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 (Ceo) (see Chapter 3) can then be calculated from:

\[ C_{eo} = \frac{V_t}{P_{plat} \downarrow - PEEP_o} \]

where \( V_t \) is exhaled tidal volume, \( P_{plat} \uparrow \) is plateau airway pressure, PEEP_o is applied positive end-expiratory pressure (PEEP) and PEEP_o is intrinsic PEEP.

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

\[ C_{dyn} = \frac{V_t}{PIP \downarrow - PEEP_o} \]

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 loops

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 exhalation is usually passive. Nevertheless, if the patient is relaxed the expiratory flow–volume loop can demonstrate bronchodilatation and reductions in auto-PEEP (see Chapter 8). The level of external PEEP required to overcome intrinsic PEEP, without worsening hyperinflation, can be assessed by ensuring that the flow–volume loop is not shifted along the volume axis.

Airway resistance (\( R_{aw} \)) can be calculated from:

\[ R_{aw} = \frac{PIP - P_{plat}}{\text{peak flow}} \]
Assessment and monitoring of respiratory function

Flow–volume loops can also be useful in the assessment of the site of the lesion in patients with upper-airways obstruction (Fig. 6.6).

### 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 ($F_iO_2$), 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.