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Utilizing Forced Vital Capacity to Predict Low Lung Compliance and Select Intraoperative Tidal Volume During Thoracic Surgery

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BACKGROUND: Tidal volume selection during mechanical ventilation utilizes dogmatic formulas that only consider a patient's predicted body weight (PBW). In this study, we investigate whether forced vital capacity (FVC) (1) correlates better to total lung capacity (TLC) than PBW, (2) predicts low pulmonary compliance, and (3) provides an alternative method for tidal volume selection.
METHODS: One hundred thirty thoracic surgery patients had their preoperative TLC calculated via 2 methods: (1) pulmonary function test (PFT; TLC_{PFT}) and (2) computed tomography 3D reconstruction (TLC_{CT}). We compared the correlation between TLC and PBW with the correlation between TLC and FVC to determine which was stronger. Dynamic pulmonary compliance was then calculated from intraoperative ventilator data and logistic regression models constructed to determine which clinical measure best predicted low compliance. Ratios of tidal volume/FVC plotted against peak inspiratory pressure were utilized to construct a new model for tidal volume selection. Calculated tidal volumes generated by this model were then compared with those generated by the standard lung-protective formula Vt = 7 cc/kg.
RESULTS: The correlation between FVC and TLC (0.82 for TLC_{PFT} and 0.76 for TLC_{CT}) was stronger than the correlation between PBW and TLC (0.65 for TLC_{PFT} and 0.58 for TLC_{CT}). Patients with very low compliance had significantly smaller lung volumes (forced expiratory volume at 1 second, FVC, TLC) and lower diffusion capacity of the lungs for carbon monoxide when compared with patients with normal compliance. An FVC cutoff of 3470 cc was 100% sensitive and 51% specific for predicting low compliance. The proposed equation Vt = FVC/8 significantly reduced calculated tidal volume by a mean of 22.5% in patients with low pulmonary compliance without affecting the mean tidal volume in patients with normal compliance (mean difference 0.9%).
CONCLUSIONS: FVC is more strongly correlated to TLC than PBW and a cutoff of about 3.5 L can be utilized to predict low pulmonary compliance. The equation Vt = FVC/8 reduced mean calculated tidal volume in patients with low pulmonary compliance and/or small lungs. (Anesth Analg 2017;125:1922–30)

Proper selection of tidal volume is crucial in mechanically ventilated patients. Numerous animal and clinical trials have demonstrated reduced lung injury, morbidity, and even mortality when smaller tidal volumes are utilized.[1–4] The currently accepted method for determining tidal volume is based only on patients' predicted body weight (PBW). Such a strategy for tidal volume selection assumes a robust correlation between PBW and lung volume. This assumption, however, is not supported in the scientific literature. In fact, normal variability of thoracic anatomy within a population, combined with changes that occur as a result of aging and lung disease, raise doubts whether a simple weight- or height-based equation can be expected to fit all individuals.[5–7] Patients with reduced lung volume and/or pulmonary compliance may be particularly at risk for ventilator-induced barotrauma if the accepted PBW-based equation is used to determine tidal volume size.

Thoracic surgery patients are a subpopulation at high risk for postoperative acute lung injury given their (1) high incidence of preoperative pulmonary disease and (2) intraoperative trauma of their surgical lung.[8–12] Unfortunately, the standard preoperative history, physical, and laboratory survey is unlikely to reliably identify low lung volumes and poor pulmonary compliance. Modern perioperative medicine is currently transitioning from standardized patient care to patient-centered precision medicine.[13,14] Pulmonary function tests (PFTs) that measure (1) respiratory spirometry, (2) lung volumes, and/or (3) diffusion of carbon monoxide are uniquely positioned to deliver lung-focused data. Personalizing tidal volume selection based on measured lung parameters, rather than relying on standardized monograms such as weight and/or height could be the natural progression of this evolution. In particular, the PFT measure forced vital capacity (FVC) encompasses both patients' pulmonary-specific performance as well as their physical stature. Such pulmonary measures may be well suited in helping to determine optimal tidal volume.

In this study involving patients undergoing thoracic surgery, we (1) determine if several PFT-derived measures are more strongly correlated to total lung capacity (TLC) than PBW, and (2) if these measures can be utilized to identify

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patients at high risk for poor pulmonary compliance. We hypothesize that FVC would more strongly correlate to TLC compared to PBW, and could be a useful tool for identifying patients at risk for low pulmonary compliance. Finally, (3) we propose an alternative formula for tidal volume selection that may better fit patients with low pulmonary compliance.

METHODS

Patient Selection and Data Collection

After obtaining institutional review board approval and permission to waive consent, the electronic medical records of 200 consecutive patients who underwent thoracic surgery between May 2013 and February 2014 at our institution were selected for review. The presentation of this article follows the STROBE checklist for observational studies and all data sheets have been deidentified. Eligibility for enrollment required the following inclusion criteria: (1) recent (<6 months) preoperative chest computed tomography (CT) scan and pulmonary function tests, (2) general anesthesia with controlled mechanical ventilation utilizing a large-bore endotracheal tube (at least 8.0-mm single lumen or 35F dual lumen), (3) stable period of 2 lung ventilation with neuromuscular blockade in the supine position before surgery. Patients with the following findings were excluded from enrollment: (1) age < 18, (2) tracheal or bronchial mass of any size, (3) previous lung lobectomy or pneumonectomy, (4) previous lung transplantation, (5) large (≥6.0 cm diameter) intrathoracic tumor, and (6) indwelling pleural catheter at the time of lung volume determination. One hundred thirty patients satisfied inclusion/exclusion criteria, and their data were analyzed in the study (Figure 1).

