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LASTING LEGACY IN INTENSIVE CARE MEDICINE

Lung recruitment

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In physiological terms, lung recruitment is "the increase in volume for the same pressure" [1]. In clinical terms, the case of bacterial pneumonia may help to explain what lung recruitment is. Infection in a lung lobe creates a consolidated mixture of bacteria and inflammatory cells. This part of the lung will not be accessible to gas flow, and will not be recruitable. However, the rest of the lung may become quickly inflamed but remaining accessible to gas flow. The effect of gravity on this latter part, the lack of respiratory muscle activity in a sedated patient and the load induced by the chest wall in obese patients will generate mostly dependent atelectasis—but a great heterogeneity inside the lung could also exist. This part constitutes the recruitable lung, which can be reopened and kept open by different approaches (recruiting maneuvers, prone positioning, higher positive end-expiratory pressure (PEEP)) [1]. Lung morphology [2] rather than the cause of lung disease (extrapulmonary or pulmonary) [3] could explain a considerable variability in recruitability among patients.

How can recruitment be measured?

Indirect methods: oxygenation, compliance and stress index

Physiologically, lung recruitment is expected to result in improved gas exchange and respiratory mechanics since more alveoli participate in tidal ventilation. The key issue with measuring "functional" recruitment is that changes in gas exchange and respiratory mechanics do not reflect solely recruitment. Improvement in oxygenation may also result from decreased cardiac output which leads to reduction of intrapulmonary shunt. Indeed, oxygenation was only weakly related to recruitment as measured with computed tomography (CT) scan [4, 5], and shunting can also be explained by intra-cardiac or vascular effects [6].

Improvement in compliance at higher pressures could represent both improved mechanical properties of already open lung units as well as recruitment of previously collapsed alveoli [7]. Compliance may also decrease at higher PEEP even in recruiters [8] due to simultaneous occurrence of overdistention [1, 8, 9].

Tidal recruitment can be estimated with the stress index (SI), a parameter obtained by mathematical curve fitting and representing the shape of the pressure–time curve during a constant flow inflation [10]. SI of 1 (i.e., linear pressure increase) suggests tidal inflation of normally aerated alveoli without overdistention. Tidal recruitment is suggested with SI < 1 (convexity, i.e., compliance increases during tidal inflation), while SI > 1 suggests overdistention (concavity, i.e., compliance decreases during tidal inflation). PEEP related changes in stress index indicate whether at a given level of PEEP tidal inflation causes tidal recruitment or tidal hyperinflation. Therefore SI-derived PEEP is not similar to CT scan recruitability [11].

Direct methods

Reference techniques: CT scan and pressure–volume curves

CT scan methods rely on voxel-by-voxel analysis. Depending on the density thresholds used for an aerated voxel (e.g., −100 or −200 Hounsfield units), tissue recruitment is quantified as the amount of non-aerated tissue at a certain pressure that reinflate at higher pressures; it is often expressed as grams of tissue in which aeration was restored, or as the reinflating fraction of total lung weight [4, 5]. The amount of recruitable lung with this approach varied widely in moderate-to-severe acute respiratory distress syndrome (ARDS) (on average 13 ± 11% of total lung weight) when increasing airway pressures from 5 to 45 cmH_2O, and was highly correlated with lung injury severity [5]. CT-based methods are not feasible for routine clinical use as they are time-consuming and expose

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patients to transportation and radiation; the latter should be reduced by scan protocols.

When merging two or more pressure–volume (PV) curves starting at different end-expiratory lung volumes or PEEP levels, a vertical shift of the PV curve with higher PEEP implies recruitment [7, 12, 13]. This is based on a hysteresis-like behavior of the lung (Fig. 1). PV curves can be obtained with a constant slow inflation technique [14] and require sedation with or without paralysis. Interestingly, the PV curve method was not correlated to CT-based recruitment [4]: CT scan measures tissue recruitment (anatomical) while PV curves detect recruited gas. It was correlated to another CT approach taking into account the poorly ventilated area [15]. In the absence of tissue recruitment on CT scan, air recruitment could still be present (owing to differences in lung tissue properties at different volumes), but not vice versa [16].

