Important management decisions, both on admission (such as the institution of mechanical ventilation) and later (such as when to start weaning the patient from respiratory support), depend on a reliable and accurate assessment of respiratory function. Respiratory monitoring is also required to evaluate the patient’s response to treatment and optimize respiratory support.

Clinical assessment is of the utmost importance. Signs of severe respiratory distress include (see Chapter 8):
- the use of accessory muscles of respiration;
- suprasternal and intercostal recession;
- paradoxical or asynchronous movement of the ribcage and abdomen;
- respiratory alternans (an increase in the breath-to-breath variation in the relative contribution of the ribcage and abdomen to tidal volume);
- tachypnoea;
- tachycardia;
- sweating;
- pulsus paradoxus (an exaggeration of the normal fall in systolic blood pressure and pulse pressure during inspiration);
- inability to speak in sentences.

Together with a subjective assessment of the degree of exhaustion, these clinical signs are often the best guides to the need for respiratory support.

The most sensitive indicator of increasing respiratory difficulty is a rising respiratory rate, although when respiratory frequency is determined by observing chest wall movement over 15 seconds and multiplying the number of excursions by four, errors of up to 4 breaths/min may easily occur (Tobin, 1992). Signs of carbon dioxide retention include a bounding pulse, warm, vasodilated peripheries, a tremor of the outstretched hand and an impaired conscious level, but the presence or absence of cyanosis is an unreliable guide to the adequacy of oxygenation.

The history and clinical examination can be supplemented by regular measurements of the pulse rate, blood pressure and respiratory rate, as well as, in selected cases, tidal volume ($V_T$) and vital capacity (VC). Repeated blood gas analysis is essential and a chest radiograph should always be obtained. In some cases maximum mouth pressures may be helpful, and in those with airways obstruction, maximum expiratory flow rates should be recorded. An assessment of lung mechanics can also be valuable in selected cases. More sophisticated investigations, such as the determination of ventilation/perfusion relationships and alveolar–capillary permeability are usually confined to research applications.

These techniques for assessing respiratory function are performed intermittently. Continuous monitoring (e.g. with pulse oximetry and capnography) is required to detect the rapid changes that may sometimes occur, for example in response to alterations in treatment or when there is rapid decompensation.

### Measurement of Lung Volumes
(see also Chapter 3)

#### Vital Capacity and Tidal Volume
VC provides an indication of the patient’s ability to inspire deeply, maintain lung expansion and cough. It is particularly useful when assessing patients with respiratory inadequacy due to neuromuscular weakness. The VC depends on:
- the power of the respiratory muscles;
- the elastic properties of the chest wall and lung parenchyma;
- the size and patency of the airways at low lung volumes;
- the volume of the lungs, which varies with sex and body size.

There are many causes of a reduced VC (Table 6.1), all of which can, if severe, eventually lead to a fall in $V_T$, the latter being a less sensitive indicator of deterioration than the former. In respiratory failure minute ventilation (the product of $V_T$ and respiratory rate) rises initially and falls precipitously only at a late stage when the patient is exhausted.

The normal VC is 65–75 mL/kg and the normal $V_T$ is 7 mL/kg (about 500 mL). In general a $V_T < 5$ mL/kg or a VC < 15 mL/kg is indicative of serious respiratory difficulty.

#### Functional Residual Capacity
Functional residual capacity (FRC) can be measured using helium dilution, nitrogen washout or a body...
plethysmograph. These techniques are difficult or impossible in ventilated intensive care patients and are generally used only for research. FRC falls when:

- the abdomen is distended;
- there are painful thoracic or abdominal wounds;
- in the supine position;
- lung volume is reduced by pulmonary pathology.

**WRIGHT’S RESPIROMETER**

The $V_T$, minute volume and VC can be measured at the bedside using a Wright’s respirometer (Fig. 6.1). Access to the airway is required, but this is easily achieved in intubated patients by attaching the device to the catheter mount. In the spontaneously breathing, unintubated patient a mouthpiece can be used or a mask can be closely applied to the patient’s face. There is therefore inevitably some interference with the patient’s airway, which has the disadvantage of interrupting the oxygen supply, as well as potentially altering the respiratory pattern.

The Wright’s respirometer is a delicate instrument and is easily damaged if dropped. Because of the inertia of the vane and the resistance of the device, it under-reads at low flows. Conversely, at high flows, the momentum of the vane causes the instrument to overread. Accuracy is also affected by condensation of water vapour and, to a lesser extent, by alterations in the composition of respired gas. Nevertheless, in clinical practice errors are rarely greater than ±10%.