Lung Volume Investigation

Preoperative TLC was independently calculated by both (1) pulmonary function tests (primarily via plethysmography technique, rarely via helium dilution) and (2) CT 3D reconstruction. Utilizing 2 "Gold Standards" for measuring TLC added a layer of quality control by ensuring that errors in measurement due to limitations of 1 technique would not confound the measured results of the other. Having 2 independently measured TLC values for each patient and comparing the correlation between these measurements to a previously published reference enabled us to assess the accuracy of our measurements.[15] Furthermore, the PFT-derived TLC (TLC_{PFT}) data enabled analysis of lung function (gas diffusion, flow spirometry), whereas the CT-derived TLC (TLC_{CT}) in turn allowed detailed assessment of pulmonary/thoracic anatomy including pathology that PFTs could not reveal. Vitrea (V6.4, Vital Images, Minnetonka, MN), an automated postimage acquisition software package, was utilized to generate the 3D reconstruction of the patients' lungs from the chest CT data (Figure 2).[16] Aerated lung and trachea were segmented from CT scan data, and the software allowed for separation of lung segmentation from the tracheobronchial tree. The lung volume from each individual CT slice was calculated and subsequently added together to generate a complete 3D lung image with corresponding TLC volume reported in milliliters. Not all patients had CT scans that were considered eligible for volumetric measurement and quantification. Sixteen patients whose CT scans exhibited motion artifact or were obtained in the expiratory phase of respiration were excluded from the study. A further 15 patients who did not have TLC

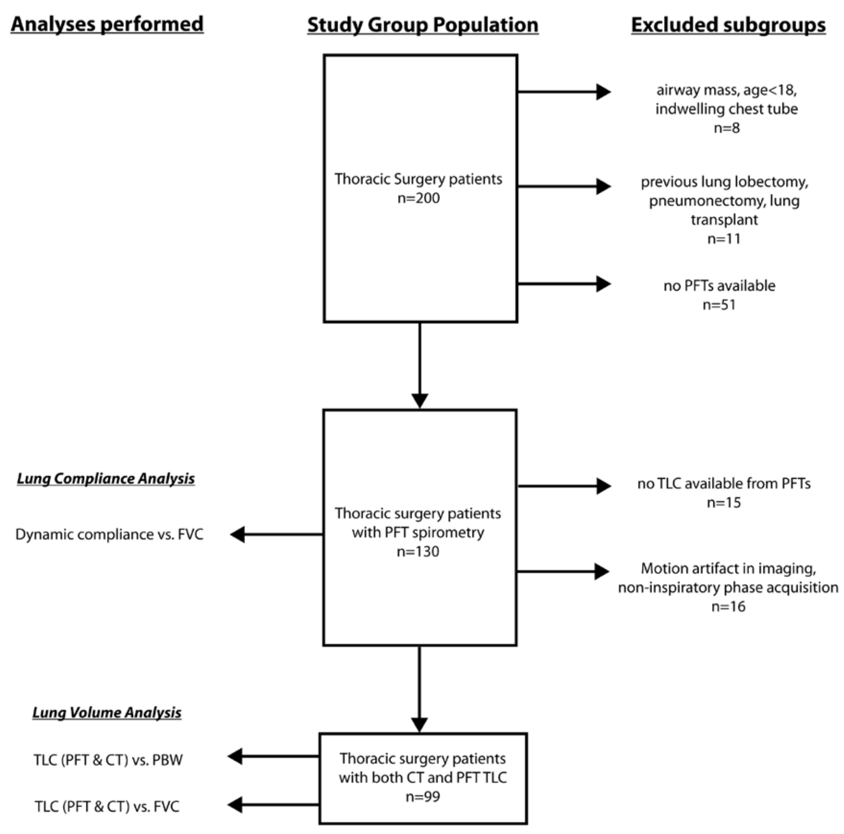

Figure 1. Study design schematic. Two hundred thoracic surgery patients were initially identified, and 130 enrolled after exclusion of 70 patients with possible confounding variables and/or incomplete data. The lung compliance analysis was performed utilizing data from all 130 patients. Lung volume analysis was performed on n = 99 patients because 15 patients were excluded for incomplete PFT lung volume data (no TLC) and 16 patients were excluded for suboptimal CT imaging. CT indicates computed tomography; PFT, pulmonary function testing; TLC, total lung capacity.

