Technical note

Device for flow-proportional admixture of tracer gas in lung-function studies

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1 Introduction

TRACER GAS techniques can be used for many different types of lung function tests. Thus the wash-in and wash-out of insoluble gases have been used for the determination of residual volume and functional residual capacity (DAVY, 1800; WILLMAN and BEHNKE, 1938). Furthermore, measurement of the uptake of soluble tracer gas by the lungs forms the basis for noninvasive determinations of the pulmonary blood flow, pulmonary capillary blood volume, lung tissue volume and diffusing capacity (CANDER and FORSTER, 1959; SACKNER *et al.*, 1975; HUGHES *et al.*, 1982). The commonly used technique has been to provide premixed gases from a bag or a demand valve. This technique is cumbersome and not very well suited for the clinical environment; especially not in critically ill patients. Recent developments in the areas of microprocessors, gas analysers and electromechanical components have offered the possibility to design improved systems for lung function studies with tracer gas. In particular, it is attractive to use as low a concentration of tracer as possible, because some tracer gases are expensive, toxic or flammable at higher concentrations. Also, with the use of low tracer gas concentrations, the dilution of background gas need not be considered. Thus JONMARKER *et al.* (1985*a*; *b*) developed a system for FRC determination incorporating the admixture of a small constant flow of the insoluble tracer gas SF_6 during the relatively constant inspiratory flow in artificial respiration. LINNARSSON and LARSSON (1985) have described a system for the flow-proportional admixture of soluble gas to inspired gas allowing selective rebreathing of soluble gas in an open breathing circuit. The present study describes a combination of these two methodological approaches in order to create a general-purpose device for exact and flow-proportional admixture of small, constant concentrations of tracer gas during a time-variable inspiratory flow as, for example, during spontaneous breathing. As one of the most obvious applications of the device is for FRC determination with SF_6, we have used this gas to demonstrate the functional characteristics of the device.

2 Materials and methods

A schematic diagram of the tracer gas dispensing and control unit is shown in Fig. 1. It consists basically of a

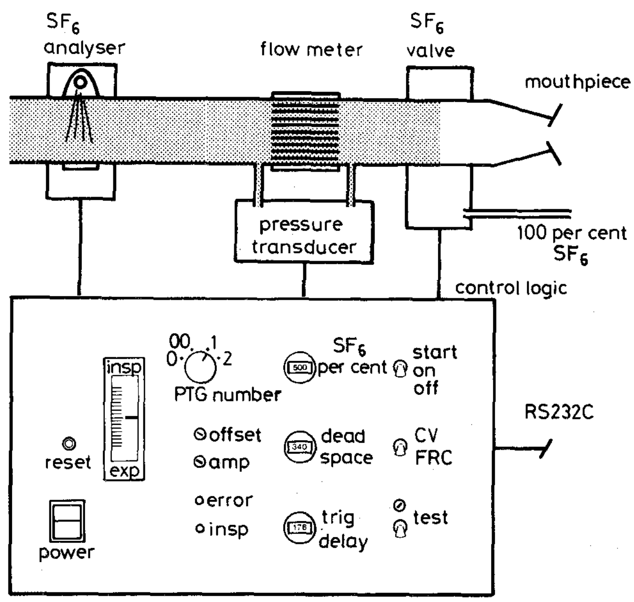

Fig. 1 *Schematic diagram of device for flow-synchronous admixture of SF_6 to inspired gas, including the front panel of the control logic. The control logic has a standard computer interface for external communication*

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miniature valve which dispenses short pulses of pure SF_6, a flow meter, an SF_6 detector and a microprocessor-based logic for flow-synchronous addition of tracer gas into the inspired gas stream. The assembly of analyser, flow meter and valve is depicted in Fig. 2.

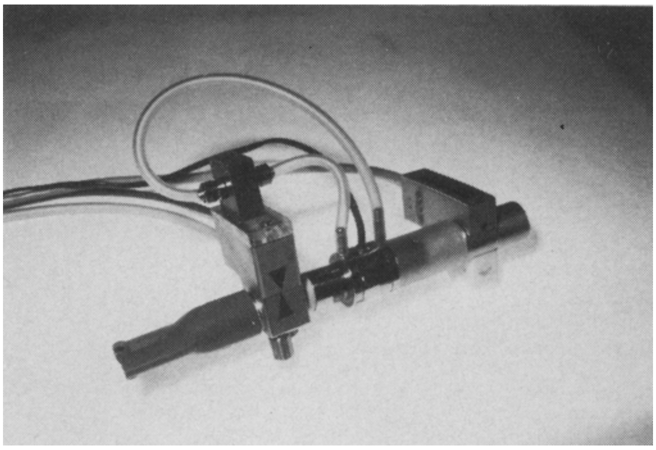

Fig. 2 *Assembly of (from left to right) mouth piece, dispensing valve, flow meter and SF_6 transducer. The pressure transducer of the flow meter is mounted on the valve housing*

