Abstract
General paediatricians will encounter myriad respiratory abnormalities during their careers. A basic knowledge of essential respiratory physiology, its subsequent derangements due to disease states and how to assess these abnormalities will help in the proper care of children. This paper will begin with an overview of normal respiratory physiology and how to monitor the efficiency of gas exchange. It will also discuss common methods of non-invasive monitoring including pulse oximetry, carbon dioxide monitoring, pulmonary function tests and respiratory impedance plethysmography. Finally, paediatric disease states will be used to illuminate the intersection between pathophysiology, clinical symptoms and monitoring capabilities.

Keywords lung volume measurements; oximetry; paediatrics; plethysmography; pulmonary ventilation; respiratory function tests

Introduction
Bearing in mind the diversity and prevalence of respiratory illnesses in children, paediatricians should understand the basics of respiratory physiology and how to monitor respiratory function. This discussion will review normal respiratory physiology and explore non-invasive forms of respiratory monitoring. With this foundation, the paediatrician can accurately diagnose and assess the severity of illness.

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Brief overview of normal respiratory physiology

Muscles of respiration
The most important and powerful muscle during the inspiratory phase of respiration is the diaphragm, a dome-shaped musculofibrous septum that separates the thorax from the abdominal cavity. When the diaphragm contracts, abdominal contents move downward and the lung expands in the vertical and horizontal planes. During normal tidal breathing the diaphragm moves approximately 1 cm, but with forced inspiration and exhalation, it can move up to 10 cm.

During inspiration, external intercostal muscles elevate and move the ribs forward. This increases the lateral and anteroposterior diameters of the thoracic cavity. The two most common accessory muscles of inspiration are the sternocleidomastoid and scalenes. The sternocleidomastoid raises the sternum while scalenes elevate the first two ribs. During normal respiration these muscles do not participate in inspiration, but during exercise or in pathological processes they can play an important role in maintaining normal alveolar ventilation.

While expiration is normally passive due to the elastic properties of the lungs and chest wall, both exercise and certain pathophysiological conditions invoke both the internal intercostal and abdominal muscles including the internal and external obliques, the transversus abdominis and the rectus abdominis. These muscles work to decrease the thoracic volume and assist in forcing air from the lungs.

Both the lungs and chest wall are elastic, and each component has a natural propensity; the lung to collapse inward and the chest wall to ‘spring’ outward. The equilibrium point of lung volume where these forces are balanced is the functional residual capacity (FRC).

Lung volumes and capacities
The various lung volumes and capacities can be measured during different phases of the respiratory cycle and change under different pathophysiological conditions. Spirometry is used to record the volume of air moved during respiration.

The are four lung volumes which, when added together, equal the total lung capacity (TLC) (Figure 1):

- tidal volume (VT) – volume of air inspired or expired during a normal breath
- inspiratory reserve volume (IRV) – the additional volume of air that can be inspired in addition to a tidal breath
- expiratory reserve volume (ERV) – the additional volume of air that can be expired after the end of a tidal breath
- residual volume (RV) – volume of air remaining after the most forceful expiration.

In evaluating a patient’s clinical status and understanding pathophysiology, it is sometimes advantageous to consider two or more lung volumes together as capacities. The four lung capacities (Figure 1) are:

- inspiratory capacity (IC) – equals tidal volume plus inspiratory reserve volume
- functional residual capacity (FRC) – equals expiratory reserve volume plus residual volume, or the volume of air remaining at the end of a normal expiratory breath
- vital capacity (VC) – equals inspiratory reserve volume plus tidal volume plus expiratory reserve volume
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• total lung capacity (TLC) – equals vital capacity plus residual volume. Note that since by definition residual volume cannot be exhaled from the lungs, it cannot be measured by spirometry. FRC and TLC also cannot be measured by spirometry alone but instead are measured by gas-dilution techniques or plethysmography.

Gas exchange
The primary purpose of the respiratory system is gas exchange to maintain cellular homeostasis. The two principal components are delivery of oxygen and removal of carbon dioxide.

Oxygenation
The respiratory system helps to extract oxygen from the atmosphere and deliver it to mitochondria. The partial pressure of oxygen in the alveolus ($P_{A}O_2$) is a primary determinant of arterial oxygen tension ($P_AO_2$).

$$P_{A}O_2 = [(P_b - P_{ho}) \times F_{O_2}] - P_{A}CO_2 / RQ$$

where $P_b$ is barometric pressure, $P_{ho}$ is the partial pressure of water vapour and $F_{O_2}$ is the fraction of inspired oxygen. $P_{A}CO_2$ is the partial pressure of carbon dioxide in the alveolus and RQ is the respiratory quotient. For most purposes RQ is assumed to be 0.8.

