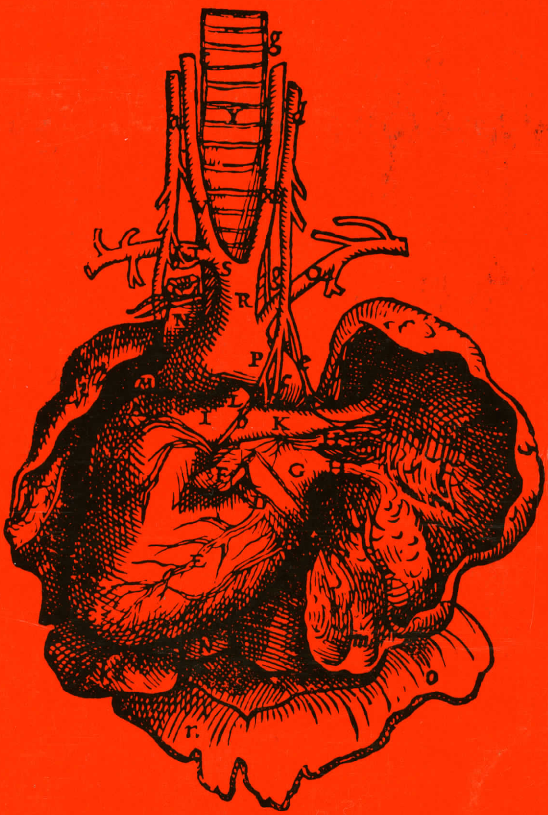
PULMOREX — PULMOSTAR
Lung-function testing units



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We don't mind if you compare us with others.
On the contrary, we are successful because we stand comparison.

To recommend the "open circuit" system for lung-function testing would be like carrying coals to Newcastle. We have been manufacturing lung-function testing units on a valveless open-circuit system since 1960 and as the result of many years of experience we shall most probably be able to give you optimum help in the solution of your measurement problems. Our motto is, "only what is best today can be still good tomorrow".

Our lung-function testing units are made in two versions, PULMOREX and PULMOSTAR. Generally the latter differs from the former in its more comprehensive equipment. A fundamental difference lies solely in the type of body plethysmograph used. The PULMOSTAR range features a constant-volume type of body plethysmograph, the PULMOREX range includes one of the pressure-corrected flow type. The PULMOREX plethysmographic unit is also available in a version which can be operated in the constant volume mode, too. An important characteristic is the possibility of extending the system in stages, which makes it possible to convert a PULMOSTAR into a PULMOREX assembly. Our units offer a well-balanced system at each stage of completion and the customer can to a large degree decide himself in which order he wishes to make additions to his assembly.

We continually keep the design of our testing assemblies up to date with the latest advances of technology. It would be hard to find more advanced systems.

S Spirography

The basic element of all versions of lung testing assemblies is the S stage.

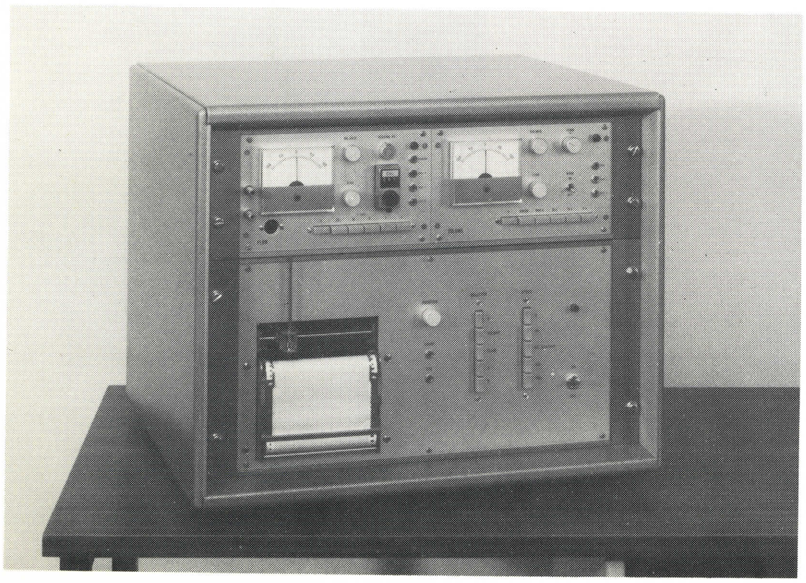
Principle of Measurement: The patient breathes room air (or, in special cases, a gas mixture) through a sterilisable, heated pneumotachograph head fitted to a mouthpiece or breathing mask. The resulting pressure difference of a few millimetres water gauge picked up by the pneumotachograph and proportional to the flow $\dot{V}$ is converted to the corresponding positive and negative voltages by means of a pressure transducer and registered in an electronic integrator after amplification. The voltage resulting from this operation is proportional to the tidal volume (TV). The factor of this proportional relationship is determined by volumetric calibration, using a calibration pump. One litre of air is pumped through the pneumotachograph head, which is pre-heated to operating temperature. This is the only reasonable method of checking the entire system. A balance control compensates for any lack of symmetry between pneumotachograph heads.