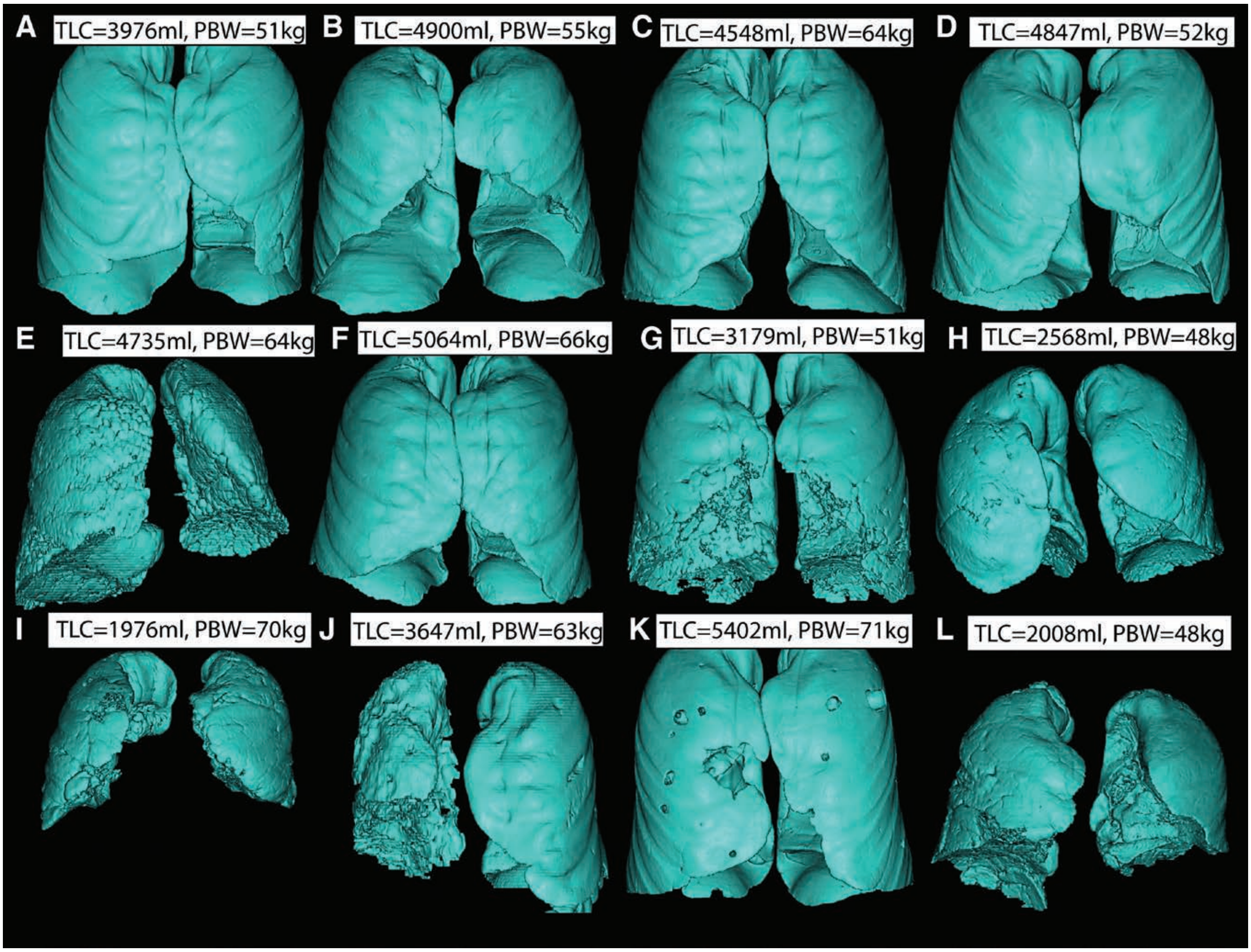

Figure 2. Vitrea generated 3D lung anatomy; normal and abnormal lungs.* Patients with normal lungs: A—29-year-old woman, mediastinal mass for resection, normal PFTs; B—64-year-old woman, lung nodule for biopsy, normal PFTs; C—54-year-old man, reflux, for fundoplication; D—59-year-old woman, lung adenocarcinoma, normal PFTs. Comment: Patient C's PBW is 23% larger than patient D's PBW, yet his lungs are 6% smaller. Patients A and C were excluded from the study due to incomplete data. Emphysema/interstitial lung disease: E—83-year-old man with emphysema, lung cancer, previous left lower lobectomy, minimal spirometry obstruction, very low DLCO; F—69-year-old woman with emphysema, lung cancer, moderate-severe spirometry obstruction, preserved DLCO; G—46-year-old woman, early interstitial lung disease, mildly reduced DLCO, normal spirometry mechanics, low lung volumes; H—48-year-old woman, advanced interstitial lung disease, very reduced DLCO and lung volumes, restricted spirometry mechanics. Comment: Both E and F have "emphysema" with similar weight and lung volumes, but their airflow and diffusion characteristics are very different. Both G and H have "interstitial lung disease", but H's disease is more advanced and clinically significant. Patient E was excluded from the study data set due to earlier left lung lobectomy. MISC pathology: I—59-year-old previously healthy man with acutely strangulated paraesophageal hernia; J—79-year-old man with right malignant mesothelioma; K—23-year-old otherwise healthy man with metastatic germ cell tumor; L—69-year-old previously healthy woman with an acute esophageal perforation. Comment: Patient I's lungs were chronically compressed, but after repair reexpanded to TLC = 5700. Both I and L have acute esophageal pathology, which resulted in large but reversible reductions in lung volumes. Patients I and J were excluded from the study due to incomplete data and large tumor size, respectively. *Several of these patients met exclusion criteria due to missing data sets, lung pathology, or motion artifacts and were not enrolled in the lung volume analysis, lung compliance analysis, or both. Their images are nevertheless displayed here to highlight the anatomical and structural details that can be gleaned from this new image-processing modality. DLCO indicates diffusion capacity of the lungs for carbon monoxide; PBW, predicted body weight; PFT, pulmonary function testing; TLC, total lung capacity.

measured in their PFTs were also excluded. Thus, we analyzed data from a total of 99 subjects with suitable CT and PFT studies in the lung volume investigation. PBW was calculated for each patient based on the ARDSnet definition[3] (men: PBW [kg] = 50 + 2.3 [height {in}-60]; women: PBW [kg] = 45.5 + 2.3 [height {in}-60]).