Substituting normal values for an individual breathing room air at sea level, the $P_{A}O_2$ is approximately 100 mmHg. As oxygen crosses the alveolar membrane into the pulmonary capillary network a negligible amount of oxygen tension is lost (around 10 mmHg). Thus, the $P_{A}O_2$ of a normal individual is approximately 90 mmHg. By examining the alveolar gas equation closely, one can see that three conditions can cause a decrease in $P_{A}O_2$: altitude (low $P_b$), hypoxic gas mixture (low $F_{O_2}$) and hypoventilation (high $P_{A}CO_2$). The most common aetiology of hypoxaemia is neither altitude nor hypoventilation, however, but a disturbance in the number of alveoli participating in matched ventilation/perfusion ($V'Q'$). With either compromised ventilation with adequate perfusion (shunt) or adequate ventilation with compromised perfusion (dead space), oxygen residing in the alveolus cannot move into the pulmonary capillary network and hypoxaemia will ensue. A wide variety of clinical conditions can cause derangements in $V'Q'$, and interventions such as continuous positive airway pressure (CPAP), biphasic positive airway pressure (BiPAP) or endotracheal intubation with mechanical ventilation correct hypoxaemia by restoring normal lung volumes, assisting cardiac function and improving the $V'Q'$ relationship.

Ventilation
The respiratory system also eliminates carbon dioxide from the blood through the alveolus. Arterial carbon dioxide tension ($P_{A}CO_2$) is directly proportional to minute ventilation ($V_T$) where:

$$V_T = \text{respiratory rate} \times \text{tidal volume}$$

$$V_T = FV_T$$

It is worth noting that $V_T$ comprises dead-space volume ($V_D$) and alveolar volume ($V_A$).

Dead-space volume is the portion of the tidal breath that does not participate in gas exchange with pulmonary capillaries. Dead space comprises anatomical dead space and non-anatomical dead space. Anatomical dead space is found within the conducting airways – nose, mouth, oropharynx, trachea, bronchi and bronchioles – and accounts for approximately 20–30% of a tidal breath, although it is relatively larger in infants. Non-anatomical dead space approaches zero in healthy individuals, as most lung units are equivalently ventilated and perfused. In infants and children with respiratory disease, however, total dead space may approach 60–70% of a tidal breath.

In contrast, alveolar volume is the portion of inspired breath that arrives at the alveoli and participates in gas exchange with pulmonary capillaries. Therefore, it is more accurate to state that $P_{A}CO_2$ is proportional to alveolar minute ventilation ($MV_A$):

$$MV_A = f(V_T - V_D)$$

Hence, an elevated $P_{A}CO_2$ can arise from a decrease in respiratory rate, a decrease in tidal volume, or an increase in dead space.

Methods of assessing respiratory function in non-intubated patients
Pulse oximetry
Cyanosis is the hallmark clinical sign of hypoxaemia, but it can only be recognized confidently when the oxygen saturation is below 75% and cannot be recognized if the haematocrit is less than 15%. Pulse oximetry allows for non-invasive and continuous monitoring of arterial oxygen saturation ($S_{O_2}$). The basic principles of pulse oximetry are that oxygenated haemoglobin (HbO$_2$) absorbs mostly infrared light while deoxygenated haemoglobin (Hb) absorbs mostly red light. Pulse oximeters exploit the pulsatile nature of arterial blood and successfully ‘ignore’ the
infrared light, leading to a falsely lowered SpO2 that generally results in respiratory failure. It is physiologically impossible for end-tidal CO₂ monitors to read greater than PₐCO₂, so any elevated value should be taken seriously and further investigated by obtaining an arterial blood gas.

**Nasal cannula end-tidal CO₂ detection:** an easy and non-invasive way of measuring end-tidal CO₂ in spontaneously breathing, non-intubated patients, is by using divided nasal cannulas that simultaneously deliver oxygen via one prong and sample exhaled gas through the other. Studies have shown that the end-tidal CO₂ correlates highly with PₐCO₂. Such monitoring is useful for procedural sedation or to monitor children at risk for impending respiratory failure. It is physiologically impossible for end-tidal CO₂ monitors to read greater than PₐCO₂, so any elevated value should be taken seriously and further investigated by obtaining an arterial blood gas.