The miniature solenoid valve (Lee Inc., type PWAA 8000120H) operates by means of a bimorph crystal, and can work at frequencies over 0·5 kHz, which is one order of magnitude faster than conventional electromagnetic valves. At frequencies in the range 0·5-1·0 kHz the valve can still operate but it dispenses gas pulses with less than desired accuracy. The valve is connected to a two stage regulator (l'Air Liquide HBS 300) which provides SF_6 at a constant pressure in the range 0·1-1·0 bar. With an upstream pressure of 0·5 bar, and valve opening times of 0·55 and 3·0 ms, each SF_6 pulse is approximately 4 and 25 μl, respectively. A constant SF_6 admixture is obtained by modulating the opening frequency of the valve in proportion to the flow rate of the inspired air. In order to increase the range of SF_6 admixture, the opening time is increased from 0·55 to 3·0 ms at 0·5 kHz and the pulse frequency is reduced proportionally. With the longer pulse time, the pulse frequency can be modulated between approximately 80 and 140 Hz.

As flow meter we have used a Fleisch pneumotachometer. In principle, any type of fast-responding flow meter can be incorporated. The present prototype can accommodate Fleish pneumotachometers of sizes 00, 0, 1 and 2. The pressure transducer was a Siemens-Elema type 6395628-E037E, modified with a larger diaphragm for increased sensitivity.

The panel of the microprocessor-based control unit is shown in Fig. 1. The control unit provides power supply and signal conditioning for the pressure and SF_6 transducers. Computations and controls are implemented on a Sattco 4680 single-board microprocessor. The calibrated flow signal is A/D converted at a frequency of 100 Hz and frequency and pulse time data for the SF_6 valve are updated with the same interval, so that the flow of pure SF_6 per unit time is kept proportional to the flow meter signal during inspiration. The proportionality factor can be adjusted by means of a dial potentiometer in the range 0·1-1·0 per cent SF_6.

Apart from this basic control of the SF_6 admixture, several other parameters can be set. One such parameter is the apparatus dead space. In order to avoid addition of SF_6 to the expired gas remaining in the apparatus dead space early during inspiration, the onset of SF_6 admixture can be delayed until a preset volume of gas has been inspired. This dead space for SF_6 admixture (stippled area in Fig. 1) includes the apparatus volume distal of the SF_6 valve. The dead space can be adjusted in the range 0–350 ml.

A second important control function concerns the timing of the zero-setting of the SF_6 meter. Its transducer has an inherent base-line drift and it therefore needs to be reset with SF_6-free gas during each inspiration. This can be performed because the SF_6 during normal use is added to the inspired gas downstream of the SF_6 detector. The SF_6 detector is reset once the dead space gas is cleared. The reset pulse to the SF_6 signal conditioner can be delayed further by up to 200 ms, by adjusting a separate dial potentiometer.

In order to obtain an accurate admixture during time-varying inspiratory flow, it is necessary that the transition between the two ranges of pulse duration/pulse frequency take place with continuity. Therefore a pulse calibration mode is provided to allow adjustment of the lower frequency limit of the range with the longer pulse time. Such adjustment may be necessary after change of gas pressure or miniature valve. When in pulse calibration mode, the control logic alternates between opening time/frequency combinations of 0·55 ms/500 Hz and 3·0 ms/80 Hz (approximately) at 5 s intervals. The resulting flow of pure SF_6 is fed through a porous disk of sintered glass. The pressure drop over the porous disk is measured with the differential pressure transducer. Thereby the SF_6 flow can be monitored during the pulse calibration.