Electrical impedance tomography

Electrical impedance tomography (EIT) is gaining popularity as a bedside non-invasive lung imaging technique [17]. Importantly, EIT does not provide images on lung aeration like CT scan, but provides dynamic information on ventilation, i.e., global and regional changes in lung volumes owing to changes in ventilator settings. Percentages of recruitable alveolar collapse can be estimated by measuring relative changes in pixel compliance. This requires a "reference" value at high PEEP and a decremental PEEP trial over a wide range of PEEP (often from 24 to 6 cmH_2O): decreased pixel compliance when lowering PEEP is indicative of collapse, while decreased pixel compliance while increasing PEEP is suggestive of overdistention [18]. Methods to quantify recruitment with EIT that include both changes in pixel compliance and estimates of recruited volume are under development (NCT04460859).

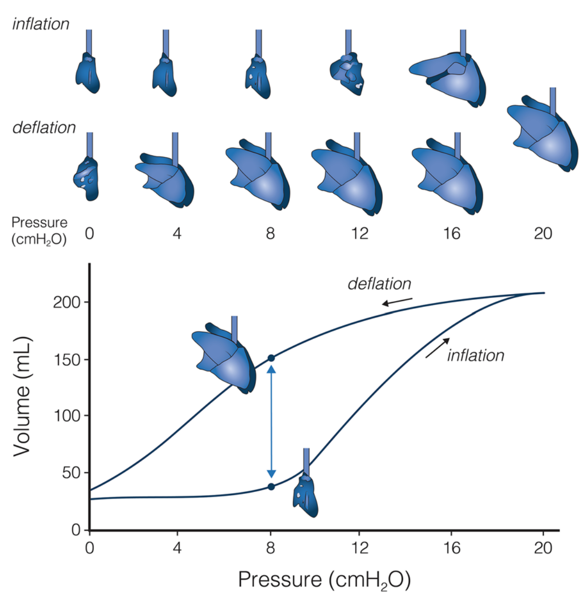

Fig. 1 Hysteresis-like behavior of a mammalian lung. Pulmonary pressure–volume curves obtained from an isolated cat lung during inflation and deflation of with air.[1] During inflation a lower inflection point is followed by a nearly linear segment. Hysteresis applies to the area between the inflation and deflation curves and is due to surface tension properties and alveolar recruitment and derecruitment. At a given pressure, lung volume during expiration is higher than the volume during inspiration. [1]Illustration based on: Radford EP (1957) Recent studies of the mechanical properties of mammalian lungs. In: Fenn WO, Rahn H, eds. Handbook of physiology. Washington, DC: Am Physiol Society, 1964

Ultrasound

Lung ultrasound (LUS) is another popular non-invasive bedside imaging modality [19]. The LUS reaeration score correlated with PEEP-induced lung recruitment as quantified with PV curves [20].Whereas LUS allows regional assessment of consolidated tissue that reaerate with higher PEEP, it cannot predict lung overdistention.

R/I ratio

The recruitment-to-inflation (R/I) ratio is obtained with a simplified single-breath maneuver that can be performed with any mechanical ventilator [8]. The presence of airway closure with corresponding airway opening pressure should be examined first. Then, the measured exhaled volume during an abrupt PEEP drop (often assessed from 15 to 5 cmH_2O) comprises of the exhaled tidal volume at high PEEP, the expected PEEP-induced inflation volume (i.e., $\Delta PEEP \times$ compliance at low PEEP), and the recruited volume. Recruitability is defined as the ratio of the recruited lung compliance to the "baby lung" compliance (at low PEEP). During the maneuver, respiratory rate should be reduced to 6–8/min for sufficient emptying of previously recruited open lung units. R/I ratio correlated with oxygenation (response), alveolar dead space, and hemodynamic response [8] and is increasingly used in studies to distinguish recruiters from non-recruiters. Using R/I ratio for setting higher or lower PEEP is being studied (NCT03963622).

Knowing lung recruitability is of crucial importance to optimize ventilatory management. Until recently no satisfying universal method was available at the bedside, which may explain why no trials have demonstrated a consistent effect of PEEP. Hopefully, recently introduced methods will better inform the clinician about the potential beneficial and harmful effects of PEEP and allow to weight the risks and benefits of PEEP for the individual patient. It still remains unknown whether achieving and maintaining maximal alveolar recruitment is required to minimize lung injury and facilitate lung healing.

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Declarations

Conflict of interest

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