**Pulmonary function tests**
In addition to measuring lung volumes and capacities, spirometry can be utilized with a forced expiratory manoeuvre that can help clinicians determine mechanical disorders of the respiratory tract, quantify the degree of disorder and classify it as obstructive, restrictive or mixed in aetiology. Using a variety of techniques, these can be done on even uncooperative (albeit sometimes sedated) infants and young children.

**Forced expiratory volume:** as discussed earlier, vital capacity (VC) is the lung volume that can be exhaled after a full inspiration. In contrast, forced vital capacity (FVC) is the lung volume that can be exhaled after a full inspiration as quickly and forcibly as possible, and is highly reproducible. When compared to forced expiratory volume (FEV₁), which by convention is the amount of gas forcibly exhaled in one second, one can quickly classify the nature of respiratory disease. In cooperative children over the age of 5 years the FEV₁/FVC ratio is normally 0.8; values less than 0.8 represent obstructive lung disease, whereas restrictive diseases have proportional decreases in FEV₁ and FVC, preserving the ratio of 0.8. Forced expiratory volumes provide an objective standard to monitor response to treatment or clinical improvement.

**Flow–volume curves:** by plotting expiratory and inspiratory flows against lung volume instead of time, the clinician can obtain more information about underlying lung or airway dysfunction. Unfortunately, forced expiratory spirometry provides information solely about expiratory dysfunction. Flow–volume curves, on the other hand, can reveal both inspiratory and expiratory dysfunction and aid in the classification of the disease as obstructive or restrictive.

**Respiratory inductance plethysmography**
The inspiratory cycle begins as the diaphragm moves downward. The abdomen and rib cage then expand in concert, known as thoraco-abdominal synchrony. However, various respiratory conditions will alter the timing of these events, resulting in thoraco-abdominal asynchrony (TAA). The asynchrony can be quantified using respiratory inductance plethysmography, and the degree of asynchrony correlates well with the amount of respiratory dysfunction.

Two elastic belts into which a wire is sewn are worn around the chest and abdomen. A current is passed through the belts, generating a magnetic field. The act of breathing changes the cross-sectional area of the abdomen (ABD) and the rib cage (RC). Altering the shape of the magnetic field generated by the belts and inducing a measurable opposing current, a computer analyses the current produced and generates (1) the phase angle, which is the degree of synchrony of the ABD and RC and (2) the directional loop.

For infants and children, the phase angle is typically less than 22° and the directional loop is anticlockwise. As the asynchrony worsens, the phase angle gets larger, although maintaining the anticlockwise direction. With complete asynchrony, the phase angle is 180°. In the case of bilateral diaphragmatic paralysis, the directional loop becomes clockwise (Figure 2). In unilateral paralysis, a ‘figure 8’ is created, and no phase angle can be measured. The clinical correlate is known as Hoover’s sign, which is the paradoxical inward movement of the lower lateral rib cage during inspiration or in the neonate an abnormal movement of the umbilicus to the contralateral side.
Pressure–rate product
A small water- or air-filled catheter of similar size to a nasogastric feeding tube can be inserted with its tip in the mid-oesophagus to measure, relatively non-invasively, both the peak-to-trough swings in oesophageal pressure with respiration, and the respiratory rate. The product of the two is called the pressure–rate product and is an excellent surrogate for work of breathing measurements.

Case studies
Obstructive airways disease
The primary pathological defect in obstructive airways disease is airflow limitation. This limitation can occur during expiration, inspiration or both. Both large airways obstruction (croup, epiglottitis, foreign-body aspiration, laryngomalacia, tracheomalacia) and medium (asthma) and small (bronchiolitis) airways obstruction have hallmark findings on physical examination and in the tests discussed above. Knowledge of these patterns assists the physician to localize the obstruction, determine disease severity, monitor disease progression and determine treatment.

Extrathoracic obstructions can be clearly differentiated from intrathoracic obstructions based on characteristic patterns in flow–volume curves. The primary abnormality of an extrathoracic obstruction is with inspiratory flow. There is a flattening of the inspiratory flow limb with a fairly normal expiratory flow pattern. Intrathoracic obstructions can be subdivided into variable or fixed lesions. A variable lesion such as intrathoracic tracheomalacia will have abnormalities with expiratory flow and produce a flattening of the expiratory limb, while the inspiratory limb will appear normal. Fixed lesions such as foreign-body aspiration, external compression from extratracheal masses or tracheal stenosis have inspiratory and expiratory flow limitation manifested as a flattening of both the inspiratory and expiratory limbs of the flow–volume curve (Figure 3).

