Appendix 1. Measuring devices and techniques of common use in respiratory physiology

**Pressure** ($P; \text{mm Hg, cm H}_2\text{O}$).

A manometer (water or mercury) is the simplest device to monitor $P$. A variety of pressure transducers are also available. A very common one is made by two chambers separated by a diaphragm. The lower chamber represents the reference chamber, at ambient pressure. An air-filled or liquid filled tube connects the measurement site to the upper chamber of the transducer. The $P$ difference between upper and lower chamber distorts the diaphragm, which is part of a Wheatstone bridge circuit, and therefore translates the mechanical event (change in $P$) into an electrical signal.

**Airflow** ($V; \text{ml/sec}$).

Usually measured by a pneumotachograph connected to the airways via a face-mask, mouth-piece, endotracheal tube, etc. The pneumotachograph is essentially a resistor which behaves linearly over the flow range specified. Hence, the pressure difference (measured with a differential pressure transducer) between inflow and outflow ports of the pneumotachograph is proportional to airflow. By convention inspiratory flow is upward [Fig.1]. During a breathing cycle there are three points of zero flow, at the onset and end of the breath, as well as at the end of inspiration.
Fig.1. Records of airflow (V) and changes in lung (VT) as function of time. The dashed vertical lines join the points of zero flow, at the beginning and end of inspiration, and end of expiration. In some cases, an expiratory pause with zero V can conclude the breathing cycle.

**Changes in lung volume**, (ΔV, ml).

Very many ingenious methods have been adopted to record the changes in lung volume as function of time, i.e. the spirogram. Each method has advantages and pitfalls, and its choice is dictated by a number of considerations, including the ability of the subject to collaborate, and his response to the instrumentation.

The most direct approach is by use of the spirometer. ΔV can also be derived by integration of the V signal [Fig.1], an operation which is usually done electronically.

An indirect approach is based on recording the motion of the chest wall, and converting it to changes in V with appropriate calibration. Measurements of chest wall motion have been obtained with wires connected to force-transducers, or with two coils placed in front of each other on opposite spots of the chest or abdomen, one coil generating a magnetic field and the other one recording it in proportion to its distance (Magnetometer®). More recently, the
respiratory induction plethysmography (Respitrace®) has been introduced. One coil of insulated wire zigzags around the chest, and a second one around the abdomen. Breathing movements change the inductance of each coil in proportion to the change in volume of the rib cage and abdomen, and the sum of the two signals is proportional to $\Delta V$. The advantage of this method is that it requires rather minimal, and not invasive, instrumentation, useful for example in studies on infants or during sleep [Fig.2].

Fig.2. Advertisement of the Respitrace® as appeared in the Journal of Applied Physiology.

The body plethysmography, with numerous variants, is usually used in adult humans, but it can be also applied for measurements in newborns or animals [Fig.3]. The increase in pressure in the plethysmograph with inspiration can be recorded as function of time, and calibrated for volume (Pressure-plethysmograph). Alternatively, the box is connected to a spirometer (volume-plethysmograph) or to a pneumotachograph (airflow-plethysmograph); in this latter case, the spirogram is obtained by integration of the flow signal. Other approaches have used a rubber collar which fits snugly around the neck, to separate the head (usually outside) from the rest of the body (inside the plethysmograph), although in some special cases the reverse (head inside, body outside) has been adopted.
Fig.3. Examples of body plethysmography. In the example at the top, the line b from the chamber can be connected to a pressure transducer. Bottom: as the animal breathes from the head-chamber, flow (V) is monitored in the back chamber with a pneumotachograph. Gas concentrations and temperature are also monitored. The syringe at right is for volume calibration.

The barometric method is a convenient approach for recordings on infants or animals, since does not require any collaboration from the subject, and is completely uninvasive. The subject rests in a sealed container [Fig.4]. During inspiration, as some air (VT) moves from the container into the lungs, its temperature slightly increases, whereas the opposite occurs in expiration. These small changes in temperature (ΔT) can be monitored as changes in chamber pressure (ΔP) by a sensitive pressure transducer (since, at constant volume, ΔT is proportional to ΔP), and calibrated for volume with appropriate conversion factors, which take into account body and ambient T and humidity. This barometric methodology is very sensitive to even small errors in T measurements, hence it is prone to inaccurate results when the difference in temperature between ambient and body is small. Nevertheless, it is the only technique completely uninvasive presently available.
Fig.4. Example of set up for application of the barometric technique for monitoring the spirogram. During the measurements, gas flow is interrupted, and the pressure oscillations (P) due to breathing are recorded by a sensitive P-transducer. The outer chamber is for temperature (T) control. Full humidification is provided by water in the chamber. The syringe is for volume calibration.