**PNEUMOTACHOGRAPH**

Whereas the Wright’s respirometer is a unidirectional device that only measures expired volumes, pneumotachographs record flows in both inspiration and expiration (Fig. 6.2). Flow rates are calculated from the measured pressure difference across the fixed resistance; inspired and expired volumes are obtained by integrating these flows.

One of the best known of the original designs is the Fleisch head, in which the resistance is formed by a piece of corrugated foil wound into a spiral. This creates a large number of parallel-sided tubes, which ensure laminar flow. Condensation of water vapour on the foil, which could alter its resistance and create turbulent flow, is prevented by surrounding the device with a heating coil. Mucus traps are also required to prevent obstruction. Although alterations in the composition and temperature of the gas mixture interfere with the measurement, when used carefully an accuracy of ±5% is possible.

Considerable care and attention to detail are required when using such devices and they have not proved suitable for routine clinical use. Alternatives have therefore been described. These have included the use of a heated wire mesh to provide the resistance (in which case, flow is turbulent and sophisticated electronics are required to produce a linear output), and light-weight devices with a variable orifice, which are unaffected by water vapour, allow tracheal secre-
tions to pass easily and are relatively insensitive to temperature changes.

**HOT WIRE ANEMOMETER**
Another approach to the measurement of inspired and expired volume is to place a heated wire through which a known current is passed in the gas stream. The magnitude of temperature changes, and hence alterations in resistance, reflect the gas flow rates.

**ULTRASONIC FLOWMETERS**
With these devices an ultrasonic signal is sent upstream and downstream. The time difference provides a measure of gas flow.

**VORTEX SPIROMETER**
The vortex spirometer generates vortices in the gas stream. These are detected and counted by an ultrasonic beam, the number of vortices being dependent on gas flow rate. These vortex spirometers are said to be accurate over a wide range of flows and are largely unaffected by gas composition, humidity or temperature.

**ASSESSING AIRWAYS OBSTRUCTION**
Clinical evaluation of the severity of airflow obstruction is notoriously inaccurate. The patient’s progress, and in particular response to treatment, can be assessed objectively by serial measurement of expiratory flow rates. These depend not only on the resistance of the intrathoracic airways, but also on lung elastic recoil; they are therefore greatest at high lung volumes (when airways resistance is least and elastic recoil maximal) and decrease progressively throughout expiration. Because increasing expiratory force leads to collapse of the distal airways, flow rates are largely independent of muscular effort. Expiratory flow rates are, however, reduced by extreme weakness. Improvement in expiratory flow rates following administration of bronchodilators distinguishes reversible from irreversible airways obstruction.

**TIMED MEASUREMENTS OF A FORCED VITAL CAPACITY**
Timed measurements of forced vital capacity (FVC) can be performed at the bedside using a **vitalograph** and provide an accurate, reproducible measure of airway calibre. The portion of the FVC exhaled in the first second is termed the **forced expiratory volume in one second (FEV)**, which is best expressed as a percentage of the FVC.

Normally the FEV is 50–60 mL/kg and represents 70–80% of the FVC. In those with airways obstruction the FEV is reduced to a greater extent than the FVC and the FEV/FVC ratio falls below 70%. In restrictive disorders, on the other hand, both FEV and FVC are reduced and the ratio is unchanged or increased.

**THE WRIGHT’S PEAK FLOW METER**
The Wright’s peak flow meter (Fig. 6.3a) is a cheap and convenient means of assessing airways obstruction at the bedside. Newer, relatively cheap, light-weight, hand-held devices which operate on a similar principle are now more commonly used (Fig. 6.3b). Peak expiratory flow rate (PEFR) is, however, relatively effort-dependent and is less reproducible than the FEV. Although it is useful for assessing the severity of airways obstruction and the response to treatment, it is not sufficiently specific to be diagnostic of airflow limitation. The normal PEFR is 450–700 L/min in adult males and 300–500 L/min in adult females. In severe airways obstruction, values as low as 60 L/min may be recorded.

**MAXIMUM MOUTH PRESSURES**
Maximum inspiratory and expiratory pressures can be measured at the mouth or via an endotracheal/tracheostomy tube using an aneroid manometer or a pressure transducer. They are useful indices of the power of the inspiratory and expiratory muscles respectively, although they do depend on patient cooperation.

- Maximum expiratory pressure is not often measured in intensive care patients.
Maximum inspiratory pressure (MIP) is usually measured during a maximum inspiratory effort against an occluded airway at residual volume or FRC.

The normal value for MIP varies with age and sex, exceeding −90 cm H₂O in young females and −130 cm H₂O in young males. Values less than −20 to −25 cm H₂O suggest that the patient is unlikely to be able to sustain adequate spontaneous ventilation (see Chapter 7).