The S basic set thus consists of a slide-in unit for measuring the flow and a linked integrator and calibrating device. Measurement ranges: 1, 2, 5, 10, 20 litres or litres/sec., respectively, on full-scale deflection; time constants: 1000, 20, 10, 5 seconds. Push-button selectors. Automatic marking of zero-flow points $\dot{V} = 0$; heating of pneumotachograph head; data output using optional built-in single- or multi-channel compensated direct recorders or X-Y recorders, respectively (see under R).

We supply pneumotachograph heads adapted to Carlens and intubation catheters.

Measured quantities: V and $\dot{V}$ ($\ddot{V}$, if desired).

Determinable parameters at rest and during exercise: tidal volume TV, inspiratory reserve volume IRV, expiratory reserve volume ERV, inspiratory capacity IC, forced inspiratory volume FIV, vital capacity VC, forced vital capacity FVC, forced expiratory volume FEV_t, percentage expired % FEV_t/VC and % FEV_t/FVC, mean inspiratory flow rate MIFR, mean expiratory flow rate MEFR, mean flow rate MFR, peak inspiratory flow rate PIFR, peak expiratory flow rate PEFR, peak flow rate PFR, forced inspiratory flow FIF, forced expiratory flow FEF, forced mid-expiratory flow rate FMF, minute volume MV, maximum breathing capacity MBC, indirect maximum breathing capacity IMBC, maximum voluntary ventilation MVV, excess exercise ventilation EEV, standardised ventilation SV, ventilation response to exercise VRE, respiratory frequency f, duration of inspiration, and expiration, respectively, flow-volume diagram[1] also with He[2] (XY recorder necessary).



PULMOSTAR S

G Exchange of Gases

One possible extension of the S basic unit is designed to determine the gas exchange G or perform ergospirography, respectively, thus representing a SG assembly. Unlike rival products this unit operates without valves, i.e. under optimum physiological conditions. For it should be noted that there are still systems on the market which require the subject to inhale through a mask fitted with inspiration valves and to exhale through a hose fitted to the mask. Of course, such systems cannot work satisfactorily since they involve inspiration valves and because dead-space air is reinhaled from the expiration hose. Our system has overcome these drawbacks.

Principle of measurement: The expired gases are continuously drawn off while changes in concentration levels occur. However, the average values necessary for further processing (e.g. O_2 uptake) are drawn off in proportion to the expiratory flow rate by a special pump of our own design which can be modulated very rapidly. The expirate is then stored in a small collecting vessel. The resulting weighted samples are then analysed in on-line analysers for their O_2 and CO_2 concentrations ($\overline{\Delta F}_{O_2}$ and $\overline{\Delta F}_{CO_2}$, respectively).

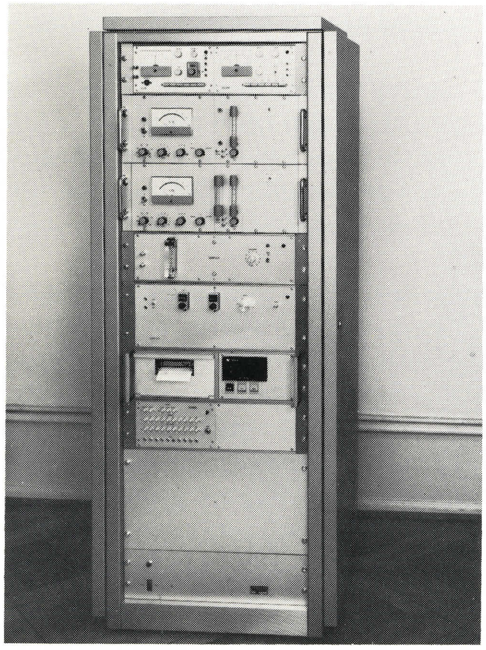
Essentially the G apparatus consists of a slide-in unit for extraction proportionate to the flow of respiratory gases during expiratory phases. A device for averaging and converting the pulsating gas flow to a steady flow required by the analyzers is included. The necessary equipment comprises O_2 and CO_2 and, optional, N_2 analyzers (see under A), as well as a multi-channel compensated direct recorder (see under R). We recommend our slide-unit for determining the MV directly (unnecessary if the assembly includes a computer) because it not only reduces working time, but also compensates for the time-lag occurring between the $\overline{\Delta F}_{O_2}$ and, respectively, $\overline{\Delta F}_{CO_2}$ quantities on the one hand, and the minute volume on the other.

Quantities measured: ΔF_{O_2}, ΔF_{CO_2}, $\overline{\Delta F}_{O_2}$, $\overline{\Delta F}_{CO_2}$ (optionally F_{N_2} and MV).