Croup

Physical examination – the major abnormality in croup (an extrathoracic obstruction) is inspiratory airflow limitation. Airflow is generated by lowering intrathoracic and intratracheal pressures below extrathoracic atmospheric pressure. According to Poiseuille’s law, the change in pressure is inversely proportional to the fourth power of the radius of the airway. Therefore, decreasing a child’s airway radius from 5 mm to 2.5 mm leads to a 16-fold increase in the pressure for airflow. To accomplish this, children will increase their work of breathing by using accessory muscles (i.e. supraclavicular retractions). Moreover, children’s subglottic submucosa is non-fibrous, and the mucous membrane is attached more loosely than in adults, allowing for oedema to accumulate more easily. The soft supporting cartilage of the larynx and the narrow radius of the child’s airway also allow for dynamic collapse of airways during inspiration. This manifests clinically with the classic inspiratory stridor that often accompanies viral croup.
Pulsus paradoxus – as intrathoracic pressure becomes more negative, afterload on the left ventricle increases and cardiac output decreases. Since the pulse oximeter waveform amplitude is proportional to arterial blood volume, there is a decrease in amplitude during inspiration known as pulsus paradoxus (Figure 4). The magnitude of depression during inspiration has been consistently correlated with the severity of extrathoracic airway obstruction and can be used to monitor disease progression or resolution.

Flow and pressure curve against time – the limitation of inspiratory airflow can be visualized when flow and pressure are simultaneously plotted against time (Figure 5).

Respiratory inductance plethysmography – phase angles increase significantly in viral croup and continuous phase-angle monitoring can demonstrate clinical improvement as resolution of the obstruction correlates with decreasing phase angles and improving pulmonary function.

Pressure–rate product – this value increases significantly in croup and can be used continuously to follow response to therapy.

Asthma

Physical examination – the major abnormality in asthma is expiratory airflow limitation. Underlying airway hypersensitivity causes reversible narrowing and an increase in airways resistance up to 500% of normal values. This increased resistance causes distal air trapping, ultimately leading to elevated end-expiratory lung volumes and a prolonged expiratory phase with wheezing. On visual inspection, patients with poorly controlled asthma often have a barrel-chest deformity due to the chronically...
With relatively high flows.

During expiration, very modest increases in pressure are associated with oesophageal pressure to its minimum but modest negative value (open arrow). No further increase in inspiratory flow despite a large increase in negative pressure. During expiration, there is also evidence of flow limitation, with oesophageal pressure higher and flows lower than those seen in the patient after epinephrine inhalation. Lower panel: after epinephrine. From the beginning of inspiration, flow increases markedly up to the point marked by the solid arrow as pressure decreases. Thereafter, there is a further small decline in oesophageal pressure to its minimum but modest negative value (open arrow). During expiration, very modest increases in pressure are associated with relatively high flows.

Elevated end-expiratory lung volumes. During an acute asthma exacerbation, children will breathe at a lower respiratory rate than normal to minimize work of breathing and will commonly have pursed lip breathing. The increased resistance prevents the dynamic collapse of the airways on expiration. As the airway resistance increases further and initial compensatory mechanisms fail, patients will become tachypnoeic and use accessory muscles to generate more negative inspiratory pressure to overcome the increased elastic recoil of the lungs and chest wall from hyperinflation and increased lung volumes. Eventually, life-threatening respiratory muscle fatigue leads to hypoventilation, hypercarbia and hypoxaemia.

**Pulsus paradoxus** – the elevated airways resistance raises intrathoracic pressure and, much as in croup, causes a transient decrease in cardiac output during inspiration. The consequential pulsus paradoxus correlates with the severity of the asthma exacerbation.

**Forced expiratory spirometry and flow-volume curves** – spirometry represents the most accessible way to gauge the severity of obstruction and monitor the effects of therapy. The measured \( \text{FEV}_1/\text{FVC} \) is less than 0.8 since the reduction in air-flow (\( \text{FEV}_1 \)) is greater than the reduction in lung volume (\( \text{FVC} \)), with the degree of reduction correlating with disease severity. The expiratory limitation is readily visible on flow–volume curves as reduced peak expiratory flow and a characteristic concave appearance on the expiratory limb. Note the change in shape in the expiratory limb after bronchodilator therapy from concave to straight, the increase in peak expired flow and \( \text{FEV}_1 \) (Figure 6).

