Respiratory mechanics versus imaging in respiratory failure

Marcelo B. P. Amato

Challenges in Mechanical Ventilation and Airway Technologies: A Massachusetts General Hospital and Harvard Medicine School Round Table
May 2016
I disclose the following financial relationships (all happening in the last 5 years) with commercial entities that produce healthcare-related products or services, relevant to the content I am presenting:

<table>
<thead>
<tr>
<th>Company</th>
<th>Relationship</th>
<th>Content Area</th>
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</thead>
<tbody>
<tr>
<td>Medtronics</td>
<td>Consultant</td>
<td>Mechanical Ventilation</td>
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<tr>
<td>Orange Med</td>
<td>Consultant</td>
<td>Mechanical Ventilation</td>
</tr>
<tr>
<td>Philips / Dixtal</td>
<td>Research grants</td>
<td>E.I.T.</td>
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<td>Timpel S.A.</td>
<td>Research grants, consultant</td>
<td>E.I.T.</td>
</tr>
</tbody>
</table>
P-V curves and the potential for recruitment

Richard et al, 2004

Dellamonica et al, 2011
EIT versus CT
Imbalances in Regional Ventilation assessed by EIT

(Victorino, Borges et al. 2004)
Conteúdo de Gás (mL) - dentro da seção da CT dinâmica

EIT – soma dos pixels – com intercepto ajustado por paciente (within patient regression)

$R^2 = 0.950$
(P<0.0001)
Swan Ganz catheter deflated

Control

Perfusion - Dynamic CT

Perfusion - EIT
Swan Ganz catheter inflated at the left pulmonary artery

Inflated volume = 1.5 mL
Swan Ganz catheter inflated at the right pulmonary artery

Inflated volume = 1.5 mL
PEEP 10 cmH$_2$O
PEEP 22 cmH₂O
Ventilation Distribution

Whole Lung

$R^2 = 0.87$

Intercept = 0.024

Slope = 0.9
Bland–Altman plot of EIT vs CT

Whole Lung

Difference: EIT - CT

Average: (EIT + CT)/2
Normal Lungs

Injured
Airway Pressures

CT

Maximum recruitment

Time
Airway Pressures

Maximum recruitment

CT

Time
Percent mass of aerated tissue
(-200HU to +100 HU)

Rastreamento

Recrutamento Máximo

Maximum recruitment
$P_{AW} = 10$

$P_{AW} = 20$

$P_{AW} = 30$

$P_{AW} = 40$
Stepwise Recruitment Strategy

Airway Pressures (cmH₂O)

Baseline
CPAP
OLA

Time

\[ T_{\text{MAX}} = 20 \text{ min} \]

\[ \Delta P = 15 \text{ cmH}_2\text{O} \]

\[ 25 \text{ cmH}_2\text{O} \]
PEEP = 25

ΔVol (REC)
Percent mass of aerated tissue
(-200HU to +100 HU)

Maximum recruitment

Rastreamento

Recrutamento Máximo
Gas Content (mL) - CT

- 1800
- 1300
- 800
- 300

Maximum recruitment

- Gas Content (mL) - CT
- Rastreamento
- Recrutamento Máximo
EIT aeration (sum of pixels)
PEEP = 15

Lung Density (Hounsfield units)

Voxel Counts

- before Recruitment
- after Recruitment
PEEP = 20

**Lung Density** (Hounsfield units)

- **before Recruitment**
- **after Recruitment**
PEEP = 24

Lung Density (Hounsfield units)

-1000 -800 -600 -400 -200 0

Voxel Counts

before Recruitment

after Recruitment
C_RS\text{-}gain = 95%  
Aeration\text{-}gain = 53%  
(\% increase of aerated mass)  
Vol\text{-}gain = 246 mL (18%)  

246

C_RS\text{-}gain = 72%  
Aeration\text{-}gain = 89%  
(\% increase of aerated mass)  
Vol\text{-}gain = 304 mL (17%)  