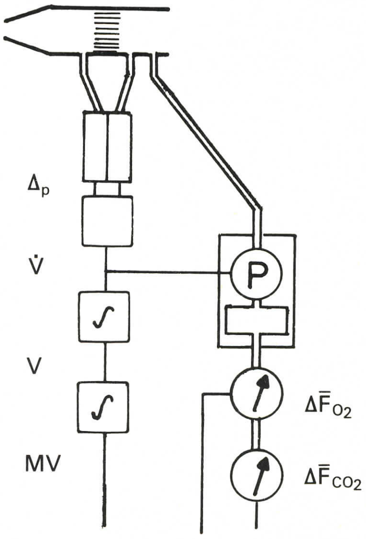
Determinable parameters at rest and during exercise in addition to the parameters listed under S: single breath CO_2 test by continuous high-speed analysis of the expired gas (information about ventilation/blood-flow ratios); relationship of alveolar ventilation to pulmonary blood flow*; information about uneven ventilation (high-speed N_2 analyser necessary); weighted mean values $\overline{\Delta F}_{O_2}$ and $\overline{\Delta F}_{CO_2}$ of the differences of concentration between the expirate and air; O_2 uptake/min. $\dot{V}_{O_2}$; O_2 debt, O_2 deficit, anaerobic work and threshold#, aerobic capacity; CO_2 production/min. $\dot{V}_{CO_2}$; respiratory quotient RQ; ventilatory equivalent VE; specific ventilation; caloric production; anatomic dead space, physiological dead space*; mean alveolar O_2 CO_2 pressure P_{AO_2} and P_{ACO_2}; alveolar ventilation, alveolar clearance*; relationship between alveolar ventilation and pulmonary blood flow*; cardiac output#; O_2 pulse $\dot{V}_{O_2}/PR$ (with additional equipment for measuring the pulse rate PR).[3]

Parameters marked with an asterisk* require equipment for measuring blood gases.

#Possible with more advanced computer; see "On-line Data Processing System".



PULMOSPORT with analogue computer and printer.



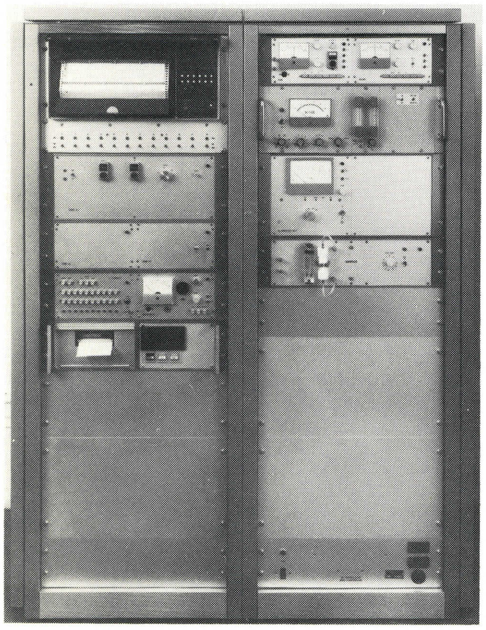
Block diagram: Gas analysis

We supply an economical analogue computer with permanent wiring for the automatic computation of the parameters of immediate interest to the physician (MV_{BTPS}, $\dot{V}_{O_2STPD}$, $\dot{V}_{CO_2STPD}$, RQ, respiratory equivalent RE, $\dot{V}_{O_2}$/PR, f, caloric production). This computer which may be acquired in three stages processes all data provided by the S and G assemblies according to the exact formulae reduced to the usual gas conditions and taking into account atmospheric pressure and the time-lag between sensing ventilatory activity and determination of gas exchange values.
Data output by printer and/or 12-channel point plotter (see under R).
When a SG assembly is combined with a C computer a SGC assembly or our PULMOSPORT group, which was especially designed for sport-physiological tests, is created.
Computer for: 1) MV_{BTPS}, $\dot{V}_{O_2STPD}$, RQ, RE, f. 2) $\dot{V}$/PR, PR. 3) Caloric production.