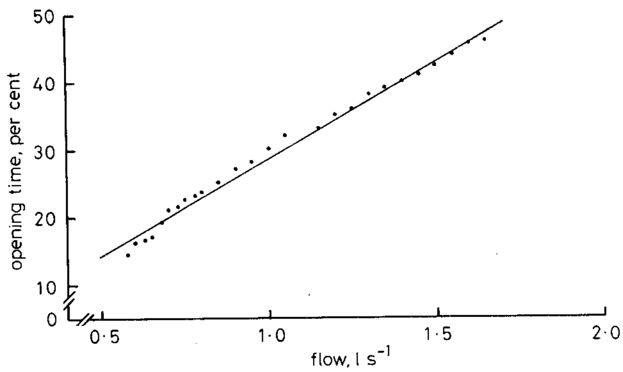

Fig. 3 *Percentage opening time of SF_6 valve as a function of the inspiratory flow at a concentration setting of 0·25 per cent*

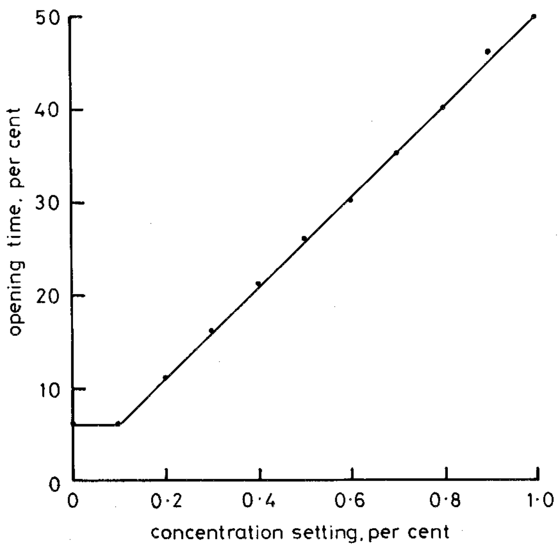

Fig. 4 *Percentage opening time of the SF_6 valve as a function of concentration setting at a constant inspiratory air flow of 0·85 l s^{-1}*

3 Results

3.1 *Static properties*

First the static properties of the control system were studied. Fig. 3 shows percentage valve opening time as a function of air flow through the flow meter and Fig. 4 shows percentage valve opening time as a function of the concentration setting. In both cases a linear relationship was found, in the latter case above 0·1 per cent. Both relationships could be extrapolated to a y (opening time) intercept, which for practical purposes was zero. This, together with the linearity gives a direct proportionality between air flow and SF_6 admixture.

The capacity of the valve for tracer gas limits the range of air flows, in which a proportionality of tracer gas flow versus air flow (i.e. constant percentage) can be obtained. At the maximum allowed gas pressure the maximum SF_6 flow was 7 ml s^{-1} corresponding to, for example, 0·45 per cent SF_6 in 1·5 l s^{-1} or 0·23 per cent in 3 l s^{-1}.

The SF_6 admixture varied with the gas pressure upstream of the miniature valve. Fig. 5 shows that $\pm 0{\cdot}1$ bar change of pressure results in an approximately ± 5 per cent relative change of the SF_6 concentration.

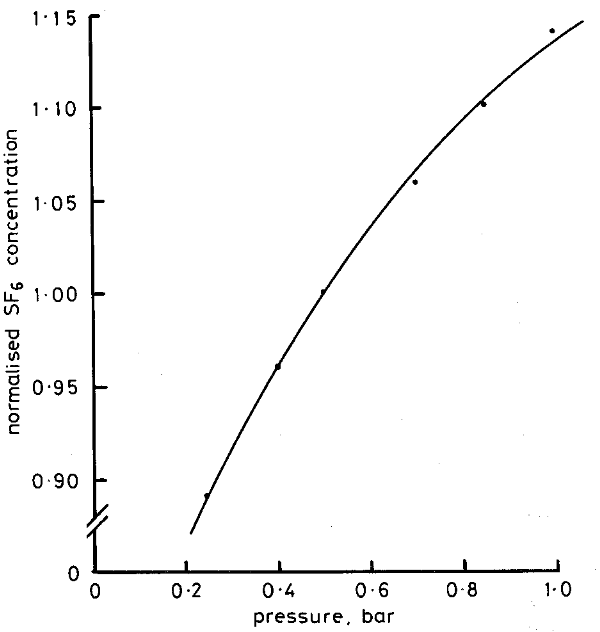

Fig. 5 *SF_6 concentration at a given control setting as a function of SF_6 pressure. Values are normalised relative to the concentration obtained at a pressure of 0·5 bar*

3.2 *Dynamic properties*

The SF_6 dispensing unit was connected to a flow regulator for air. Air flows of 0·18, 0·28, 0·38 and 0·61 l s^{-1} were used. For each air flow the following test procedure was performed. A time-varying signal was generated by a function generator. This sine-wave signal simulated inspiratory flow and was used to drive the control system and thereby the SF_6 valve. The resulting time-varying SF_6 concentration was monitored with the SF_6 analyser. For the purpose of this test the analyser was located downstream of the SF_6 valve. In order to promote gas mixing, a small humidity/heat exchanger was located between the SF_6 valve and the analyser.