All the above techniques can be used to measure changes in lung volume, hence not only tidal volume (VT), but also inspiratory and expiratory reserve volumes, and capacities (vital capacity, inspiratory capacity), whereas, they cannot provide measurements of absolute lung volume.

**Absolute lung volume** (V, ml).
Two methodologies are most commonly used for determination of absolute lung volume, body plethysmography, and gas dilution.
Body plethysmography. The subject is sitting in an airtight box ("body box") of known volume (Vbox), and breathing through a mouthpiece connected to a shutter [Fig.5]. The pressure is monitored in two places, in the box (Pbox) and at the subject's airways (Paw), the latter via a side-port of the mouthpiece. At end-expiration (functional residual capacity, FRC), the airways are momentarily occluded by the shutter, and the subject is invited to make an inspiratory effort against the occlusion. During the inspiratory effort, Paw decreases below atmospheric and lung volume expands because of decompression. Because there is no flow, Paw corresponds to alveolar pressure. In conditions of constant temperature, the lung volume expanded ($\Delta V_{lung}$) must be equal to the gas volume compressed in the box ($\Delta V_{box}$); hence, it can be calculated from the corresponding increase in Pbox. In fact, at constant temperature,

$$Pbox \cdot Vbox = (Pbox + \Delta Pbox) \cdot (Vbox - \Delta Vbox)$$

Once $\Delta V_{box}$ (which equals $\Delta V_{lung}$) is calculated, the absolute lung volume (FRC) can be calculated by applying, again, Boyle's law:

$$FRC \cdot Paw = (Paw - \Delta Paw) \cdot (\Delta V_{lung} + FRC),$$

from which

$$FRC = \frac{\Delta V_{lung} \cdot (Paw - \Delta Paw)}{Paw}$$
In a variation of this approach, Vlung can be measured directly by connecting the mouth piece to a spirometer placed outside the plethysmograph, instead of calculating it as Vbox.

Gas dilution technique. At FRC, the subject is connected to a spirometer of volume Vsp, filled with a gas not easily soluble in the blood, for example helium, the concentration of which is known (He1). The subject is invited to take a few deep breaths, in order to mix the pulmonary air with the gas of the spirometer. After a good mixing, the concentration of helium in the spirometer (He2) will be equal to that in the lungs. Since the total quantity of helium (concentration · total volume) cannot have changed, it follows that

\[ \text{He1} \cdot \text{Vsp} = \text{He2} \cdot (\text{Vsp} + \text{FRC}), \]
from which
\[ \text{FRC} = \frac{\text{Vsp} \cdot (\text{He1} - \text{He2})}{\text{He2}} \]

**Work** (W; g·cm)

It is difficult to measure the total work involved in the breathing act; in fact, it is somewhat easier to estimate it from the respiratory cost and an appropriate value of efficiency for the skeletal muscles. The external component of the work of breathing, on the other hand, can be calculated with good precision from the pressure, volume and flow. For example, the work done by the respiratory muscles on the lung during one breath can be computed by planimetry from the transpulmonary pressure-volume loop (cfr chapter "Respiratory Mechanics, Fig.13").

**Oxygen consumption** (VO₂; ml/min)

One simple approach for the measurement of VO₂ is by use of a spirometer with separate inspired and expired lines. In series with the expired line is a CO₂ scrubber (Soda lime). The subject consumes O₂ from the spirometer, but because the CO₂ that he produces is not exhaled into it, the reduction of the spirometer volume as function of time reflects the subject's VO₂.

VO₂ can also be calculated by collecting the expired air into appropriate bags over a fixed period of time. By measuring the concentration of O₂ in the air and in the bag, as well as the volume of gas in the bag, VO₂ can be calculated.

These approaches give VO₂ values in ATPS; it is normal practice to convert the data to STPD conditions (cfr 'Appendix 2').