Lung Compliance Investigation

The electronic intraoperative anesthesia record of every patient (n = 130) was manually reviewed by an anesthesiologist with expertise in thoracic anesthesia. Mechanical ventilation data (tidal volume, respiratory rate, peak inspiratory pressure, positive end expiratory pressure) was extracted from the time period immediately after bronchoscope-assisted tracheal tube positioning but before patient positioning for surgery. At the time, all patients were undergoing 2-lung volume control mechanical ventilation in the supine position under deep anesthesia and neuromuscular blockade. This highly controlled setting promoted low ventilator pressures; peak inspiratory pressures

≥ 25 cm H_2O were unusual (seen in only 6% of patients) and were defined as "elevated" based on our clinical experience. Pulmonary static compliance could not be accurately determined due to the retrospective nature of the data collection and lack of a verifiable inspiratory pause (with true cessation of gas-flow and pressure equilibration) during the collection period of plateau pressure. Therefore, pulmonary dynamic compliance was calculated for each patient using the following equation: compliance = tidal volume / (peak inspiratory pressure – positive end expiratory pressure).[17,18] Patients whose dynamic compliance was reduced by at least 50% from the lower limit of normal (compliance ≤ 25 mL/cm H_2O) were identified as having markedly reduced pulmonary compliance.[19,20] This subgroup of patients was then compared with the remaining patients (compliance > 25 mL/cm H_2O) to identify any differences in their baseline characteristics.

Analysis and Statistics

Total lung capacity values (TLC_{PFT} and TLC_{CT}) were individually plotted against PBW and then FVC to determine each of those correlations, respectively. Patient characteristics and outcomes were summarized using means/SDs for continuous variables and frequencies/percentages for categorical variables. Pearson correlation coefficients were computed to assess the associations between lung volume measures (TLC_{CT} and TLC_{PFT}) and PBW or FVC. We compared the correlation coefficients using Williams Test.[21]

Dynamic pulmonary compliance was separately plotted against all baseline variables which differed statistically between the 2 compliance groups (compliance ≤ 25 mL/cm H_2O versus compliance > 25 mL/cm H_2O). Fisher exact test was utilized to compare incidence of elevated peak inspiratory pressure between the 2 compliance groups. Logistic regression models were constructed for the lung compliance analyses. Receiver operating characteristic curves were created and optimal cutoff points that maximized sensitivity/specificity were identified using the Youden index.[22] The respective areas under the curve were then compared utilizing the Delong test.

Ratios of tidal volume/FVC were plotted against peak inspiratory pressure to characterize this relationship. We hypothesized that as tidal volume/FVC ratio decreased, so would the probability of seeing high peak pressures due to excessive tidal volume. We then set out to identify the ideal tidal volume/FVC ratio which would achieve the clinical needs of ventilation while adequately protecting the lungs from barotrauma. These data were utilized to construct a model for tidal volume selection that would better fit patients with wide ranges of pulmonary compliance. The tidal volume generated by this novel formula was then calculated for each patient and compared to the tidal volume determined from the accepted lung-protective equation (tidal volume = 7 mL/kg PBW).

Lung volume analyses were performed using R V3.1.2 (Vienna, Austria). Lung compliance and tidal volume analyses were performed using IBM SPSS V23 (Armonk, NY). $P < .05$ were considered statistically significant.

Before data collection, we hypothesized that the correlation between PBW and TLC would be around 0.5 (Pearson correlation coefficient) and between FVC and TLC would be about 0.7. This estimate was based on informal clinical observation and analysis over the past decade. An a priori power analysis determined that at least 80 patients would be needed to show such a difference with 80% power (at $\alpha = .05$). Based on our initial observation that only around 50% of patients met all the inclusion and exclusion criteria, we decided to review 200 patient charts. Given our secondary goal of developing a model for selecting tidal volume in patients with low pulmonary compliance, we chose to enroll all eligible patients from the original patient cohort to enhance that analysis.

RESULTS

Baseline patient demographics and pulmonary characteristics are summarized in Table 1.

Lung Volume Investigation

The correlation between FVC and TLC (0.82 for TLC_{PFT} and 0.76 for TLC_{CT}) was stronger when compared with the correlation between PBW and TLC (0.65 for TLC_{PFT} and 0.58 for TLC_{CT}). This finding remained consistent irrespective of whether TLC_{CT} or TLC_{PFT} was used in the comparisons, as graphically illustrated in Figure 3. Such consistency was the result of the very strong correlation between TLC_{CT} and TLC_{PFT}, equal to that published in the historical reference. All the correlations coefficients and statistical comparisons are summarized in Table 2.

Lung Compliance Investigation

A comparison of baseline patient demographics and pulmonary characteristics between patients with markedly low pulmonary compliance and the rest of the population is summarized in Table 3. The low compliance subgroup included 21 patients (16% of total study population), 8 of whom experienced elevated intraoperative peak inspiratory pressures (≥25 cm H_2O), while no patients from the normal compliance subgroup experienced elevated peak pressures ($P < .001$). Patients with markedly low compliance

Table 1. Baseline Patient (n = 130) Demographics and Pulmonary Characteristics

	Average (SD)
Demographic	
Age (y)	64 (15)
Weight (kg)	76 (19)
Height (cm)	168 (10)
Predicted body weight (kg)	62 (10)
Male (%)	54
Body mass index	27 (6)
Pulmonary function testing	
TLC (mL)	5508 (1436)
FEV1 (mL)	2456 (824)
FVC (mL)	3330 (965)
FEV1/FVC (%)	74 (10)
RV (mL)	2109 (919)
DLCO (% predicted)	80 (22)
Time between PFTs acquisition and surgery (days)	37 (30)
Vitrea generated lung volume	
TLC_{CT} (mL)	4369 (1233)

Abbreviations: DLCO, diffusion capacity of the lungs for carbon monoxide; FEV1, forced expiratory volume at 1 second; FVC, forced vital capacity; RV, residual volume; TLC, total lung capacity.