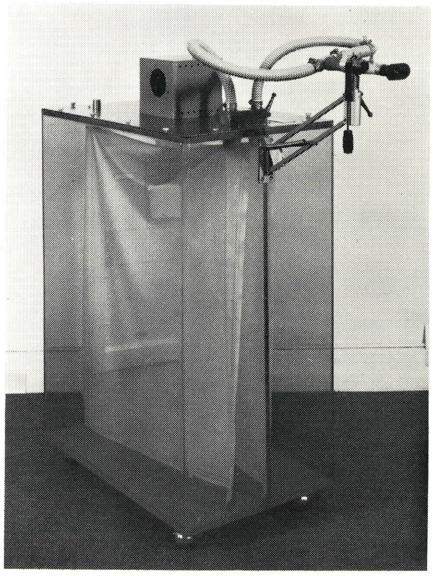
W Douglas Box

Our Douglas Box offers a very versatile extension of the S series apparatus, thus forming a SW assembly.
Principle of measurement: Inhalation of a known mixture of gases and collection of the expirate. Measurement of quantity and composition or of the gas transfer occurring with each breath.
Construction: A transparent plastic box on castors houses two bags containing a maximum of 100 litres each for the inspiratory and expiratory air, respectively. A valve system connects the bags to a pneumotachograph which measures the inspiratory and expiratory air. A three-way stopcock makes it possible to let the patient breathe ambient air or air from the bag according to choice. The expirate can be collected in the expiratory bag or released into the atmosphere. Device for filling and fan for deflating the bags. The gas concentration can be measured in the bags and continually monitored at the mouth. Additional equipment: gas analyzer, depending on test objectives (see under A), multi-channel compensated direct recorder (see under R), computer for direct MV determination.
Determinable parameters: In addition to the parameters listed under S: *using a high-speed N_2 analyzer:* functional residual capacity FRC and residual volume RV (N_2 wash-out method), total lung capacity TLC, N_2 clearance curves (uneven ventilation), anatomic dead space (Fowler single-breath method), N_2 closing volume; *using a high-speed CO analyzer:* diffusion capacity by steady-state CO technique (if the CO analyzer is not of the high-speed variety, it is necessary to use a device, collecting the endexpiratory gases, such as a Rahn-Otis valve or to measure the arterial P_{CO_2}* and to determine the F_{CO_2}* of the expirate), CO ductance; *using a CO_2 analyzer:* CO_2 ductance*; *using an O_2 analyzer:* O_2 ductance*.

Parameters marked with an asterisk* require equipment for measuring blood gases.



PULMOSPORT with analogue computer, printer and point plotter.



Douglas Box Unit

M **Respiratory Mechanics**

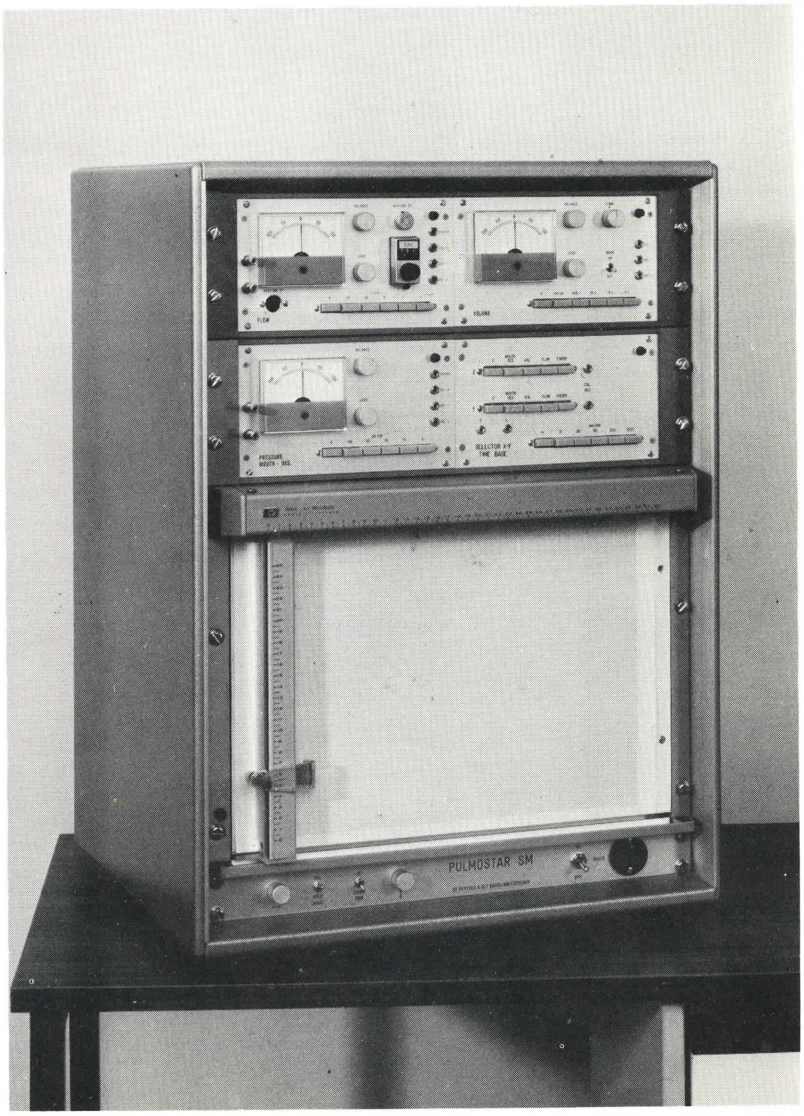
The S basic unit may be extended to a SM assembly by adding a slide-in unit for the measurement of changes in oesophageal pressure, thus making tests of respiratory mechanics possible. As the zero-flow points (i.e. the points of inversion) can be marked automatically, it is possible to determine the elastic axis in the diagrams of mouth volume in relation to oesophageal pressure even under uncertain conditions (as they often occur in patients suffering from emphysema). This makes evaluation considerably easier.

