Quantification of lung recruitment by respiratory mechanics and CT imaging: what are the clinical implications?

Andrew C. McKown, Lorraine B. Ware

Division of Allergy, Pulmonary and Critical Care Medicine, Department of Medicine, Vanderbilt University School of Medicine, Nashville, TN 37232-2650, USA

Correspondence to: Andrew C. McKown, MD. 1161 21st Ave S. T-1218, MCN, Nashville, TN 37232-2650, USA. Email: andrew.c.mckown@vanderbilt.edu.

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Acute respiratory distress syndrome (ARDS) is characterized by increased elastance of the lung and respiratory system (1). Depending on the precipitating factor, pulmonary *vs.* extrapulmonary, the distribution of pathologic findings and altered respiratory mechanics in the lung is heterogeneous (2). Portions of the lung can be collapsed and/or fluid-filled while others are well-aerated. In order to facilitate gas exchange, recruitment maneuvers are sometimes employed in patients with ARDS (3). These can be performed with a constant high pressure inspiratory hold for 30–40 seconds (4,5) or via stepwise recruitment by increasing the positive end-expiratory pressure (PEEP) (6), typically followed by application of PEEP at a higher level than the previous baseline to maintain aeration of the recruited lung units (7). Recruitment maneuvers have been proposed as useful tools in managing patients with ARDS in order to add previously non-participatory lung units to gas exchange as well as to assess disease severity. The potential effectiveness of recruitment maneuvers in incorporating previously collapsed lung units into gas exchange or in improving the distension of previously poorly aerated pulmonary units differs from patient to patient consequent to the variability in etiology of the lung injury and the heterogeneity of lung parenchyma (8).

A recent study by Chiumello and colleagues compared computed tomographic (CT) to respiratory mechanics methodologies for the measurement of the effectiveness of lung recruitment in ARDS (9). For the CT method, CT scans of the lungs at two levels of inflation were used to assess the effectiveness of increased PEEP for recruitment of new lung units to gas exchange (8). For this method, pulmonary voxels are classified into groups based on relative density as measured by CT Hounsfield units (HU). By established convention, regions with HU of >–100 are designated as having no aeration, –100 to –500 poorly aerated, –500 to –900 good aeration, and –900 to –1,000 as over-distended. Comparing the number of voxels in each group in CT scans performed at 5 cmH_2O PEEP and 15 cmH_2O PEEP established recruitment as the change in mass of non-ventilated lung between the CT scans.

By contrast, respiratory mechanics methods for determining recruitment measure the change in total lung volume of a single breath at different levels of PEEP compared with the anticipated change in volume if compliance were unchanged. One method (termed the EELV-Cst, RS method by Chiumello *et al.*) measures the static compliance of the respiratory system for one breath at 5 cmH_2O PEEP and calculates the anticipated lung volume at 15 cmH_2O PEEP if compliance were stable. The expected increase is compared with measured end-expiratory lung volume by helium dilution at 15 and 5 cmH_2O PEEP. The lung volume measured at PEEP 15 cmH_2O in excess of what was predicted from compliance measurement is attributed to recruitment (10). A related method of slow-flow pressure-volume curves generated at PEEP 5 and 15 cmH_2O (termed the P-Vrs curve method by Chiumello *et al.*) similarly calculates recruitment in volume of gas as the measured volume at PEEP 15 cmH_2O compared with the volume anticipated at PEEP 15 cmH_2O when initiating the breath from PEEP 5 cmH_2O (10,11).

As should be expected, the two assessments of recruitment based on respiratory mechanics, both of which premise pulmonary recruitment on the change in static compliance of the lung, yielded highly correlated results, though the absolute measured gas recruitment differed between the two techniques. The CT scan method, however, yielded levels of tissue recruitment that bore no relation to the gas recruitment estimated using the two respiratory mechanics methods.

Closer examination of the measured variables makes this the anticipated result. The measured gas recruitment from both respiratory mechanics methods is spread across the entirety of the lungs: the relative portion applied to changing distension of pulmonary units that were aerated at the lower PEEP *vs.* to the filling of previously non-aerated pulmonary units cannot be differentiated by respiratory mechanics. As a result, there is a positive correlation between well-inflated tissue at baseline and absolute gas recruitment measured by the respiratory mechanics methods (0.85 mL recruitment per gram of well-inflated tissue at PEEP 5 cmH_2O, R^2=0.25, P=0.02). In contrast, the CT method specifically quantitates the shifting of previously non-aerated lung (HU >−100) to aerated lung (HU −1,000 to −100). As one would expect, the more non-aerated lung there is at baseline, the more recruitment occurs with increased PEEP, (0.12 mL recruitment per gram of not inflated tissue at PEEP 5 cmH_2O, R^2=0.44, P<0.001). In other words, increased PEEP can only recruit non-aerated pulmonary units if there are non-aerated pulmonary units at baseline.