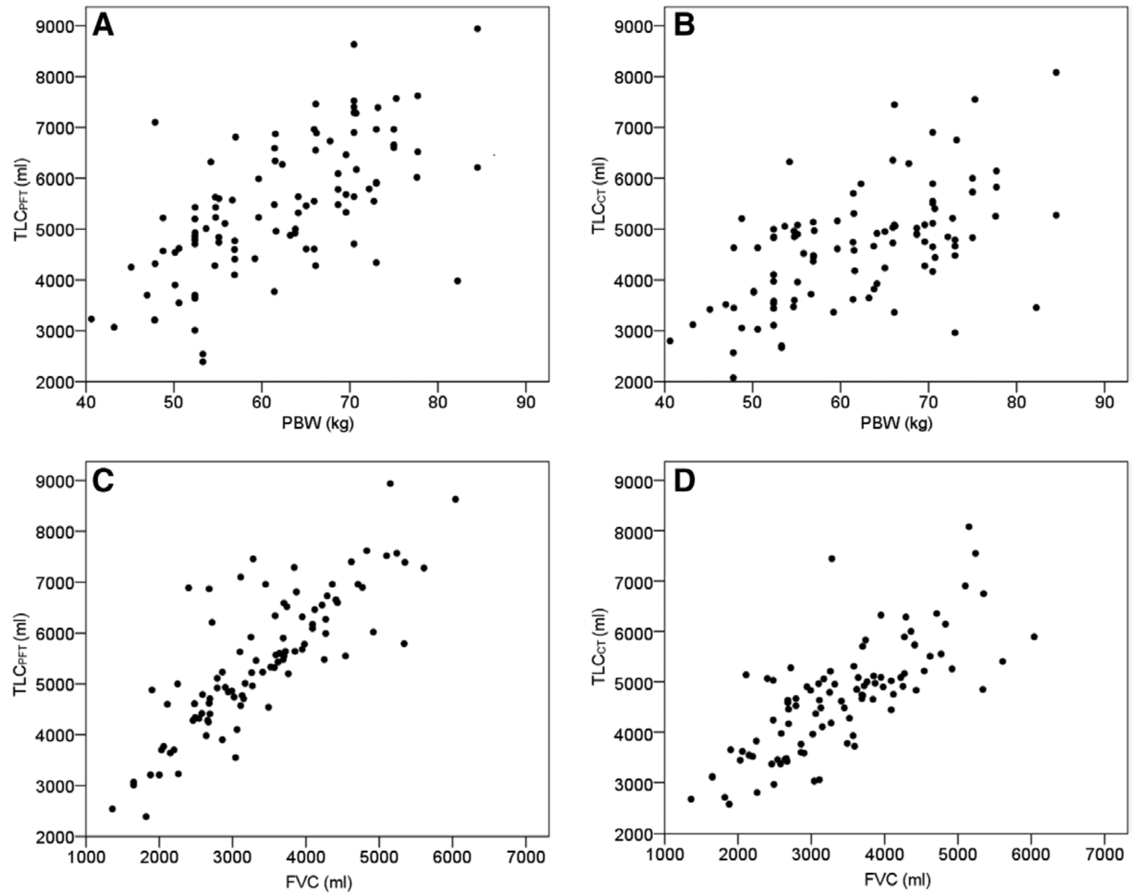

Figure 3. PBW versus FVC; how each correlates to TLC. Graphical representation highlighting the correlation strength of (1) PBW versus TLC and (2) FVC versus TLC. Both PFT generated TLC and Vitrea (CT)-generated TLC are individually plotted against each variable (total of 4 comparisons). A, Graph of PFT generated TLC versus PBW (R = 0.65, CI 0.52–0.75). B, Graph of Vitrea (CT)-generated TLC versus PBW (R = 0.58, CI 0.43–0.70). C,Graph of PFT-generated TLC versus FVC (R = 0.82, CI 0.75–0.88). D, Graph of Vitrea (CT)-generated TLC versus FVC (R = 0.76, CI 0.66–0.83). FVC is more strongly correlated to TLC than is PBW, regardless of the type of TLC measure used. The correlation coefficients of similar comparison graph pairs were not statistically different (A versus B: *P* = .097, C versus D: = .079, respectively) due to the very strong correlation between TLC_{PFT} and TLC_{CT} (R = 0.86, CI 0.80–0.90). CI indicates confidence interval; CT, computed tomography; FVC, forced vital capacity; PBW, predicted body weight; TLC, total lung capacity.

had significantly smaller lung volumes (forced expiratory volume in 1 second [FEV1], FVC, TLC) and lower carbon monoxide diffusing capacity (DLCO) when compared with patients with compliance >25 mL/cm H_2O. Receiver operator curves generated for the comparisons between pulmonary compliance and PBW, FEV1, TLC, FVC, and DLCO, respectively, demonstrated that DLCO and FVC yielded the highest area under the curve (0.79 and 0.78, respectively). The area under the curve for FVC was significantly greater than that of PBW (0.78 vs 0.58, *P* = .002). These results are summarized in Figure 4. As a clinical test, an FVC cutoff of 3470 mL was 100% sensitive (95% CI 0.81–1.00) and 51% specific (95% CI 0.41–0.61) for predicting low pulmonary compliance.

Proposed Formula for Tidal Volume Selection

We propose a new "lung-centric formula" for selecting tidal volume: Vt = FVC/8. Tidal volumes calculated for each patient by this formula differed by an average of 4.4% from those calculated by the standard PBW-based lung-protective equation (tidal volume = 7 mL/kg PBW). This proposed lung-centric formula reduced calculated tidal volume in patients with markedly low compliance by an average of 22.5%; 8 of these patients who also experienced high intraoperative peak airway pressures saw a 30% mean reduction in calculated tidal volume compared to the PBW-based equation. Those with compliance >25 mL/cm H_2O demonstrated an average difference of 0.9% between the 2 methods. When compared with the standard equation, the proposed formula reduced calculated tidal volume in patients with small lungs (smallest quartile) and enlarged calculated tidal volume in all patients with large lungs (largest quartile). These results are summarized in Figures 5 and 6.