Principle of measurement: The oesophageal catheter is connected to an electric pressure-gauge with capacitive differential pressure transducer and an amplifier. Frequency response linear up to approx. 100 c/s. Measurement ranges: 5, 10, 20, 50, 100 cm water gauge on full-scale deflection.

An X-Y recorder is to be provided as a curve plotter (see under R).

Measured quantities: $\dot{V}$, V, P_{OES}.

Determinable parameters at rest and during exercise in addition to the parameters listed under S: lung compliance ("dynamic" and static), elastance, viscance, oesophagus pressure curves, work of breathing (during inspiration, during expiration, incl. any active expiratory phase, work against elastic resistance, inspiratory and expiratory work against tissue and airway resistance, metabolic work), total resistance (body respirator and curarisation necessary), pulmonary resistances, flow-volume diagram (also with He breathing; see references 1 and 2). If desired also with $^1/_3$ sec. marks in the flow or volume expiratory values. $P_{0.1}$ method[3a)] to give information about "Respiratory centers" (XY-recorder and shutter with timer necessary).



PULMOSTAR SM

B Body Plethysmography

Whole-body plethysmograph for adults and children (4 years and over).
Principle of measurement: The patient sits in a box and breathes through a pneumotachograph head. Measurement of either the pressure change occurring in the box (constant-volume type) or the volume change (constant-pressure type) which consists of a volume difference ΔV between thoracic volume change and tidal volume as measured at the mouth.
Alveolar pressure is measured by having the patient breathe against a shutter and by equating mouth pressure with alveolar pressure.
We make both types of body plethysmographs, which operate on entirely different physical principles while being very similar in their design.
We use a strut-braced aluminium cell of high rigidity which, unlike wooden or plastic constructions, guarantees many years of dimensional stability, tightness and rapid temperature compensation. In fact, 2 to 3 minutes after beginning of a test there is thermal equilibrium in the cabin and the cabin temperature will not rise by more than 2° C above ambient temperature. Its practical design allows us to keep the cabin volume down to 690 litres which lies in the interest of superior frequency characteristics. To prevent the patient from developing claustrophobia the cabin has not only a large window in its front, but also a plexiglass door fitted with solenoid-operated lock which can also be opened by the patient. The patient's comfort is considerably enhanced by a fan that can be kept blowing during measurements. An adjustable seat and an intercom system are installed, too.
If the air inhaled is not of the same nature as the air in the lungs, the problem of avoiding artefacts arises when working with the body plethysmograph. In this case, temperature and saturation of the respiratory air with water-vapour change during each breathing cycle, which in turn changes air volume. These volume changes are superimposed on the parameter of interest to us, i.e. the changes in thoracic gas volume, and have to be eliminated. This can be done in three ways:
The oldest method, still practised in the US, consists of making the patient perform rapid shallow chest breathing (so-called panting), so that the above errors cannot occur for lack of time. But rapid shallow chest breathing (panting) apart from not being physiological, cannot be performed by many patients.
Another method was described by BARGETON et al.[4] as early as 1957. It is the electronic compensation for the error described above, a method which BARGETON himself no longer recommends. At first sight the method appears attractive because the patient breathes cabin air under physiological conditions and the error introduced is eliminated from the measurement result by an electronic computer. The drawback is that it is not possible to establish any criteria for instructions for correcting errors to be fed to the computer in a specific case. BOUHUYS and JAEGER[5] have shown that uneven ventilation produces the same effect as do artificially introduced errors, so that one runs the risk of "compensating away" the former phenomenon, too. Feeding the compensating computer with statistical empirical data is also not feasible for any specific case. The reason why we include a compensating logic in our equipment is that we wish to make occasional small "cosmetic" curve corrections possible and that we, too, have to conform to market demands.
The method most commonly used in Europe today, if not altogether physiological, is to let the patient breathe air of BTPS quality, which ensures that the inspired air does not differ in humidity and temperature from the air in the lungs.
As even small deviations from BTPS conditions may cause gross errors[6], respiratory air is automatically conditioned in our testing units. Conditioning takes place in a resistance-free plastic breathing-bag in a closed circuit. The bottom of the bag holds a reservoir of hot water. From it water flows through an adjustable thermostat and is then pumped into a spraying device contained in the upper part of the bag. From there the water is sprinkled down into the breathing bag. The pipes connecting the breathing bag and the mouth-piece are heated to prevent the water-vapour from condensing. A blower facilitates filling and airing of the breathing bag which holds about 50 litres. It guarantees a favourable CO_2 concentration in the breathing bag during determination

