Clinical measurement of end-expiratory lung volume on the intensive care unit

End-expiratory lung volume (EELV) is the volume of gas remaining in the lungs at the end of a normal expiration. It represents the relaxation volume when the recoil pressure of the lung is opposite and equal to the chest wall recoil pressure. End-expiratory lung volume and functional residual capacity (FRC) are definitions of the same subdivision of lung volume. EELV measurement is important in the management of patients requiring mechanical ventilation for acute lung injury (ALI) and acute respiratory distress syndrome (ARDS).

The normal EELV of about 3–4 litres is reduced in ARDS to less than 1 litre and in ALI to 1.5 litres. In contrast, patients with chronic obstructive pulmonary disease (COPD) often have an increased EELV. Furthermore, ventilator setting can increase EELV by application of external positive end-expiratory pressure (PEEP). PEEP improves arterial oxygenation by alveolar recruitment and is thereby associated with an increase in EELV. Therefore, the use of PEEP is considered part of the standard therapy for patients with ALI requiring mechanical ventilation. Additionally, intrinsic PEEP using inverse ratio ventilation increases EELV. Therefore, the ability to assess and monitor EELV accurately is essential in the management of patients requiring mechanical ventilation. The results assist in diagnosis, optimise mechanical ventilatory support, and predict the likelihood of weaning success from the respirator.

This review describes different techniques for EELV measurement, including advantages, disadvantages and possible bedside use of these techniques on the intensive care unit (ICU). Recently it became obvious that recruitment of lung volume is a phenomenon that occurs in different regions of the lungs. Therefore, a special focus of this review is on those techniques that take into account regional measurements.

DEFINITION OF LUNG VOLUMES

The gas volume inside the lung is considered in different subdivisions. The definitions of lung volumes in normal breathing and during specific manoeuvres, such as forced inspiration and forced expiration, are shown in Figure 1.

Tidal volume (VT) is the gas volume during normal inspiration and expiration. In adults it is about 700 ml (10 ml/kg). Expiratory reserve volume (ERV) is the gas volume additionally exhaled during forced expiration and inspiratory reserve volume (IRV) is that after a forced inspiration. The sum of VT and IRV is the inspiratory capacity (IC).

Even after a maximum expiratory effort, some air is left in the lung; no lung region normally collapses. This persisting gas volume is called residual volume (RV) and amounts to 2–2.5 litres in adults. Expiration stops at residual volume for two reasons: distal airways of diameter ≤ 2 mm will close before the alveoli collapse; the chest wall, rib cage and diaphragm cannot be distorted to the point where all gas in the lung has been exhaled.

The EELV – the gas volume remaining in the lungs after an ordinary expiration – amounts to about 3–4 litres, depending on sex, age, height, and weight. The existence of this persisting gas volume prevents collapse of the alveoli and ensures that the variation of gas concentration inside the alveoli is minimised.

The gas volume in the lung after a maximum inspiration is called the total lung capacity (TLC). In adults, typically, it is 6–8 litres. The volume expired after a maximal inspiration is called the vital capacity (VC) and is therefore equal to the difference between TLC and RV.

TECHNIQUES OF MEASURING LUNG VOLUME

The different lung volumes, including the EELV, can be estimated by various methods: spirometry, functional residual capacity (FRC) measurement, gas dilution, and computerised tomography. EELV measurement is important in the management of patients requiring mechanical ventilation for acute lung injury (ALI) and acute respiratory distress syndrome (ARDS).

This review describes different techniques for EELV measurement, including advantages, disadvantages and possible bedside use of these techniques on the intensive care unit (ICU). Recently it became obvious that recruitment of lung volume is a phenomenon that occurs in different regions of the lungs. Therefore, a special focus of this review is on those techniques that take into account regional measurements.

Figure 1. Definitions of lung volumes in normal breathing and during specific manoeuvres such as forced inspiration and forced expiration. For abbreviations see text.
try and radiographic techniques (i.e. chest radiographs or computed tomography of the thorax); gas dilution techniques; body plethysmography; respiratory inductive plethysmography; and electrical impedance tomography. The requirements of a technique for lung volume measurement on the ICU are: user-friendly equipment, accuracy of the technique, no radiation exposure to the patient and the capacity for bedside use.

