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An Analyzer for In-line Measurement of Expiratory Sulfur Hexafluoride Concentration

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An infrared analyzer for the inert tracer gas sulfur hexafluoride (SF_6) is described and evaluated. The analyzer consists of a transducer and a processor unit. It is designed to operate in a nonrebreathing system with a ventilator and a computer. The transducer, which is placed over a cuvette with windows in the ventilator tubings, reads the SF_6 concentration in the airway during the expiratory phase. At the end of the inspiratory phase, the zero level of the instrument is automatically reset. The response time and linearity of the analyzer were tested, and interference by other gases was assessed. Full response was reached within 20 ms after a sudden introduction of 0.5% SF_6 into the cuvette. The analyzer–computer system had adequate linearity below 0.5% of SF_6. Oxygen, nitrogen, and humid air had no influence on the analyzer signal. One hundred per cent nitrous oxide, 4% enflurane, 4% isoflurance, and 4% halothane caused signals corresponding to 0.010, 0.023, 0.022, and 0.043% SF_6, respectively. Due to the method for zero reset, the importance of interference from these gases is greatly reduced when inspired and expired concentration approach each other. The disturbance from CO_2 (10% CO_2 gave a signal corresponding to 0.020% SF_6) can be compensated for by including a CO_2 analyzer in the set-up. The rapid response and the high sensitivity of the analyzer may make it useful for studies of pulmonary gas mixing and for measurements of lung volume during mechanical ventilation. (Keywords: Lung. Measurement technique: washout. Ventilation: mechanical.)

ANALYZERS for nearly insoluble tracer gases are commonly used in studies of pulmonary physiology. This article describes and evaluates an analyzer for sulfur hexafluoride (SF_6). When designing the instrument, which employs the infrared absorption principle, special emphasis was placed on the speed of response so that SF_6 elimination from the patient could be computed directly from signals representing instantaneous SF_6 concentration and flow in the airway. Our primary intention was to use the analyzer for measurement of functional residual capacity (FRC) as described in another communication,[1] but the analyzer may also be useful in other studies of pulmonary physiology. The response time, the linearity, and the stability of the analyzer were tested, and interference by other gases was assessed.

Apparatus Design and Working Principles

The general design and many of the specific technical solutions, including the method for zero adjustment, are the same as for the Siemens-Elema CO_2 Analyzer 930®.[2] The SF_6 analyzer consists of a transducer and a signal processor. It is designed to work with a computer (LSI 11/23, Digital Equipment Corporation) and a ventilator (Servo® 900 B or 900 C, Siemens-Elema Company), which can provide timing pulses for inspiration and expiration. The transducer is placed around a cuvette with windows in the airway (fig. 1). The infrared beam is mechanically chopped at a frequency of about 300 Hz. This makes it possible to measure small signals superimposed upon large drifting ones.[2] The beam passes an infrared filter, which transmits light with a wavelength of approximately 10.6 μm at which SF_6 has a major absorption peak. In order not to lose any information and to retain a fast response, analog filtering of the signal has been avoided. Hence, the signal contains high-frequency noise (fig. 2). The noise does not prevent accurate measurement of mean SF_6 concentration (see "Discussion"). Because of the geometry of the cuvette turbulence and hence a square velocity profile probably occurs at all flow rates prevailing at early expiration. Toward the end of expiration laminar flow may appear, but this is of little consequence, since airway concentration of SF_6 changes slowly during this phase. At the end of the inspiratory phase, the SF_6 signal is automatically reset to zero. The cuvette must be free of SF_6 during this period. Consequently, the analyzer can only be used in a nonrebreathing system. The automatic zero adjustment has the advantage that the influence of disturbing factors present both during inspiration and expiration (*e.g.*, stains on the cuvette windows) can be eliminated. The signal is partially linearized in the signal processor. Final linearization is made in the computer, which also presents the SF_6 reading.