The linearised output of the SF_6 meter was displayed on an oscilloscope as a function of the reference sine-wave signal. The SF_6 control system and the function generator were set so that the concentration varied between 0 and 0·5 per cent.

Fig. 6 shows schematically how the data were analysed. From the oscillogram three parameters were extracted (symbols refer to Fig. 6): (*a*) The amplitude of the SF_6 concentration at a very low frequency of the reference sine-wave signal, approximately 10 mHz (y); (*b*) The amplitude of the oscillations of the SF_6 concentration at reference signal frequencies up to 6 Hz (y_2); (*c*) the parameter y_1.

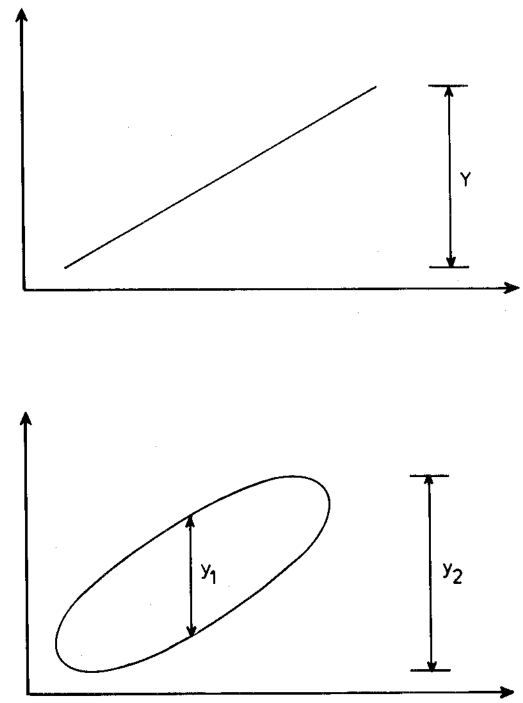

Fig. 6 *Schematic representation of oscillographic recording of SF_6 concentration as a function of a simulated sinusoidal flow signal, at a very low frequency (top) and at a high frequency (bottom)*

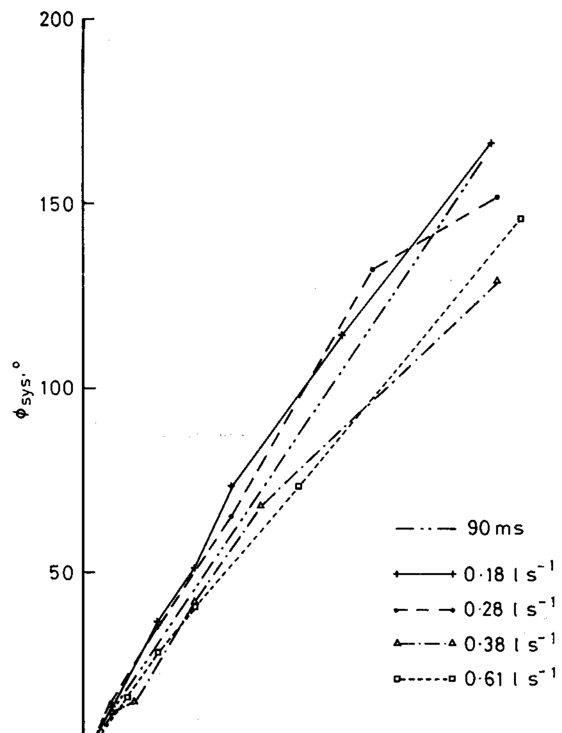

Fig. 7 *Phase lag of the SF_6 concentration response to a simulated sinusoidal flow signal as a function of the frequency of the flow signal. The line denoted 90 ms represents a theoretical system with a constant phase lag of 90 ms*

It can be shown that

$$y_1/y_2 = \sin \varphi_{tot} \tag{1}$$

where φ_{tot} is the total phase lag between the reference flow signal and the output of the SF_6 analyser. The total phase lag has several components, one arising from the time of passage through the volume of the small humidifier interposed between the SF_6 valve and the SF_6 analyser. As this volume was known, its resulting phase lag could be calculated and subtracted from ϕ_{tot}, thereby obtaining the phase lag φ_{sys} which arises from functions of the control logic and the SF_6 valve.