**Spirometry**

Spirometry, introduced by Hutchinson,16 measures lung volume during either normal or forced breathing. The classic water spirometer has been replaced by a ‘dry’ spirometer introduced by Fleisch,17 based on the measurement of gas flow through a pneumotachograph. Gas flow is derived from pressure drop over a fixed resistance, which consists of a bundle of parallel capillary tubes or a metal screen. Following the Hagen–Poiseuille’s-law, it is proportional to the pressure drop over the resistance. Volumes are calculated by flow integration over time. Spirometers should be designed to meet the European Thoracic Societies accepted standards.15

Spirometry is the standard method for measuring VT and VC at the bedside. However, measurement of RV, TLC and EELV, which are not exhaled, is not possible by spirometry. Thus, a different approach to measurement is required for these quantities. Furthermore, the expiratory phase of a spirometry measurement is used to measure obstruction within the lungs. The problem of this method in the intensive care environment is that it requires a co-operative and motivated patient for accurate results. Such conditions, especially in mechanically ventilated patients, are unlikely to be met in the ICU.

**Body plethysmography**

Lung volume is measured by the application of Boyle’s law, which states that, under isothermal conditions, when gas in a closed container is compressed, its volume decreases, while the pressure inside the container increases. Therefore the product of volume and pressure, at any given moment, is constant. There are two types of body plethysmographs: variable volume and constant volume. In the variable volume plethysmograph, a change in lung volume is measured directly by a spirometer or pneumotachograph.18 In the constant body plethysmograph, a change in lung volume is measured as a change in box pressure.

For the measurement procedure, the patient sits inside an airtight chamber equipped to measure pressure, gas flow, or volume changes, and inhales or exhales to a particular volume (usually end-expiratory lung volume). After a shutter drops across the breathing tube, the patient makes respiratory efforts against the closed shutter, causing the chest volume to expand and decompressing the air in the lungs. The increase in the chest volume slightly reduces the box volume and thus slightly increases the pressure in the box. The most common measurements taken using the body plethysmograph are thoracic gas volume and airway resistance.

The advantages of plethysmography are that recording of lung volume takes only a few breaths and can be repeated very quickly between each measurement. The technique shows a high degree of precision indicated by a coefficient of variation of about 5% during repeated measurements.19 The disadvantages of this technique are that the equipment is expensive and requires careful maintenance. Note also that body plethysmography measures the total lung volume including that volume trapped behind closed airways. Therefore, it may deliver different lung volume results compared with data from other measurement techniques. This technique is practicable in spontaneously breathing, co-operative and motivated patients. Although it has been effective in anaesthetised patients, using a specially designed body plethysmograph that allows the patient to be in a supine position,20,21 it is difficult to use with critically ill patients in the intensive care setting and impossible in mechanically ventilated patients. Up to now, no commercially produced body plethysmograph is available for measurement in the supine position.

**Gas dilution techniques**

Any gas that is nontoxic and poorly soluble in blood and tissue (e.g. helium, xenon, sulphur hexafluoride (SF₆), nitrogen) can be used as tracer gas for measurement of EELV. This technique is either based on rebreathing the tracer gas in a closed circuit, or the wash-in/wash-out of the tracer gas is analysed in a multiple breath procedure. Additionally, information about regional lung volumes and regional ventilation can be derived from mathematical compartmental analysis of tracer wash-out curves.22 A major criticism of this approach to assessment of regional ventilation is that the measurement is not direct and the calculation of regional ventilation depends on assumptions about ideal tracer wash-out curves.

Nitrogen is most frequently used as the tracer gas in multiple breath wash-out investigations. An open circuit multibreath nitrogen wash-out manoeuvre was first described by Darling et al.23 and modified later.24,25 The multiple breath nitrogen wash-out technique measures EELV with a high level of accuracy.24 The necessary change in nitrogen concentration during the wash-in/wash-out means that oxygen fraction is altered, so that the patient cannot be continuously ventilated with the preselected inspired oxygen fraction. This is a limitation in severe hypoxaemia. The tracer gas sulphur hexafluoride (SF₆) provides a solution to this problem by allowing EELV measurements to be taken without interference with the inspired oxygen fraction.26,27

To overcome the problem of wash-in/wash-out
tracer gas techniques needing a fast and sensitive gas analyser to allow breath-by-breath measurements of tracer gas, a technique has been proposed that requires only those analysers frequently used in an ICU. Presuming that air consists mainly of nitrogen, oxygen and carbon dioxide, the tracer gas nitrogen is calculated by deduction from the measurements of oxygen and carbon dioxide concentrations. An alternative proposal is a system that collects the expired gas over a number of breaths in a large bag or spirometer and records the mixed expired gas concentration together with expired volume. This solution requires bulky equipment and is difficult in the ICU.

A simple helium dilution technique, which utilises a short period of rebreathing six breaths from a 1-litre bag, produces consistent estimates of EELV in those patients suffering from ALI. Xenon has anaesthetic properties, which limit its use in awake patients. During mechanical ventilation, xenon can be used as an interesting research tool. When combined with a computed tomogram (CT) study it allows the calculation of both total and regional lung volume.