DISCUSSION

This study demonstrated that (1) FVC is more strongly correlated to TLC than is PBW, (2) low FVC can identify low lung compliance, and (3) FVC can be utilized to determine tidal volume. The weaker correlation between PBW and TLC was not surprising given that the PBW calculation uses height as its major determinant, and human height is much more heavily influenced by femur length than thoracic girth.[23] Clinically, this weaker correlation translated to a greater than 2-fold difference between the smallest and

Table 2. Analysis From Subset of Patients (n = 99) With Both TLC_{PFT} and TLC_{CT}

A)	Correlations Between Variable Pairs		
Variables	**Correlation (r)**	**95% Confidence Intervals**	
(1)	PBW and TLC_{PFT}	0.65	(0.52–0.75)
(2)	FVC and TLC_{PFT}	0.82	(0.75–0.88)
(3)	PBW and TLC_{CT}	0.58	(0.43–0.70)
(4)	FVC and TLC_{CT}	0.76	(0.66–0.83)
(5)	TLC_{CT} and TLC_{PFT}	0.86	(0.80–0.90)

B)	Statistical Comparison of Correlation Strength (Williams Test)	
Comparison	***P* Value**	**Interpretation**
Correlation 1 vs 2	.001	FVC is more strongly correlated to TLC_{PFT} than is PBW
Correlation 3 vs 4	.003	FVC is more strongly correlated to TLC_{CT} than is PBW
Correlation 1 vs 3	.097	PBW/TLC_{PFT} and PBW/TLC_{CT} were not statistically different
Correlation 2 vs 4	.079	FVC/TLC_{PFT} and FVC/TLC_{CT} were not statistically different

Abbreviations: FVC, forced vital capacity; PBW, predicted body weight; TLC, total lung capacity.

Table 3. Baseline Demographics and Pulmonary Characteristics: Low Versus Normal Pulmonary Compliance

	Pulmonary Compliance		
	Low (n = 21)	**Normal (n = 109)**	***P* Value**
Demographic			
Age (y)	66 (13)	64 (16)	.52
Weight (kg)	81 (21)	75 (18)	.18
Height (cm)	167 (10)	168 (9)	.46
PBW (kg)	60 (10)	63 (10)	.32
Male (%)	38	57	.11
Body mass index	29 (7)	26 (5)	.08
Pulmonary function testing			
TLC (mL)	4689 (1259)	5651 (1422)	**.01**
FEV1 (mL)	1922 (463)	2559 (840)	**.001**
FVC (mL)	2581 (504)	3474 (967)	**<.001**
FEV1/FVC (%)	75 (12)	74 (10)	.67
RV (mL)	1871 (877)	2151 (924)	.25
DLCO (% predicted)	63 (18)	83 (22)	**<.001**
Vitrea-generated lung volume			
TLC_{CT} (mL)	3592 (898)	4518 (1235)	**.001**

Bold numbers signify statistically significant *P* values.

Abbreviations: DLCO, diffusion capacity of the lungs for carbon monoxide; FEV1, forced expiratory volume at 1 second; FVC, forced vital capacity; PBW, predicted body weight; RV, residual volume; TLC, total lung capacity.

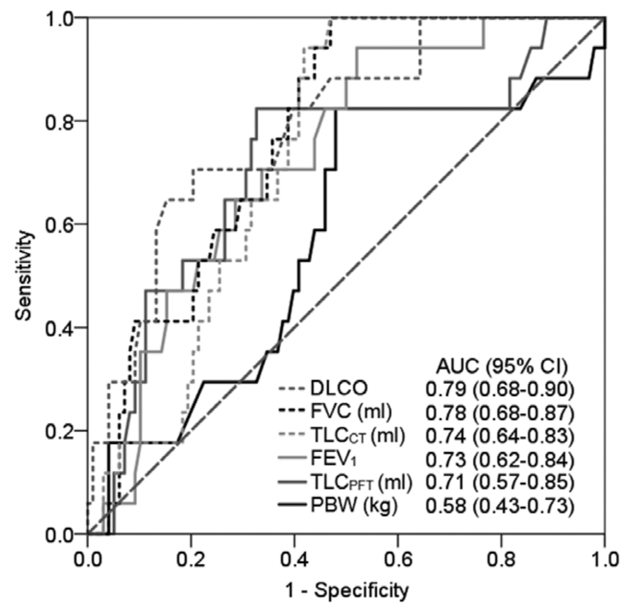

Figure 4. Receiver operating characteristic curves of all variables in the logistic regression model. Each variable was tested to see if a cut point could be determined that would separate patients with low versus normal lung compliance. AUC for each variable is proportional to the combined sensitivity + specificity of the test for predicting low lung compliance. FVC had a significantly larger AUC compared with PBW (0.78 vs 0.58, *P* = .002). FVC and DLCO had similar AUCs (0.78 vs 0.79, *P* = .770), as did FVC and TLC_{CT} (0.78 vs 0.74, *P* = .335). As a clinical test for predicting low lung compliance, PBW performed most poorly, whereas FVC and DLCO performed best. Among these tested variables, only FEV1, FVC, and PBW are easily obtained at the bedside; TLC_{CT} requires a CT scan and Vitrea software package, and TLC_{PFT} and DLCO require a physiology laboratory. Therefore, FVC is the best clinical measure for predicting low lung compliance. AUC indicates area under the curve; CT, computed tomography; DLCO, diffusion capacity of the lungs for carbon monoxide; FEV1, forced expiratory volume at 1 second; FVC, forced vital capacity; PBW, predicted body weight.