In sum, Chiumello *et al.* find that lung recruitment measured in ARDS via respiratory mechanics is quite distinct from recruitment measured by CT scan. The respiratory mechanics methods quantitate increased aeration of already open pulmonary units on top of the addition of previously non-participatory, collapsed pulmonary units to gas exchange, whereas the CT scan method measures only the addition of previously collapsed pulmonary units to gas exchange.

CT scan has the added benefit of quantitating how much lung parenchyma shifts from "under-inflated" or "well-inflated" as defined by HU to "over-inflated." On average, increasing PEEP from 5 to 15 cmH_2O yielded a decrease in non-inflated tissue from 656 grams (44%) to 579 grams (37%) (P<0.001), which was partially offset by an increase in over-inflated lung from 4 grams (0.3%) to 10 grams (0.7%) (P=0.288). The increase in over-inflated lung when quantitated by gas volume was statistically significant, but the absolute numbers were not reported. Importantly, over-distension as measured by CT was at end-expiration—over-distension at end-inspiration is probably more relevant for ventilator-induced lung injury and was not measured.

It is notable that the recruitment as quantified by either methodology correlates poorly with indices of gas exchange. Plotting delta PaO_2, delta PaO_2/FiO_2, delta $PaCO_2$, and delta shunt *vs.* recruitment from each method yielded only two statistically significant correlations (CT-measured tissue recruitment correlated with delta PaO_2 and with delta shunt but with correlation coefficients of just 0.26 and 0.19, respectively). Thus, as the investigators duly note, improved oxygenation after recruitment with increased PEEP cannot be proportionally attributed to increased lung volume alone.

While Chiumello *et al.* nicely differentiate the features of recruitment by CT compared to respiratory mechanics, they comment little on the significance for clinical practice because at present these remain research tools. As the investigators point out, CT scans are unappealing for routine use since they are laborious, require radiation exposure, and require potentially dangerous transport. Respiratory mechanics are theoretically more attractive because of their potential for measurement at bedside, though they require heavy sedation and frequently neuromuscular blockade to perform reliably (10,11). That they measure different components of pulmonary recruitment ignores the fact that the benefit of recruitment maneuvers in routine clinical practice is unproven, and the clinical utility of quantitated measures of recruitment is unknown.

To date, studies of recruitment maneuvers with hard patient-centered outcomes such as survival have largely incorporated recruitment maneuvers as part of a package of interventions for lung protection; benefits of their isolated use are unclear (4,6,12-14). While the opening of collapsed pulmonary units by recruitment maneuvers seems intuitively beneficial, it may be accompanied by harmful over-distension of already well-aerated lung, and determining the balance of benefit *vs.* harm is challenging. Indeed, critical care research is rife with examples where a logical physiological endpoint did not equate to better patient-centered outcomes. Consider that in the now classic ARDS Network trial of lower tidal volume ventilation, the higher tidal volume group had better oxygenation yet had an 8.8% absolute higher mortality rate (15). At present, the best evidence for lung protective ventilation in ARDS incorporates relatively low tidal volume ventilation with minimized plateau pressures. The balance of the risk of over-distension of some lung units to the benefit of keeping open and preventing atelectotrauma in others is uncertain and probably varies for the individual patient and their relative at-risk pulmonary units, though there is growing belief that higher PEEP is beneficial in severe ARDS (16). Some large trials which include the use of recruitment maneuvers are ongoing and will potentially better inform the critical care community on the utility of recruitment maneuvers in the future (NCT01667146, NCT01374022).

To the practicing critical care physician, there are two useful take home messages from Chiumello *et al.*'s investigation: (I) changes in respiratory exchange measures (i.e., PaO_2, $PaCO_2$, and shunt) are minimally associated with quantitated recruitment either by CT or respiratory mechanics; and (II) measurement of gas recruitment by respiratory mechanics in ARDS does not imply that previously non-aerated lung units were added to gas exchange. The investigators posited that "[r]ecruitability may be important in clinical practice for assessing the severity of ARDS, planning recruitment maneuvers and setting adequate PEEP levels during mechanical ventilation", but the current study does not yet allow us to define the clinical role of assessing "recruitability" (9). Thus, there is no compelling reason as of yet for a clinician to attempt to quantitate lung "recruitability" as part of clinical care in ARDS. As for whether recruitment maneuvers should be routinely applied in management of ARDS: the answer is not yet known.

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Footnote

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