Rebreathing techniques require a gas-tight circuit system including the ventilator in order to reach an equilibrium of the tracer gas concentration. This may be hard to achieve in intubated patients. Wash-in/wash-out procedures are less demanding in this respect, but require as much equipment and effort as rebreathing techniques. Gas dilution techniques, whether based on rebreathing or wash-in/wash-out, have the inherent limitation that they can only measure the lung volume that participates in ventilation. Completely closed lung regions behind collapsed airways or mucus plugs will not be detected. Poorly ventilated regions with very long wash-in/wash-out times may also be disregarded. However, ALI appears to be associated more with lung collapse and no ventilation at all than with obstructed airways causing poor ventilation of lung regions. Thus, gas dilution techniques may be reasonably accurate for assessing EELV in patients with ALI. Unfortunately, no commercial gas dilution techniques are available for bedside measurement on the ICU.

**Chest radiography and computed tomogram**

Chest radiography shows frontal and lateral views of the lungs. It gives qualitative information about aeration, in case of atelectasis or hyperinflation, but does not allow any quantitative analysis of the EELV. With repeated transverse CT or spiral CT of the chest, EELV can be quantified from a three-dimensional reconstruction of CT slices. This method enables total and regional volume calculation. Furthermore, information on alveolar recruitment can be obtained from CT scanning. Unfortunately, CT is not a bedside method and it is associated with radiation exposure.

**Respiratory inductive plethysmography**

Respiratory inductive plethysmography (RIP) measures chest and abdomen movement (Respiritrace Plus, NIMS Inc., Miami, USA). It consists of a pair of insulated coils strapped over the upper abdomen and chest. The change of cross-sectional area of the coil caused by chest and abdominal wall displacement modifies the inductance of the coils proportional to tidal volume and lung volume. For calibration of RIP, a simultaneous recording of lung volume by spirometry is necessary. The calibration should be repeated every time that body posture is even slightly changed. RIP is a non-invasive technique which can be used at the bedside on the ICU in mechanically ventilated patients.

Unfortunately, Neumann et al. found a high and unstable baseline drift of 25.4–29.1 ml/min of the RIP signal from the Respiritrace Plus monitor. Although other authors found lower baseline drifts of 1 ml/min, they concluded that these high drifts raise doubts about this method, especially for long-term measurements. They found that RIP failed to be consistently accurate enough for quantitative measurement of tidal volume and the determination of EELV. Improvement in calibration and long-term stability in RIP may in due course result from a 2002 study by Millard, who introduced more advanced mathematical algorithms to improve the RIP signals.

**Electrical impedance tomography**

Barber and Brown developed electrical impedance tomography (EIT) in 1984. EIT offers the possibility of non-invasive, bedside measurement of EELV, regional lung volume and regional ventilation. The principle of EIT is based on a small alternate current injection (5 mA, p-p) and voltage measurement via surface electrodes placed around the thorax (Figure 2). The electrical properties of the chest vary depending on changes in the air content. Therefore, chan-
An example of end-expiratory lung volume (EELV) increased with a PEEP-induced increase of end-expiratory lung impedance (ELI). Barber and Brown found a spatial resolution of approximately 8% of the thorax diameter, so that within the thorax a resolution of 8 ml is achieved.

A study performed by Hinz et al. showed that a PEEP-induced increase of EELV is accompanied by a proportional increase of end-expiratory lung impedance (ELI). An example of end-expiratory lung impedance at different measurements of EELV is shown in Figure 3. However, use of ELI results in a slight underestimate of lung volume changes. The reasons are, first, that impedance changes within the lung are generated either by the air content or changes of the central blood volume by the pulsatile blood flow, second, that pulmonary air content and impedance change may not correlate linearly, if stretching of lung parenchyma itself causes impedance changes; and, third, that impedance is linearly correlated to the impedance of a polyacrylamide gel, up to an increase of 20%. If gels with higher impedance were used, the changes were underestimated by the EIT system. This result may depend either on the electrical properties of the EIT system used or on the image reconstruction algorithm.

**DISCUSSION**

It may appear surprising that so many techniques, even some that can be used at the bedside, have been refined for EELV measurement in mechanically ventilated patients, yet the use of EELV as a guide in the treatment of the patient and setting of the ventilator is still not common in the ICU. The reasons seem to be that the process of measurement is complicated and the benefit is not perceived not warrant the effort. The lack of access to a simple, and preferably automated, technique has so far limited the acceptance of measuring EELV in the intensive care setting. Electrical impedance tomography may become a simple bedside method for monitoring change in EELV in the near future.

**CONCLUSION**

Bedside measurement of EELV is desirable, but not yet standard practice on the ICU. The unfulfilled need for a simple and preferably automated technique has so far limited the acceptance of measuring EELV in the intensive care setting. Electrical impedance tomography may become a simple bedside method for monitoring change in EELV in the near future.