largest TLC values measured among patients with identical PBW. Given the natural variability in thoracic proportions within a population, a tidal volume equation based solely on PBW could over- or underestimate required tidal volumes, especially in patients with small or large lungs.[5]

An FVC value less than 3.5 L was found to be 100% sensitive and about 50% specific for detecting low compliance. Although other variables including TLC_{CT} and DLCO had equivalent areas under their respective receiver operator curves, FVC was better suited for clinical care given its high sensitivity and ease of acquisition at the bedside. We deliberately chose a cutoff point that maximized sensitivity to ensure that all patients with low compliance would be identified to receive lung protection. The low specificity of the cutoff was not surprising, because patients with low FVC likely represented two different subpopulations: (1) small patients with normal, compliant lungs, and (2) average sized patients with diseased, small noncompliant lungs. Differentiating which subpopulation a patient with low FVC belonged to is beyond the capabilities of a single cutoff value, because it would require calculation of pulmonary compliance. Nevertheless, having a simple tool to identify patients potentially at risk for barotrauma could still aid clinicians in everyday ventilator management.

Precisely to aid in these challenging clinical scenarios, we developed an experimental model that may better select

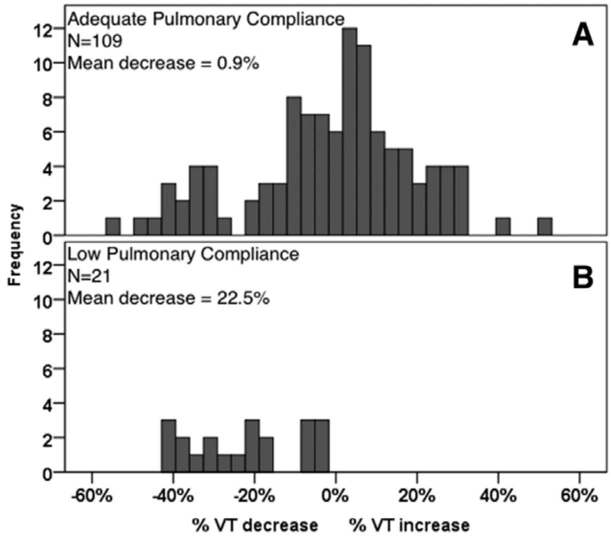

Figure 5. FVC versus PBW-generated tidal volumes; low versus normal lung compliance. Graphic representation of the percent difference in tidal volume when determined with the standard PBW-based lung-protective equation versus the newly proposed FVC-based lung-centric equation ([FVC/8 – 7 mL/kg PBW] / 7 mL/kg PBW). A negative value on the *x* axis represents the percent reduction in tidal volume by the equation FVC/8 compared with the equation 7 mL/kg, whereas a positive value represents percent increase in tidal volume. The *y* axis delineates the number of patients with any given percent difference in tidal volume. A, The mean change in calculated tidal volume by the FVC-based equation in patients with adequate lung compliance was −0.9% (median 1.9%, IQR −11.2% to 12.4%) when compared with the PBW-based equation. The bell-shaped distribution highlights that patients with normal compliance experienced increased, decreased, or unchanged tidal volume with the new equation. It is highly likely that the FVC value determined the change an individual patient would experience. B, The mean change in calculated tidal volume by the FVC-based equation in patients with significantly reduced lung compliance was −22.5% (median −22.2%, IQR −36.0% to −7.9%) when compared with the PBW-based equation. Every patient had a decreased tidal volume with the new equation. FVC indicates forced vital capacity; IQR, interquartile range [Q1–Q3]; PBW, predicted body weight.