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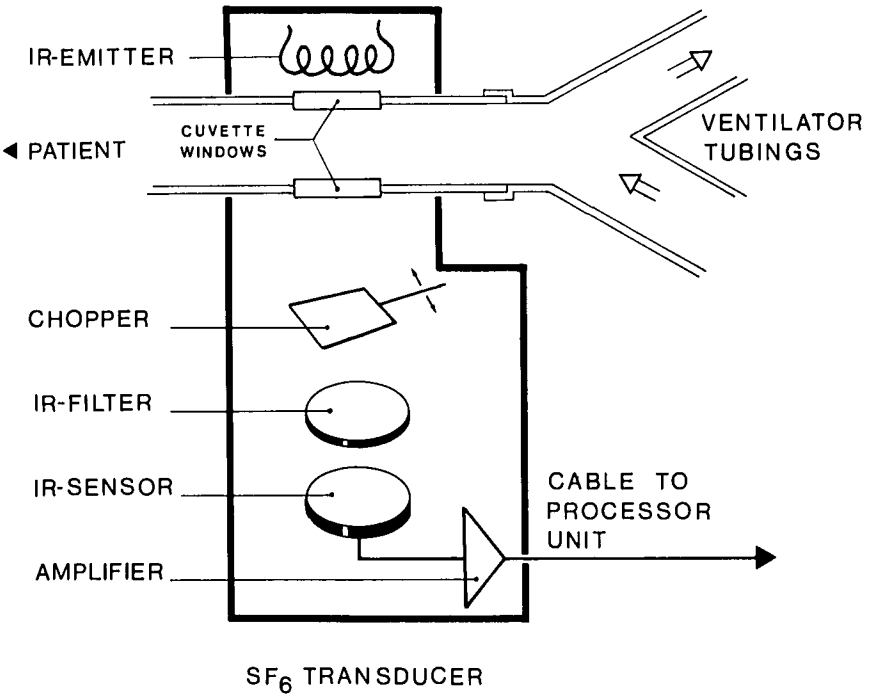

FIG. 1. The SF_6 transducer. A beam of infrared light passes through the airway via windows in a detachable cuvette connecting the patient to the Y-piece of the ventilator tubings. The beam is mechanically chopped, filtered, and sensed. The signal is amplified and transmitted to the processor unit. Modified from Olsson *et al.*[2] with the permission of the main author and the publisher.

Methods

Response Time

The response to a step change in SF_6 concentration was tested by suddenly introducing SF_6 into the cuvette. This was done by bursting a latex membrane separating the cuvette from an anesthetic bag containing 0.5% SF_6 under pressure. To detect this event, the other side of the cuvette was connected to the expiratory flowmeter of a Servo® ventilator. The time lag between bursting of the membrane and a change in the flow was 4 ms.¶

Linearity

Normally, the calibration curve of the primary output signal of an infrared gas analyzer is nonlinear. This follows from the exponential nature of Beer's law; an increase in the number of molecules within the cuvette will cause an exponential decrease in transmitted light.[3] To test the linearity of the analyzer after linearization in the processor unit and in the computer we used a precision gas mixer (Digamix G 18®, H. Wösthoff, Bochum, West Germany) to prepare a series of gas mixtures containing from 0.002 to 0.890% SF_6. The mixtures were prepared by diluting 0.989% SF_6 (in N_2/O_2:1/1) with air. Each SF_6 mixture was then introduced into the cuvette via a test gas valve (66 98 393 EO37E, Siemens-Elema Company). The valve was governed by a Servo® ventilator set at a rate of 7 min^{-1}. The SF_6 mixture was present inside the cuvette during the "expiratory" phase. This occupied 50% of the full ventilator cycle. During the remaining period, the SF_6 cuvette was flushed with air from the ventilator. The reading was obtained as the mean over 5–10 ventilator cycles.

The same set-up was used for testing interference from other gases and stability (see below).

Interference due to Infrared Absorption by other Gases

This occurs if a gas absorbs infrared light at the wave length of the SF_6 analyzer. To test this, CO_2, N_2O, humid air, enflurane, isoflurane, and halothane were

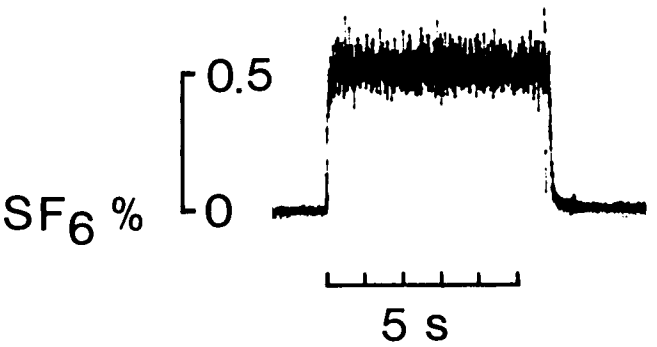

FIG. 2. The analyzer signal obtained when a gas containing 0.5% of SF_6 was introduced into the cuvette.

¶ Fletcher R: The single breath test for carbon dioxide. Thesis, Lund, Sweden, 1980, pp 50–51.

