ion pump to evacuate the vacuum. Background pressures below 10⁻⁸ torr

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* Consolidated Electrodynamics Division of Bell & Howell Corp. Monrovia, California, Type 21–614.