FLOW–VOLUME AND PRESSURE–VOLUME LOOPS

Many modern mechanical ventilators continuously measure pressure, volume and flow and display the resultant waveforms. In general, pressure–volume (PV) relationships of the lung and chest wall can be used to assess changes in compliance, whereas flow–volume curves provide an indication of alterations in airways resistance.

Pressure–volume curves

During mechanical ventilation it is possible to determine the shape of the PV curve and, provided the patient is relaxed and flow during inspiration is constant, effective static compliance (Cₑ) (see Chapter 3) can then be calculated from:

\[ Cₑ = \frac{Vₑ}{Pₚₐₜ \ - \ PEEPₐ \ - \ PEEPᵢ} \]

where \( Vₑ \) is exhaled tidal volume, \( Pₚₐₜ \) is plateau airway pressure, PEEPₐ is applied positive end-expiratory pressure (PEEP) and PEEPᵢ is intrinsic PEEP.

Dynamic compliance (Cdyn) (see Chapter 3) is given by:

\[ C_{dyn} = \frac{Vₑ}{PIP \ - \ PEEPₐ \ - \ PEEPᵢ} \]

where PIP is peak inspiratory pressure.

The stiffness of the lung and chest wall can also be assessed by performing a series of small inflations (e.g. 200 mL) from a large (1.5 litre) calibrated syringe, each inflation being followed by a measurement of pressure when flow has ceased. The lung is deflated in similar steps and the pressure is again recorded at intervals (Fig. 6.4). The PV curve obtained in this way can be used to identify the pressure required to open collapsed lung units (the lower inflection point) and an upper inflection point, which in normal lungs corresponds to maximum lung volume (see Chapter 3). Compliance can be calculated from the linear portion of the PV slope. In acute respiratory distress syndrome (ARDS), for example, the first change is the appearance of a lower inflection point, indicative of alveolar collapse, whilst later the slope of the PV curve becomes less steep as compliance decreases and hysteresis (Fig. 6.4) increases. This technique does, however, require specialized equipment and the patient has to be disconnected from respiratory support, although it is possible to obtain a quasistatic PV curve using automated single-volume steps without the need for ventilator disconnection (Sydow et al., 1991).

Flow–volume curves

Flow–volume loops can be used to assess the effects of changes in airways resistance in cooperative subjects in a respiratory function laboratory (Fig. 6.5). In intubated patients flow–volume loops are not normally performed over the total lung volume range, forced manoeuvres are rarely performed and expiration is usually passive. Nevertheless, if the patient is relaxed the expiratory flow is reduced. FRC, functional residual capacity. Adapted from Webb et al., 1999 Oxford Textbook of Critical Care, Oxford Medical Publications with permission.
MEASURING THE WORK OF BREATHING

Measurement of the work of breathing requires simultaneous determination of the transpulmonary pressure change (i.e. airway pressure – intrapleural pressure) and $V_T$. Because an oesophageal balloon has to be inserted, the work of breathing is rarely measured in routine practice; a clinical estimate is usually considered to be adequate.

NON-INVASIVE MONITORING OF VENTILATION

There have been a number of attempts to develop a satisfactory method for continuously monitoring respiratory function that does not intrude on the airway. One example, which can be used in the spontaneously breathing patient, is the inductance plethysmograph (Tobin, 1992). The inductive elements are formed by two coils of insulated wire sewn on to bands placed around the ribcage and abdomen. Changes in thoracic and abdominal volumes alter the inductance of the coil. Provided the device is correctly calibrated, it can provide accurate measurements of respiratory timing and thoracic abdominal coordination, as well as a reasonably accurate assessment of changes in $V_T$ (Tobin, 1992). Changes in impedance detected by ECG electrodes can be used to continuously monitor respiratory rate.

When using such non-invasive devices, the most valuable information is obtained by analysing changes in the pattern of respiration (e.g. the increasing respiratory rate, the later reduction in $V_T$ and the loss of the normal breath-to-breath variation in $V_T$ which is seen during the onset of acute respiratory failure). The reverse trend may be seen during weaning from mechanical ventilation.

MONITORING INSPIRED AND EXPIRED GAS COMPOSITION

OXYGEN

Usually the inspired oxygen concentration ($F_{O_2}$), which is expressed as a decimal fraction of 1, is measured using either a polarographic or a fuel cell method. Determination of the expired oxygen fraction is less frequently required.