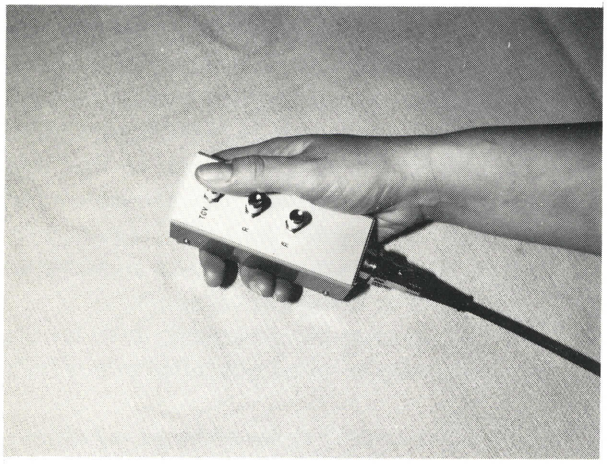
of the airway resistance[6]. The use of breathing bags of very large sizes is also necessary to determine accurately MEFV, (resp. MIFV) and IVPF, which have gained increasing diagnostic significance in recent years[7,8]. The patient is connected with the breathing bag via our novel heated breathing-air selector. This device eases control by selectively connecting the patient with the BTPS breathing bag, the plethysmograph-cabin air or ambient air (extracorporal spirography and accurate determination of the important iso-volume pressure-flow curves IVPF[9]) or with a bag containing foreign gas at a 90° turn of a lever. A fourth lever position allows one to calibrate the patient breathing-tube and the plethysmograph by means of a one-litre calibration pump. Owing to its design the breathing-air selector makes it possible to perform forced breathing measurements, too.

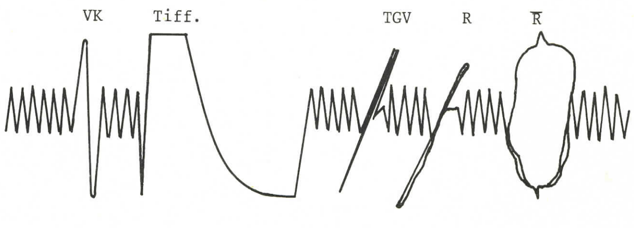
The design of the unit permits easy cleaning and sterilization. The shutter-pneumotachograph head-breathing-air selector system can be dismantled, as it is the most important system as hygienic conditions are concerned. The remote-controlled shutter, too, can be dismantled and cleaned after loosening no more than four bolts.

The electronic measuring circuitry and the data-output units necessary for plethysmographic operation are housed in a 19 inch single or double cabinet on castors. The standard equipment includes a cathode ray oscilloscope for screening and a high-speed X-Y recorder. Both units may be used for recording both respiration loops and events against time. Random selection of programme. In addition, the PULMOREX range is equipped with a 4-channel magnetic-tape recorder with frequency-transposition device. The equipment works according to the standby principle and the main transducers are thermostatically controlled.

Quantities measured: ΔV_{BODY} resp. ΔP_{BODY}, V, $\dot{V}$, P_{OES}, P_{MOUTH}.

Our *remote programme-control* ensures easy operation. A hand-sized control unit with 3 push-buttons is connected to the plethysmograph assembly by means of a cable. If no button is pressed, spirograms will be written. By pressing the appropriate button measurement is switched automatically to thoracic gas volume TGV, airway resistance (flow-body loop) or mean airway resistance. The control unit allows one not only to close the shutter automatically in the end-expiratory phase immediately following the switching signal, but also to register the tidal volume present at the time when the shutter closes, so that the thoracic gas volume can be accurately determined even with irregular breathing.





PULMOSTAR SMB

Our PULMOSTAR SMB is a whole-body plethysmograph of the constant-volume type, i.e. it measures pressure changes due to thoracic volume-change differences[10]. Measurements are made against the pressure in a compensating chamber. The compensating vessel is built into the plethysmograph and communicating with it through a high resistance (time constants of 50, 10 and 20 seconds may be selected). This offsets slow, e.g. thermally induced pressure changes while pressure fluctuations occurring simultaneously with respiration are registered. This also eliminates or dampens interfering influences reaching the plethysmograph chamber and the compensating vessel cophasally. The zero position can be restored at any time by allowing both the plethysmograph chamber and the compensator to assume atmospheric pressure through a valve system.

The electronic measuring unit is a capacitive differential pressure transducer with a linear frequency response up to 50 Hz. Measurement ranges: 1, 2, 5, 10, 20 mm water-gauge on full-scale deflection.

The advantages of the constant-volume type are:

a) comparatively low cost;

b) simple compensation of interfering influences;