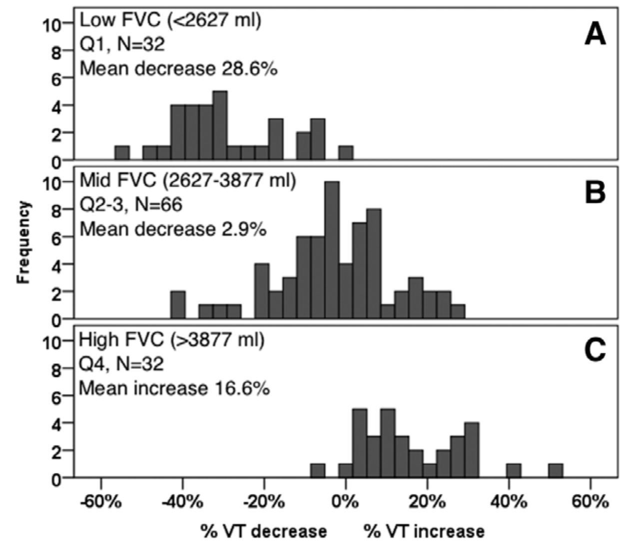

Figure 6. FVC versus PBW-generated tidal volumes; data analyzed per FVC quartile. Graphic representation of the percent difference in tidal volume when determined with the standard PBW-based lung-protective equation versus the newly proposed FVC-based lung-centric equation ([FVC/8 – 7 mL/kg PBW] / 7 mL/kg PBW). A negative value on the *x* axis represents the percent reduction in tidal volume by the equation FVC/8 compared with the equation 7 mL/kg, whereas a positive value represents percent increase in tidal volume. The *y* axis delineates the number of patients with any given percent difference in tidal volume. A, The mean change in calculated tidal volume by the FVC-based equation in patients with small lungs (smallest FVC quartile, <2627 mL) was −28.6% when compared with the PBW-based equation. All but 1 patient (who saw a small increase in tidal volume) experienced tidal volume reduction with the new equation. B, The mean change in calculated tidal volume by the FVC-based equation in patients with mid-sized lungs (middle FVC quartiles, 2627–3877 mL) was −2.9% when compared with the PBW-based equation. The bell-shaped distribution highlights that patients with mid-sized lungs experienced increased, decreased, or unchanged tidal volume with the new equation. It is highly likely that the FVC value determined the change an individual patient would experience. C, The mean change in calculated tidal volume by the FVC-based equation in patients with large lungs (largest FVC quartile, >3877 mL) was 16.6% when compared with the PBW-based equation. All but 2 patients (1 saw a small decrease in tidal volume, and the other no change) experienced tidal volume increase with the new equation. FVC indicates forced vital capacity; PBW, predicted body weight.

tidal volumes for patients with small lung volumes and low pulmonary compliance. Compared with the standard lung-protective formula, the proposed equation reduced mean calculated tidal volume in patients with small, noncompliant lungs, increased it in patients with large lungs, and left it largely unchanged in the remainder of the population. The mechanism for ventilator-associated lung injury is complex and not fully understood, but evidence suggests that excessive alveolar stretch, combined with repetitive alveolar open/close cycles, contribute to the injury.[24] For this reason, low lung volumes and positive end expiratory pressure have been widely adopted with the goal of reducing barotrauma/volutrauma and atelectotrauma, respectively. However, ventilator settings that reduce tidal volume often increase atelectasis, requiring increasing levels of positive end expiratory pressure, which can be detrimental in some settings.[25,26] A tidal volume formula based on lung dimensions rather than weight or height could possibly aid in selection of safe ventilator settings while balancing these often opposing requirements. This pilot study was not designed or powered to answer such questions, nor were its results validated on a secondary, nonthoracic surgery patient cohort. Future studies would need to be conducted to determine whether the tidal volume reductions suggested by our proposed equation actually reduce lung inflammation and injury, and whether tidal volume increases in patients with large lungs are indeed safe. Nevertheless, the time has come to look past the dogma of weight- and height-based formulas; new parameters must be studied in the quest for individualized, precision medical care delivery.

There were several limitations due to study design that we wish to address. First, the TLC_{CT} was generated from images acquired in a CT scanner, and thus patients were not coached to the same degree as they were when they had their TLC_{PFT} measured. It is therefore possible that the TLC_{CT} values could have been artificially low due to reduced patient inspiratory effort. However, CT technicians at our facility routinely instruct patients to take a maximally deep breath and hold it during scanning. Furthermore, any images with motion artifact or evidence of submaximal inspiratory effort were eliminated from data analysis. Finally, the correlation between TLC_{CT} and TLC_{PFT} was very strong and identical to a study that compared prospectively collected CT volumes with PFT volumes, thus validating the quality of the CT-generated data.[15] Second, our decision to enroll thoracic surgery patients could confound the relationship between lung volumes and PBW given the higher incidence of lung pathology in this patient population. However, to see an effect difference in a small pilot trial we needed to study a population with an expected high incidence of pulmonary disease and reduced compliance that would likely benefit most from the intervention. Detailed patient history review and analysis of 3D lung images enabled us to identify and exclude patients with anatomical thoracic abnormalities (such as previous lung lobectomy, large intrathoracic mass) that could confound the expected relationship between TLC and PBW. Third, the retrospective nature of ventilator data collection introduced several potential confounders. Because of the lack of a consistent inspiratory pause, we could not reliably measure plateau pressure and thus could not calculate static airway compliance. Instead, we measured dynamic airway compliance, which could be influenced by endotracheal tube diameter, inspiration to expiration (I:E) ratio, and respiratory rate.[27,28] To mitigate the effects of these and other confounders, we excluded patient with tracheal tubes smaller than 8.0-mm single lumen or 35F dual lumen, and collected ventilator data during deep anesthesia and neuromuscular blockade. We are thus confident that endotracheal tube gas flow resistance and patient extrinsic muscle tone did not significantly affect our measured compliance value. Ventilator settings such as respiratory rate and I:E ratio were not different among the 2 compliance subgroups, making it unlikely that these variables had an appreciable effect on our results. Fourth, given that a significant portion of our initial sample population was excluded from analysis due to missing data, we could not exclude the possibility of unforeseen biases skewing the results. For example, only patients with both TLC_{CT} and TLC_{PFT} were included in the lung volume investigation, which further reduced the sample size of that analysis to n = 99. We chose this design in order to eliminate comparisons between 2 overlapping but different (and numerically uneven) patient cohorts, thus simplifying the methods without significantly impacting the results. Finally, the perioperative surgical population studied did not include any critically ill patients with acute lung injury, a cohort that could perhaps benefit most from precise ventilator settings. FVC measurement, being highly effort dependent, may not be well suited for this debilitated patient population.

In conclusion, (1) FVC was more strongly correlated to TLC than was PBW. (2) An FVC value below 3.5 L was 100% sensitive and about 50% specific for detecting patients with low pulmonary compliance. (3) When compared with the PBW-based lung-protective formula (tidal volume = 7 mL/kg PBW), the proposed lung-centric formula Vt = FVC/8 reduced calculated tidal volume in patients with low pulmonary compliance without significantly affecting mean tidal volume in patients with normal compliance. Future research will need to confirm the validity of this model in prospective studies with diverse patient populations.

DISCLOSURES

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