![Figure 3. End-expiratory lung volume (EELV) measurement by electrical impedance tomography during mechanical ventilation with identical tidal volume at different positive end-expiratory pressures (PEEP 0, PEEP 5, PEEP 10, and PEEP 15) in one patient. The figure shows four examples of lung impedance time course (impedance) at different lung volumes induced by different PEEP. Note that the end-expiratory lung impedance (ELI) increased with increasing EELV.](image-url)
### Table 1. Methods for measuring lung volumes, their principles, advantages and disadvantages. The ability to measure regional lung volume and regional ventilation (regional parameter) and the possibility of bedside use on the ICU are noted

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Advantage/disadvantage</th>
<th>Regional parameter</th>
<th>Bed-side</th>
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<tbody>
<tr>
<td>Spirometry</td>
<td>Classic water spirometer has been replaced by ‘dry’ spirometer based on the technique of pneumotachography. Application of Hagen-Poiseuille’s law</td>
<td>It measures tidal volume and vital capacity. It needs a co-operative and motivated subject, so is unlikely to be appropriate in the ICU, especially in mechanically ventilated patients</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Body plethysmography</td>
<td>Application of Boyle’s law: patient in closed box, panting against an occluded shutter with the recording of airway and box pressures</td>
<td>Reference technique. Requires expensive equipment. Measures all gases in the lung even behind occluded airways and gas in poorly ventilated regions. Enables measurement in rapid sequence</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Respiratory inductive plethysmography (RIP)</td>
<td>RIP measures chest and abdomen movement by a pair of insulated coils strapped over the upper abdomen and chest. This displacement modifies the inductance of the coils proportional to tidal volume and lung volume</td>
<td>High and unstable signal baseline drift</td>
<td></td>
<td>✔</td>
</tr>
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</table>

### Table 2. Wash-in/wash-out techniques of measuring lung volumes, their principles, advantages and disadvantages. The ability to measure regional lung volume and regional ventilation (regional parameter) and the possibility of bedside use on the ICU are noted

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Multiple breath methods</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Helium rebreathing</td>
<td>Rebreathing of the poorly soluble helium until full mixing between lung volume and spirometer</td>
<td>Requires CO₂ absorber in circuit and O₂ to compensate for the uptake</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Multiple breath N₂ wash-out</td>
<td>Wash-out of N₂ in lung by O₂ breathing. Knowing the initial and final N₂ concentrations in lung gas and the expired amount of N₂ lung volume can be calculated</td>
<td>Less reliable if patient is ventilated with high fractions of O₂, because less N₂ can be washed out. Some of expired N₂ comes from body stores and must be subtracted before the calculation of EELV</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Xenon wash-in/ wash-out</td>
<td>Wash-in of a tracer gas that does not normally exist in the lungs and then wash-out similar to N₂ wash-out</td>
<td>Xenon attenuates x-rays which may enable regional volume radiographs; poor resolution, anaesthetic properties</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>SF₆ wash-in/wash-out</td>
<td>Wash-in of a tracer gas that does not normally exist in the lungs and then wash-out similar to N₂ wash-out</td>
<td>Very low concentration of tracer gas, which allows maintenance of inspired oxygen fraction</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Single breath methods</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>N₂ wash-out</td>
<td>An inspired VC of O₂ followed by slow expiration to RV during the recording of N₂</td>
<td>Easy and rapid to perform. Less accurate than multiple breath wash-out</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Helium wash-out</td>
<td>Inspired VC of O₂ with 5–10% helium, followed by slow expiration to RV during the recording of N₂</td>
<td>Less reliable than multiple breath techniques. Can be used with other tracer gases, for example SF₆</td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>

### Table 3. Imaging techniques of measuring lung volumes, their principles, advantages and disadvantages. The ability to measure regional lung volume and regional ventilation (regional parameter) and the possibility of bedside use on the ICU are noted

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</thead>
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<tr>
<td>Chest radiography</td>
<td>Frontal and lateral view of the lungs</td>
<td>Gives qualitative information but does not allow any quantitative analysis</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Computed tomogram</td>
<td>Repeated transverse CT scans or spiral CT of the chest during breath-hold</td>
<td>Not a bedside technique. Enables regional volume calculation</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Isotope techniques ¹³³X</td>
<td>Similar to SF₆ wash-in/wash-out</td>
<td>Expensive equipment and radiation</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Electrical impedance tomography</td>
<td>Reconstruction of impedance change via surface electrodes placed around the thorax induced by alternate current injection and voltage measurement</td>
<td>Delivers total and regional lung volumes, and regional ventilation, non-invasive, radiation-free, bedside use, continuous measurement possible</td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>

### ACKNOWLEDGEMENT

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### REFERENCES


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