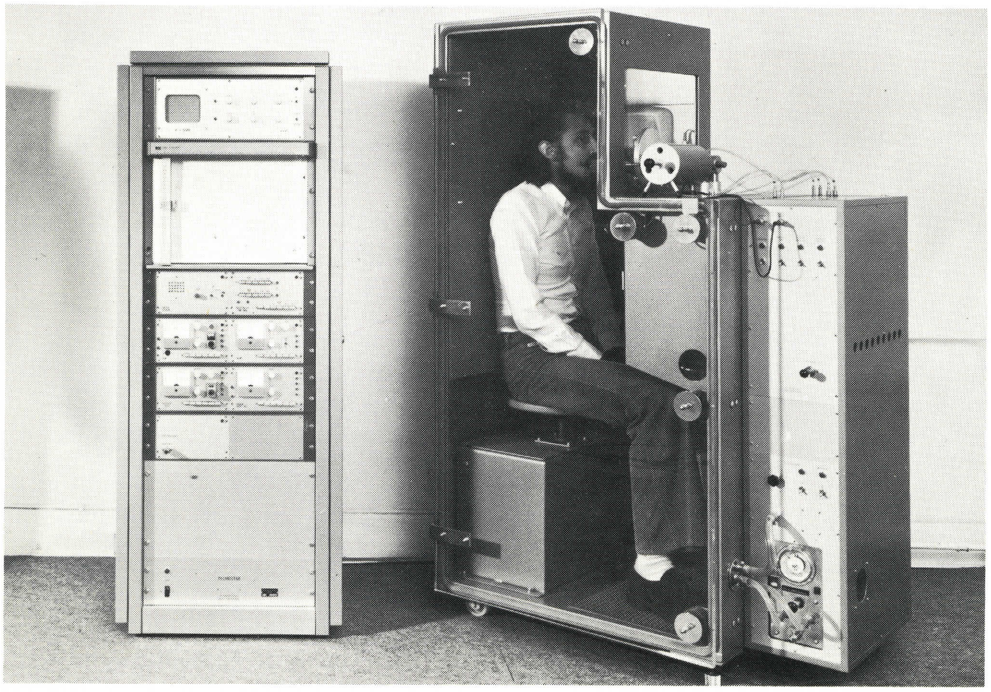
The drawbacks of this type of plethysmograph are:

a) the patient's volume enters into the calculation. However, we were able to overcome this difficulty and to make our measurement technique allow for the patient's volume.

b) A back-pressure on the patient is caused rendering some types of measurement inaccurate.

c) Polytropic conditions exist in the chamber. Since the degree of polytropicity is unknown, calibration of the chamber ought to be carried out under simulated breathing conditions to eliminate errors, which is only possible, of course, by way of approximation.

Determinable parameters: In addition to the parameters listed under S and M: thoracic gas volume TGV, total capacity, airway resistance momentary and mean, R_{AW}, $\bar{R}_{AW}$.



PULMOSTAR SMB

PULMOREX SMB

Our PULMOREX body plethysmograph incorporates the pressure-corrected flow principle, but can also be equipped with the constant-volume operational mode in addition. Presently, this type of body plethysmograph is probably the most perfect.
In order to explain the functioning of this plethysmograph we will proceed from the simpler constant-pressure plethysmograph. In 1960 MEAD described his "volume displacement" plethysmograph[11] which he used in conjunction with a Krogh spirometer to determine changes in chamber volume. We replaced the Krogh spirometer with a pneumotachograph and a linked integrator. The resulting assembly is an "open-box" "volume-displacement", i.e. constant-pressure, plethysmograph.
Flow recorded by the chamber pneumotachograph is measured by a thermostatically controlled differential pressure transducer so sensitive that it permits one to detect pressure changes of as little as a thousandth mm water-gauge. Linear frequency response up to 50 c/s.

Measurement ranges: 0.1; 0.2; 0.5; 1; 2 litres/sec. on full-scale deflection. The linked integrator for the measurement of the volume change within the chamber has a push-button selector for the measurement ranges of 0.1; 0.2; 0.5; 1; 2 litres on full-scale deflection and for the time constants of 1000, 20, 10, 5 seconds. This unit also incorporates the computer and coupling unit, which are necessary (see below) to make a pressure-corrected flow plethysmograph of the arrangement described above. The slide-in unit contains a computer for electronic simulation of BTPS conditions as well as a symmetry unit for correction of the thermal drift, i.e. the effect of the difference in temperature between chamber and ambient air.

Advantages of the constant-pressure system:

(1) Constant-pressure plethysmography is independent of the characteristics of the plethysmograph. This is evident from the fact that with this type of plethysmograph only the lung-gas equation with its implicated isothermal conditions is necessary. The constant-volume type, however, requires the gas equations of the body plethysmograph in addition. In this type polytropic conditions prevail, i.e. Poisson's Law applies ($p \cdot v^k = \text{const.}$ where $1<k<1.4$). Which value k assumes, depends both on whether the conditions inside the chamber tend to be more isothermal or more adiabatic and thus on the subject's respiratory frequency, especially when the subject hyperventilates.

(2) The results obtained with the constant-pressure plethysmograph are independent of the patient's volume, which must be taken into account when using a constant-volume type. In practice, however, patient volume can only be determined via body weight and specific gravity, a method which may not be very accurate. (This does not apply to our PULMOSTAR, see above.)

(3) With a constant-volume type, correlation of alveolar pressure with box pressure depends on the mean level of the diaphragm, which is not necessarily the same during calibration and measurement.

(4) Constant-pressure plethysmographic measurements allow simple checking of whether the important BTPS conditions are fulfilled exactly[12]. Incidentally, this is always the case with our apparatus owing to its automatic conditioning control.