304

C_RS\text{-}gain = 9\%  
Aeration\text{-}gain = 11\%  
(\% increase of aerated mass)  
Vol\text{-}gain = 542 mL (31%)  

542
A/P 16% 84%
R/L 58% 42%

Z mínimo

ΔZ

Ventilation Map

Dynamic Image

Ventilation Distribution

2%
23%
68%
8%
A comprehensive equation for the pulmonary pressure-volume curve

Jose G. Venegas, R. Scott Harris, and Brett A. Simon

Departments of Anesthesia and Critical Care, and Pulmonary Unit, Department of Medicine, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts 02114

Venegas, Jose G., R. Scott Harris, and Brett A. Simon. A comprehensive equation for the pulmonary pressure-volume curve. J. Appl. Physiol. 84(1): 389–395, 1998.—Quantification of pulmonary pressure-volume (P-V) curves is often limited to calculation of specific compliance at a given pressure or the recoil pressure (P) at a given volume (V). These parameters can be substantially different depending on the arbitrary pressure or volume used in the comparison and may lead to erroneous conclusions. We evaluated a sigmoidal equation of the form, \( V = a + b[1 + e^{-(P - c)/d}]^{-1} \), for its ability to characterize lung and respiratory system P-V curves obtained under a variety of conditions including normal and hypocapnic pneumoconstricted dog lungs \((n = 9)\), oleic acid-induced acute respiratory distress syndrome \((n = 2)\), and mechanically ventilated patients with acute respiratory distress syndrome \((n = 10)\). In this equation, \( a \) corresponds to the \( V \) of a lower asymptote, \( b \) to the \( V \) difference between upper and lower asymptotes, \( c \) to the \( P \) at the true inflection point of the curve, and \( d \) to a width parameter proportional to the \( P \) range within which most of the \( V \) change occurs. The equation fitted equally well inflation and deflation limbs of P-V curves with a mean goodness-of-fit coefficient \((R^2)\) of 0.997 ± 0.02 (SD). When the data from all analyzed P-V curves were normalized by the best-fit parameters and plotted as \((V - a)/b\) vs. \((P - c)/d\), they collapsed into a single and tight relationship \((R^2 = 0.997)\). These results demonstrate that this sigmoidal equation can fit with excellent precision inflation and deflation P-V curves of normal lungs and of lungs with alveolar derecruitment and/or a region of gas trapping while yielding robust and physiologically useful parameters.
EQUATION FOR PULMONARY PRESSURE-VOLUME CURVES

\[ \frac{V-a}{b} = \left( \frac{1}{1 + e^{\frac{P-c}{d}}} \right) \]

\( (R^2 = 0.997) \)

\[ V = (A - B e^{-kP}) \]

\( (R^2 = 0.991, \text{ for } (V-a)/b > 0.5) \)
These analyses have been used to describe the effect of aging (Colebatch et al., 1979a), to characterize emphysema (Gibson et al., 1979; Greaves and Colebatch, 1980), and to assess the role of intermediate alpha-1-antitrypsin deficiency in the etiology of emphysema (Tattersall et al., 1979).

![Graph of exponential representation of static deflation pressure (P)–volume (V) curve fitted to data between functional residual capacity (FRC) and total lung capacity (TLC). The curve is extrapolated to define the volume at infinite pressure (V_{max}) and volume at P = 0 (V_o). The difference V_{max} - V_o defines A.](image)

Fig. 1. Exponential representation of static deflation pressure (P)–volume (V) curve fitted to data between functional residual capacity (FRC) and total lung capacity (TLC). The curve is extrapolated to define the volume at infinite pressure (V_{max}) and volume at P = 0 (V_o). The difference V_{max} - V_o defines A.
Fig. 9. Hypothetical P–V curves with values for k from 0.05 to 0.30. The volume axis is expressed as percent of Vmax and $V_o = 0^\circ$. For explanation, see text.
$R^2 = 0.76$
(global – within-patients)

Regression Confidence Interval : 95% CI for individuals
\[ R^2 = 0.91 \]
(global – within-patients)