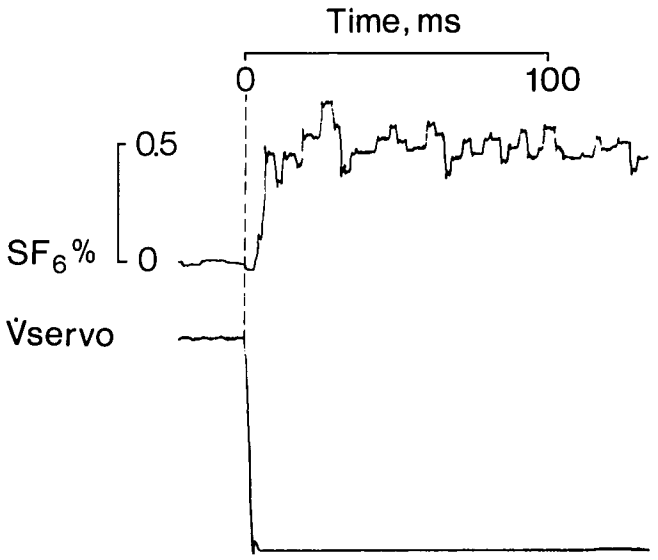

FIG. 3. SF_6 and flow tracings obtained during a measurement of response time. (The recording also demonstrates the stepwise changes caused by the activity of the chopper.) The descent in the flow signal marks the sudden introduction of 0.5% SF_6 into the cuvette. In the depicted experiment the time lag between flow and SF_6 signal was 3.5 ms. A full response in the SF_6 signal was reached within another 15 ms. The precise time was difficult to assess, because of the noise. The flow signal went out of range at 0.4 l s^{-1}, which explains the plateau shape of the flow tracing.

introduced into the cuvette via the test gas valve. Although no infrared absorption by O_2 and N_2 was expected, these gases were also tested. In all experiments, 50% N_2 in O_2 was used as "flush" gas during the "inspiratory" phase.

Interference due to Intermolecular Interaction between SF_6 and other Gases

A more subtle form of cross-sensitivity may occur if a gas interacts with the SF_6 molecule and changes the infrared absorption characteristics of the latter.[3] This effect is also known as collision broadening. To test whether such interaction occurred between SF_6 and O_2, N_2, or N_2O, the gas in a bottle containing 0.989% SF_6 in N_2/O_2:1/1 was diluted 30:70 in the gas to be investigated, using the precision gas mixer. In order that the experiment should not be disturbed by the known infrared absorption caused by N_2O, 70% N_2O in O_2 was used in flush-gas when testing for intermolecular interaction between SF_6 and N_2O.

Short- and Long-term Stability

The precision gas mixer was used to prepare three SF_6 mixtures on different days. These were passed through the analyzer as described above. In March 1982, 0.989% SF_6 was diluted in air in the proportions 1:9, 1:3, and 1:1. In September 1984 0.518% SF_6 was diluted in the proportions 1:4, 1:1, and 1:0. The original gas was prepared by weighing. According to the manufacturer, actual concentration was within ±1% of the stated value.

Statistics

The line of regression was obtained by the method of least squares. The residual standard deviation (RSD) around the regression line was calculated.

Results

Response Time

Four tests showed a time lag between the flow signal and the SF_6 signal of 3.5, 0, 3.5, and 2 ms. Full response, defined as the mean reading after the signal had clearly reached a plateau, was reached within another 15, 10, 10, and 5 ms respectively. A typical test is shown in figure 3.

Linearity

The linearity was satisfactory for SF_6 concentrations below 0.5% (fig. 4). The equation of regression below this concentration was as follows: SF_6-reading = $-0.0014\% + 0.993 \cdot SF_6$-concentration of test gas, r = 0.9998 and RSD = 0.0034%.

Interference due to Infrared Absorption by other Gases

There was a disturbance from CO_2, N_2O, enflurane, isoflurane, and halothane but not from humid air, O_2, or N_2 (table 1).

Interference due to Intermolecular Interaction between SF_6 and other Gases

The reading obtained with 0.297% SF_6 was the same, regardless of the composition of the carrier gas (table 2).

Short- and Long-term Stability

The signal remained linear both during the tests in March 1982 and the test in September 1984 (fig. 5).