Fuel cells produce a voltage that is proportional to the partial pressure of oxygen ($P_{O_2}$) to which they are exposed. They are unaffected by water vapour, but have a slow response time and are relatively inaccurate. Furthermore, they are depleted by continued exposure to oxygen and this limits their lifespan.

Polarographic electrodes also have a slow response time, although this can be increased electronically to allow breath-by-breath analysis.

Paramagnetic analysers are extremely accurate, but require careful calibration. They are affected by water vapour and, again, the response time is slow. They are only suitable for the intermittent analysis of discrete samples of dried gas and consequently their use is generally confined to research.

Mass spectrometers are also very accurate and have the added advantages of a rapid response time and the ability to analyse multiple gas concentrations in the presence of water vapour. They are therefore well suited to the continuous analysis of both inspired and expired gas concentrations in ventilated patients, but are expensive, bulky and require considerable expertise during operation and maintenance. These difficulties have limited their introduction into clinical intensive care practice.
CARBON DIOXIDE

Traditionally, the fractional concentration of carbon dioxide in mixed expired gas (\(F_{\text{ICO}}\)) was determined by analysing a Douglas bag collection with an infrared carbon dioxide analyser. \(F_{\text{ICO}}\) has to be measured in order to determine \(V_{\text{e}}/V_{\text{T}}\) and the amount of carbon dioxide excreted per unit time (\(V_{\text{CO}_2}\)), as described in Chapter 3.

Capnography (Fig. 6.7)

Continuous breath-by-breath analysis of expired carbon dioxide, using either an infrared analyser or a mass spectrometer, also provides clinically useful information. The infrared absorption technique is inexpensive and simple to use. Expired gas is either sampled from a sidestream port and analysed by a remote sensor or the sensor is positioned in the mainstream of expired gas. The disadvantage of sidestream sampling is that the tubing may become occluded by mucus and water vapour. Mainstream sensors also have a faster response time.

Absence of a carbon dioxide waveform indicates misplacement of the tracheal tube, usually due to oesophageal intubation, or poor/absent pulmonary perfusion (e.g. cardiac arrest or massive pulmonary embolism). Variations in the carbon dioxide waveform can indicate:
- changes in the production or transport of carbon dioxide;
- alterations in lung function;
- apparatus malfunction;
- altered cardiac output when ventilation is constant.

Changes in the waveform are not, however, diagnostic and other clinical observations are usually required to determine the underlying cause.

The end-tidal carbon dioxide tension (\(P_{\text{ICO}}\)) can be considered to reflect the partial pressure of alveolar carbon dioxide (\(P_{\text{ICO}}\)) and therefore the partial pressure of arterial carbon dioxide (\(P_{\text{ICO}}\)). \(P_{\text{ICO}}\) can therefore be used as an immediate guide to the patient's ventilation requirements, bearing in mind the normal gradient between alveolar and arterial carbon dioxide tensions. The discrepancy between \(P_{\text{ICO}}\) and \(P_{\text{ICO}}\) does, however, increase as lung function deteriorates and changes in \(P_{\text{ICO}}\) may also be caused by alterations in the distribution of ventilation or in the ventilatory pattern. It has been suggested that capnography may be a useful non-invasive means of assessing alveolar ventilation during weaning from mechanical ventilation (Saura et al., 1996).

MEASUREMENT OF RESPIRATORY GAS EXCHANGE

Direct measurements of oxygen consumption (\(\dot{V}_{\text{O}_2}\)) and \(\dot{V}_{\text{CO}_2}\) by analysing respiratory gases can be used to estimate energy expenditure and to calculate alveolar/dead-space ventilation and cardiac output by the Fick principle (see Chapters 3 and 4). Determination of respiratory \(\dot{V}_{\text{O}_2}\) may also be indicated when evaluating the relationship between oxygen supply and demand (see Chapter 5).

Traditionally \(\dot{V}_{\text{O}_2}\) has been determined by collecting expired gas in a Douglas bag over a timed period. The volume of gas in the bag can be measured most accurately using a wet gas meter. \(F_{\text{ICO}}\) and \(F_{\text{ICO}}\) are determined using one of the methods already described (e.g. a paramagnetic analyser). If the subject is breathing air, \(F_{\text{ICO}}\) is, of course, known to be 20.98% and need not be measured. Often, the inspired volume is not measured directly, but is derived using a standard formula. \(\dot{V}_{\text{O}_2}\) is then calculated from:

\[
\dot{V}_{\text{O}_2} = (V_{\text{T}} \times F_{\text{ICO}}) - (V_{\text{e}} \times F_{\text{ICO}})
\]

This technique is, however, relatively complicated and time-consuming and the principle on which the method is based only applies under steady-state conditions, when respiratory
References pp 139 - 144


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