Regression Confidence Interval: 95% CI for individuals
Is CT enough ????!
Red = hyperaerated tissue
PEEP=25 - Inspiração

Red = hyperaerated tissue
PEEP = 5; $P_{\text{PLAT}} = 25$
PEEP = 25; $P_{PLAT} = 40$
PEEP 5 – ΔP 6 cmH$_2$O
PEEP 25 – ΔP 6 cmH$_2$O
Bedside estimation of recruitable alveolar collapse and hyperdistension by electrical impedance tomography

Cumulated collapse (%) = \[ \sum_{\text{Pixel}=1}^{860} \left( \text{Collapse}_{\text{pixel}}(\%) \times \text{Best compliance}_{\text{pixel}} \right) \]
\[ \sum_{\text{Pixel}=1}^{860} \left( \text{Best compliance}_{\text{pixel}} \right) \]
Hyperdistension image

Cum. Collapse image

No arbitrary thresholds!!

Not biased by baseline densities!!
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
25.4
delta P
8
Collapse (%)
0
Overdistension (%)
28.02

BERALDO, MA. UNPUBLISHED DATA . LIM 09
FMUSB
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
23.4

delta P
8.02

Collapse (%)
1

Overdistension (%)
22.2

BERALDO, MA. UNPUBLISHED DATA. LIM 09
FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
21.4

delta P
8.06

Collapse (%)
1.45

Overdistension (%)
16.9

BERALDO, MA. UNPUBLISHED DATA. LIM 09
FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step 19.4
delta P 7.97
Collapse (%) 2.04
Overdistension (%) 10.99
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step 17.4

delta P

7.94

Collapse (%) 5.09

Overdistension (%) 6.59

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FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
15.6

delta P
7.93

Collapse (%)
10.37

Overdistension (%)
3.88

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FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
13.5

delta P
7.92

Collapse (%)  
16.92

Overdistension (%)  
2.32

BERALDO, MA. UNPUBLISHED DATA . LIM 09
FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
11.4

delta P
7.91

Collapse (%)
26.8

Overdistension (%)
0.95

BERALDO, MA. UNPUBLISHED DATA. LIM 09
FMUSP
PEEP TITRATION BY EIT

Overdistension

Collapse

PEEP Step
9.5
delta P
8.01
Collapse (%)
35.56
Overdistension (%) 0

BERALDO, MA. UNPUBLISHED DATA. LIM 09 FMUSP
SUPINE POSITION DECREMENTAL PEEP TITRATION
Lung US score and collapse EIT

Collapse estimated by EITw vs. LUS

Lung Ultrasound Score

Collapse estimated by EIT (%)
PEEP 25 – ΔP 6 cmH₂O
<table>
<thead>
<tr>
<th>Step</th>
<th>PEEP</th>
<th>delta P</th>
<th>Collapse (%)</th>
<th>Overdistension (%)</th>
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<td>8</td>
<td>0</td>
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<td>8.02</td>
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**SUPINE POSITION**

**DECREMENTAL PEEP TITRATION**
PRONE POSITION
DECREMENTAL PEEP TITRATION
Amount of overinflated tissue by EIT

PEEP LEVELS (cmH$_2$O)

% of overinflated tissue

Decremental

N=10

Prone

Supine
Severe case of ARDS caused by Influenza H1N1
25 year-old female patient
Computerized tomography

EIT image – hyperdistended areas during high PEEP (23)
Graph representing the estimates of collapse and overdistension during the PEEP titration. The red arrow represents the PEEP level where we have the best compromise between both phenomena.
Airway Pressure (PEEP) = 0 cmH₂O

Collapse: 55.6 %

Patient # 9
Pneumocystis carinii pneumonia

Slow
Patient #9

Pneumocystis carinii pneumonia

Airway Pressure = 0 cmH₂O

Collapse: 38.4%
AIRWAY PRESSURE = 0 (slow decay)
AIRWAY PRESSURE = 0  (fast decay)

Fast
Thank You!