Discussion

The analyzer was designed with the intention that the SF_6 signal should be combined with an airway flow signal to yield instantaneous flow of SF_6. The expired volume of SF_6 would then be obtainable through integration of SF_6 flow. Hence, mixing systems for expired gas would not be needed. The approach necessitated that the SF_6 signal should be a true representation of airway concentration at each instant. Both a long time

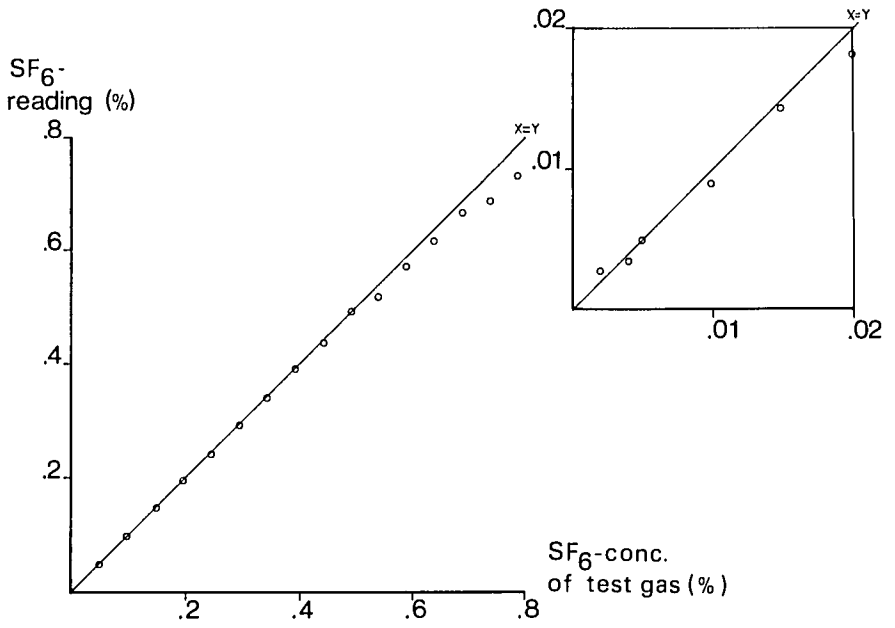

FIG. 4. The readings obtained with different SF_6 mixtures. The insert shows the low concentration range. The line of identity is shown.

lag and a slow rise time would therefore have introduced difficulties.[4] The emphasis on a fast response explains why we have avoided filtering of the signal in the analyzer, in spite of the marked high-frequency noise. The noise does not prevent that the computer calculations yield a precise estimate of mean expired concentration as this is obtained by sampling the signal over an extended period of time. The noise therefore does not disturb FRC measurements,[1] although it may hamper the interpretation of washout curves. In lung volume measurements, the low solubility of SF_6 in body tissues[5,6] is advantageous, although the low diffusivity[7] may be a drawback in patients with obstructive lung disease. SF_6 is biologically inert and has been used fairly extensively and in high concentrations to study different aspects of human pulmonary physiology. While sulfur hexafluoride is nontoxic, sulfur tetrafluoride (SF_4) and disulfur decafluoride (S_2F_{10}) are considered possible contaminants in commercially available SF_6.** To exclude the presence of these toxic impurities each lot of gas should be biologically tested by the manufacturer. The high sensitivity of the analyzer is advantageous as it makes it possible to use low alveolar SF_6 concentrations (0.5% or less), which increases the margin of safety. The high sensitivity has the additional advantage that very little alteration in the supply of other gases is needed. The prototype analyzer is significantly disturbed by carbon dioxide and by the tested anesthetic gases. In practice, we have compensated for the CO_2 disturbance by including a CO_2 analyzer in the measurement system. The disturbance caused by N_2O will, due to the method for zero adjustment, be greatly diminished when inspired and expired concentration approach each other. Equilibrium between inspired and expired concentration of enflurane, isoflurane, or halothane occurs much more slowly. However, provided conditions do not vary markedly during the measurement, *e.g.*, because of a recent change in inspired halothane concentration, the remain-

TABLE 1. Test for Infrared Absorption by other Gases

Test Gas	Reading (%SF_6)
100% O_2	0.000
100% N_2	0.000
5% CO_2 in N_2	0.010
10% CO_2 in N_2	0.020
Humid air at 37° C	0.000
100% N_2O	0.010
2% enflurane in O_2	0.014
4% enflurane in O_2	0.023
2% isoflurane in O_2	0.011
4% isoflurane in O_2	0.022
2% halothane in O_2	0.021
4% halothane in O_2	0.043

TABLE 2. Test for Intermolecular Interaction between SF_6 and Carrier Gas

Gas Mixture	Reading (%SF_6)
0.297% SF_6, 85% O_2, 15% N_2	0.300*
0.297% SF_6, 15% O_2, 85% N_2	0.295*
0.297% SF_6, 70% N_2O, 15% O_2, 15% N_2	0.295†

* Flush-gas: 50% N_2 in O_2.
† Flush-gas: 70% N_2O in O_2 (see text).