The relative amplitude of the SF_6 concentration was obtained as

$$A = y_2/y \tag{2}$$

The phase lag φ_{sys} is shown as a function of the reference signal frequency in Fig. 7. The corresponding changes of the amplitude function are shown in Fig. 8.

The practical consequence of the dynamic properties of the system described above are shown in Fig. 9, where rapid air flow transients had been induced in the intact SF_6 dispensing system. Also, the flow direction was reversed so that SF_6 was added upstream of the analyser.

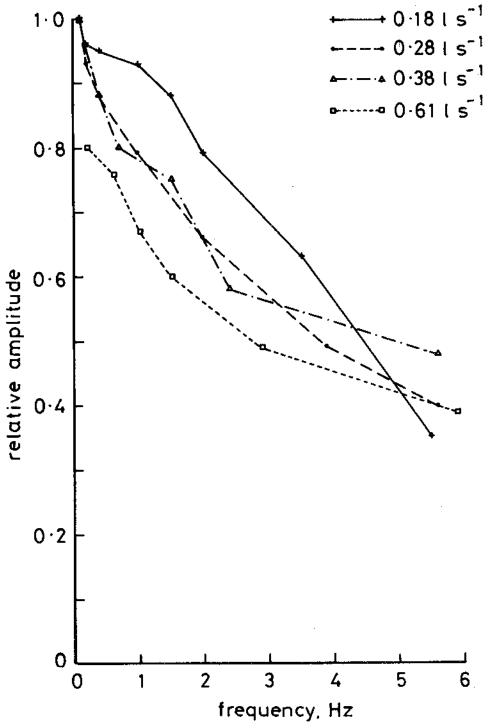

Fig. 8 *Relative amplitude of the SF_6 concentration changes in response to a simulated sinusoidal flow signal as a function of the frequency of the flow signal. Abscissa as in Fig. 7*

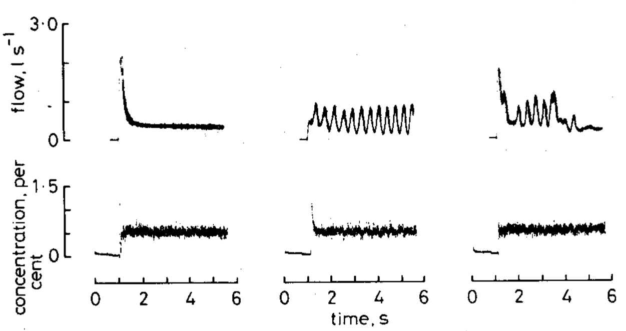

Fig. 9 *SF_6 concentration responses of the control/valve system to various induced air flow transients superimposed on a step change of air flow from 0 to 0·35 l s^{-1}*

When the air flow through the flow meter/dispensing valve/analyser assembly had a rapid initial spike, the phase lag of the system caused a short delay before a practically constant SF_6 concentration was reached. On the other hand, when the onset of air flow was more gradual, there was an initial spike in the SF_6 concentration, probably due to pressure build-up in the SF_6 lines upstream of the miniature valve.

4 Discussion

The purpose of the system described is to provide a reasonably constant level of a tracer gas during a time-variable inspiratory flow. Thereby, an even and well-defined concentration of tracer can be obtained, at the end of a wash-in period, which is a prerequisite for accurate determinations of, for example, functional residual capacity. In order to provide inspired gas with a reasonably constant SF_6 concentration during spontaneous breathing, it is necessary that the system is linear and has a satisfactory dynamic response to flow transients. However, minor high-frequency oscillations of inhaled tracer gas concentration are not critical as such variations are damped by gas mixing in the airways. The demands on frequency response of a dispensing system for tracer gas are therefore lower than those generally recommended for pulmonary measurements (10 Hz, Quanjer, 1983). The behaviour of our system can roughly be described as a linear system with a delay between the dispensing of SF_6 and a change of flow of roughly 90 ms (Fig. 7). The resulting variations of inhaled SF_6 concentration are small even at highly irregular breathing patterns (Fig. 9). The present system, therefore, appears suitable for dispensing tracer gas in proportion to inspiratory flow for lung function studies. This must, however, be confirmed in realistic tests. We are presently investigating the use of the system for FRC determinations using SF_6.

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