**Restrictive lung disease**

Whereas obstructive airways diseases are rooted in airflow limitation, the hallmark of restrictive lung disease is decreased TLC. The aetiologies are diverse – increased elastic recoil (interstitial inflammation/fibrosis), decreased outward recoil of the chest wall (scoliosis), respiratory muscle weakness (spinal muscular atrophy), alveolar destruction (pneumonia), thoracic space-occupying lesions (tumour, blood, air, effusion, cysts), significant abdominal distension (acute abdomen, intra-abdominal masses) – but the consequences are the same: decreased TLC with preservation of normal airflow.

**Scoliosis**

**Physical examination** – deformities of the thoracic cage in scoliosis lead to decreased lung capacities. In fact, the degree of restrictive pulmonary disease is clearly correlated with the severity of scoliosis, and those with severe thoracic cage deformities are prone to more rapid decompensation when afflicted with respiratory infections. Initial attempts at compensation prompt patients to breathe with faster respiratory rates and deeper than normal airflow.

**Figure 5** Flow–pressure curve for a child with croup. Flow and pressure curves plotted against time. Top panel: before epinephrine – traces demonstrating inspiratory flow limitation. During initial inspiration there is a positive increase in inspiratory flow associated with a change in oesophageal pressure (left of solid arrow). To the right of the solid arrow, until inspiratory effort decreases (open arrow), there is virtually no further increase in inspiratory flow despite a large increase in negative pressure. During expiration, there is also evidence of flow limitation, with oesophageal pressure higher and flows lower than those seen in the patient after epinephrine inhalation. Lower panel: after epinephrine. From the beginning of inspiration, flow increases markedly up to the point marked by the solid arrow as pressure decreases. Thereafter, there is a further small decline in oesophageal pressure to its minimum but modest negative value (open arrow). During expiration, very modest increases in pressure are associated with relatively high flows.

**Figure 6** Flow–volume curve for a child with asthma. The expiratory limitation is readily visible on flow–volume curves as reduced peak expiratory flow and a characteristic concave appearance on the expiratory limb. Note the change in shape in the expiratory limb after bronchodilator therapy from concave to straight, the increase in peak expired flow and \( \text{FEV}_1 \).
their normal tidal volume. As they begin to fatigue, baseline end-expiratory lung volumes decrease. Alveolar collapse, worsening V/Q mismatch and hypoxia soon follow.

**Forced expiratory spirometry and flow-volume curves** – given the insidious nature of scoliotic deformities, measurement of lung volumes and capacities is an effective way to gauge the resulting decline in pulmonary function over time. It has been shown that postoperative pulmonary complications increase with deterioration in pulmonary function tests. Since restrictive diseases produce a proportional reduction in airflow and lung volume, the FEV1/FVC remains unchanged or even slightly greater than normal. However, the lung volumes obtained will be lower than predicted.

**Neuromuscular disorder (e.g. spinal muscular atrophy, infant botulism)**

**Physical examination** – most children with neuromuscular disorders do not exhibit prominent respiratory symptoms. Similarly to patients with scoliosis, their respiratory abnormalities usually become apparent when they are affected by an infection of the respiratory tract. Unlike patients with scoliosis, however, their restrictive lung disease is further complicated by underlying muscular weakness. If disease progression is severe enough, they will manifest other signs on physical exam unique to neuromuscular disorders. The diaphragm is initially seemingly ‘spared’ compared with the weaker intercostal muscles and children will use their accessory muscles to breathe at higher respiratory rates than normal individuals to minimize work of breathing. Eventually this will progress to paradoxical breathing, usually apparent clinically and on respiratory inductance plethysmography.

**Respiratory inductance plethysmography** – patients with spinal muscular atrophy will often progress to complete thoracoabdominal asynchrony. The rib cage is neither stabilized nor expanded during inspiration and the resulting negative intrathoracic pressure causes the rib cage to collapse. The phase angle will be above normal or up to 180° and the directional loop anticlockwise (Figure 2).

**Conclusion**

There is a wide array of non-invasive tools available to the paediatrician for diagnosis and management of various respiratory diseases. With a basic knowledge of respiratory physiology and how pathophysiological states can be monitored, the clinician can optimize therapeutic interventions and readily track disease progression.

**FURTHER READING**


**Practice points**

- Pulse oximetry, TCOMs and nasal cannula end-tidal CO\(_2\) devices are easy and reliable ways to monitor gas exchange
- Characteristic changes in pulmonary function assist in classifying underlying respiratory dysfunction
- Ongoing use of pulmonary function tests allow for monitoring of disease progression and efficacy of treatment