** Lowry PL, Richards CP, Geoffrion LA, Yasuda SK, Wheat LD, Bustos JM, Douglas DD: Respirator studies for the National Institute for Occupational Safety and Health. LA-7317-PR Progress Report, HEW Publication No (NIOSH) 78–161, 1978, p 4.

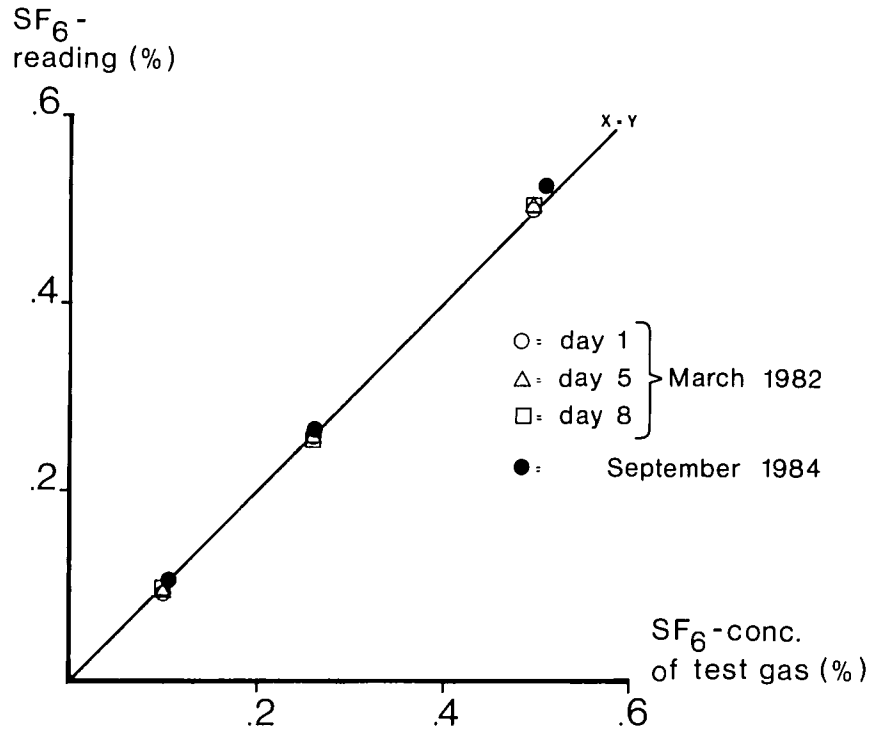

FIG. 5. Short- and long-term stability. The line of identity is shown.

ing small disturbance from these gases may be corrected for, by observing the signal before starting SF_6 washin. Possibly, the disturbance from the anesthetic gases may be eliminated altogether by a redesign of the analyzer. To compensate for electronic drift zero adjustment needs to be done repeatedly. Even though it is not necessary to reset the zero level in each inspiration we have found this practical. With the present instrument, the time needed for the automatic zero adjustment sets a lower limit of 400 ms for the duration of the inspiration. The signal ultimately obtained, after the various processing steps, is quite stable (fig. 5), and no readjustment of the gain of the instrument has been necessary during studies in the operating room and in the intensive care unit in over 80 patients.

Addendum

A recent redesign of the analyzer has eliminated the interference caused by CO_2, N_2O, and halothane. A slight interference from enflurane and isoflurane remains.

References

1. Jonmarker C, Jansson L, Jonson B, Larsson A, Werner O: Measurement of functional residual capacity by sulfur hexafluoride washout. ANESTHESIOLOGY 63:89–95, 1985
2. Olsson SG, Fletcher R, Jonson B, Nordström L, Prakash O: Clinical studies of gas exchange during ventilatory support—a method using the Siemens-Elema CO_2 analyzer. Br J Anaesth 52:491–498, 1980
3. Hill DW, Powell T: Non-dispersive Infra-red Gas Analysis in Science, Medicine and Industry. London, Adam Hilger, 1968, pp 115–125, 145
4. Mitchell RR: Incorporating the gas analyzer response time in gas exchange computations. J Appl Physiol 47:1118–1122, 1979
5. Hlastala MP, Meyer M, Riepl G, Scheid P: Solubility of helium, argon, and sulfur hexafluoride in human blood measured by mass spectrometry. Undersea Biomed Res 7:297–304, 1980
6. Cander L: Solubility of inert gases in human lung tissue. J Appl Physiol 14:538–540, 1959
7. von Nieding G, Löllgen H, Smidt U, Linde H: Simultaneous washout of helium and sulfur hexafluoride in healthy subjects and patients with chronic bronchitis, bronchial asthma, and emphysema. Am Rev Respir Dis 116:649–660, 1977