(5) Our "open" constant-pressure plethysmograph permits one to reach thermal equilibrium within 2—3 minutes after the beginning of a test. There will be no essential drifting, an inevitable drawback encountered with all closed-box plethysmographs.

(6) As there is no back-pressure problem with the open constant-pressure plethysmograph, several investigation techniques may be employed reasonably only with this system, e.g. determination of momentary pulmonary blood flow, cardiac minute volume and stroke volume as well as studies on the mechanics of breathing by means of iso-volume alveolar pressure-flow diagrams[13, 14].

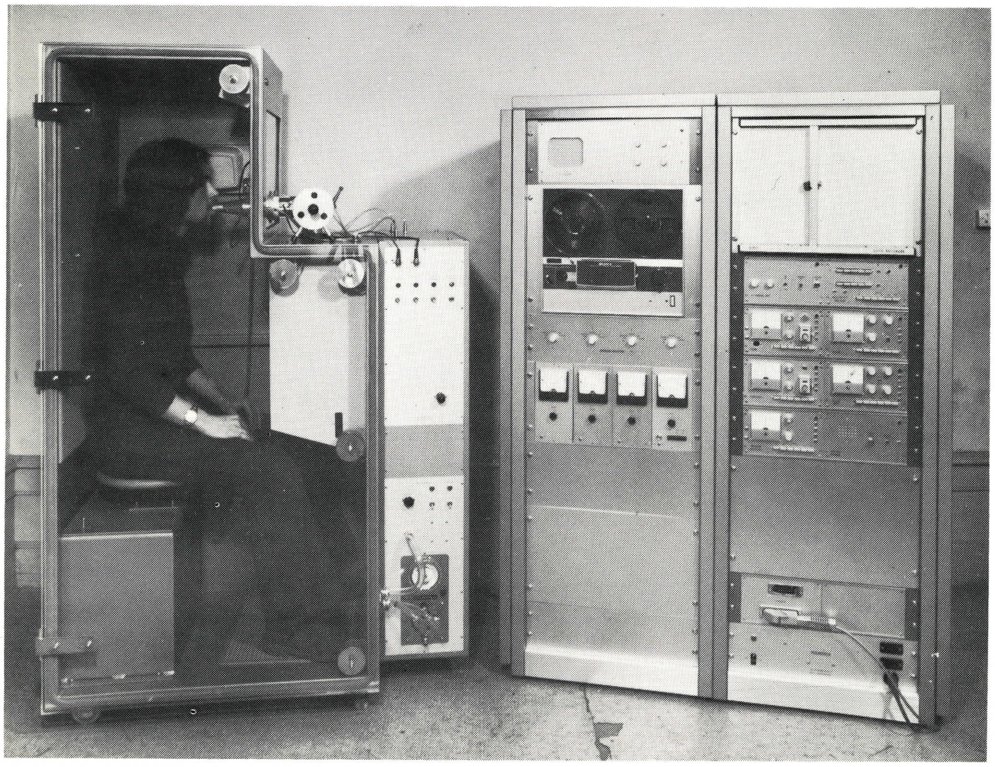
(7) The fact that a constant-pressure plethysmograph does not require absolute air-tightness increases operational safety considerably.

The very substantial advantages mentioned above, which are features of the constant-pressure system, are obtained at the cost of two disadvantages with the conventional design, but not with PULMOREX:

First, it is considered difficult to restore initial conditions (zero position) in a constant-pressure plethysmograph of conventional design. Unlike the constant-volume system, where the box need only be allowed to communicate with the ambient air, volume changes occurring in a constant-pressure plethysmograph have to be drawn off. With our "open" constant-pressure plethysmograph this drawback is eliminated: the mean pressure is always equal to the atmospheric-pressure level, i.e. initial conditions.

As a second disadvantage it has been stated that the constant-pressure system is slower than the constant-volume one, thus increasing the problem of phase shifts. Basically, this is correct, for in the constant-pressure system the signal propagates at group velocity, i.e. at the speed of material transport (air molecules), whereas in the constant-volume system the signals spread at the phase velocity of the pressure wave. We combined both systems by introducing an additional pressure receptor in the body plethysmograph, the signal of which is appropriately combined with the signal of the constant-pressure system. The following process takes place. Owing to the inertia of the air molecules a pressure builds up inside the plethysmograph as if it were of the constant-volume type. This pressure can last only until the air molecules start moving, resulting in a slow decrease of the pressure signal, while the volume-displacement signal starts. Thus, one arrives at an arrangement that combines the advantages of constant-pressure and constant-volume systems, an arrangement which MEAD calls a "pressure-volume plethysmograph" and which was called a "pressure corrected flow body plethysmograph" by VAN DE WOESTIJNE.

The overwhelming superiority of the pressure-corrected-flow system is confirmed by the study of STANESCU, DE SUTTER, VAN DE WOESTIJNE[15].



PULMOREX SMB