Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2524, 2 Pages

Infinite Science Publishing

Estimating respiratory effort: a systematic model analysis

C. Globig[1*], T. Lerg[1], P. Rostalski[1,2], and J. Graßhoff[1]

[1] Fraunhofer Research Institution for Individualized Medical Technology and Engineering IMTE, Lübeck, Germany

[2] Institute for Electrical Engineering in Medicine, University of Lübeck, Lübeck, Germany

[*] Corresponding author, email: charlotte.globig@imte.fraunhofer.de

Abstract: Assessment of respiratory effort is essential during mechanical ventilation, especially in patients suffering from acute respiratory distress syndrome (ARDS). Surface electromyography (sEMG) provides a non-invasive, model-based approach for continuously monitoring inspiratory effort. However, the optimal model for the widespread, but challenging case of ARDS patients remains unclear. Hence, we evaluated models of varying complexity combining pneumatic and sEMG measurements for 16 patients. The complex models best describing our data do not improve estimation results with a simpler model reaching similar performance, likely due to increasing susceptibility to multicollinearity for increasing model complexity.

I. Introduction

Mechanical ventilation (MV) plays a crucial role in the intensive care unit, allowing for adequate gas exchange and preventing lung collapse [1]. Especially for patients suffering from acute respiratory distress syndrome (ARDS), MV remains crucial. However, if the ventilation support is not adapted correctly to the patient's breathing effort, MV may be harmful, resulting in lung injury and diaphragm atrophy [2].

To assess the patient's breathing effort, measurements of esophageal pressure (P_{es}) can be employed. Using an air-filled balloon catheter, placed in the esophagus, it allows for the derivation of inspiratory muscle pressure (P_{mus}). However, P_{es} measurements are uncomfortable for the patient and require expensive, single-use catheters, limiting their application in the intensive care unit [3]. Another approach utilizes the non-invasive, electrical measurement of inspiratory muscle activity using surface electromyography (sEMG). Combined with a respiratory model, it has been shown to achieve accurate assessment of breath wise P_{mus} for non-ARDS patients ($\rho \geq 0.87 \pm 0.09$) [4]. However, model-based estimation is generally limited by model accuracy and identifiability. Combined with changes in lung mechanics as expected for ARDS patients, a simple model might not be sufficient to reliably assess muscular pressure. Hence, this article investigates the capability of lumped-parameter pneumatic and electromyographic models of varying complexity to assess P_{mus} using sEMG measurements.

II. Material and methods

This study was based on data from ARDS patients at Charité – Universitätsmedizin Berlin, previously published by Sauer et al. [5]. Data collection yielded 84 recordings across 36 patients, including airway pressure (P_{aw}), airway flow ($\dot{V}$), sEMG for the diaphragm and intercostal muscles and esophageal pressure (P_{es}). Cardiac activity was suppressed in sEMG and P_{es} signals. Chest wall elastance was determined and a volume-dependent recoil correction was applied to P_{es} to obtain a reference P_{mus}. Envelopes of both sEMG signals were calculated using a 250 ms root-mean-square filter. For each recording, the sEMG channel with best SNR as stated by Graßhoff et al. [4] was selected. Recordings that showed inspiratory activity in each signal and where correct P_{es} scaling could be ensured through occlusion maneuvers were included, resulting in 24 recordings across 16 patients.

II.I. Models

Different approaches for lumped-parameter pneumatic and electromyographic modeling were compared. Pneumatic models were based on the equation of motion (EqM) [6]:

$$P_{\mathrm{aw}} = R \cdot \dot{V} + E \cdot V - P_{\mathrm{mus}} + P_0. \qquad (1)$$

This basic model simplifies the lung as a single, distensible compartment with volume V. Airflow $\dot{V}$ passes in and out through a tube with flow resistance R. The compartment recoils with elastance E [6]. At the end of the tube airway pressure P_{aw} is measured. This model was extended from its passive form by incorporating P_{mus}. In the most basic form, the electromyographic models assume a linear relationship between P_{mus} and the sEMG envelopes via

$$P_{\mathrm{mus}} = K \cdot \mathrm{sEMG}. \qquad (2)$$

Both models were gradually extended by adding additional, nonlinear components, comprising, in the most complex pneumatic model considered in this analysis, flow-dependent resistance and volume-dependent elastance:

$$P_{\mathrm{aw}} = R_1 \cdot \dot{V} + R_2 \cdot \dot{V} \cdot |\dot{V}| + E_1 \cdot V + E_2 \cdot V^2 - P_{\mathrm{mus}} + P_0. \qquad (3)$$

The sEMG model was extended analogous yielding in its most complex form considered:

$$P_{\text{mus}} = K_1 \cdot \text{sEMG} + K_2 \cdot \text{sEMG}^2 + K_0 \qquad (4)$$

with an additional quadratic term to capture nonlinear behavior at high breathing effort [6] and an offset. Initially, both types of models use P_{mus} derived from P_{es} as reference. Substituting the sEMG model into the pneumatic model yields a fusion model that enables reference-free parameter estimation for the most complex models:

$$P_{\text{aw}} = R_1 \cdot \dot{V} + R_2 \cdot \dot{V} \cdot |\dot{V}| + E_1 \cdot V + E_2 \cdot V^2$$
$$-K_1 \cdot \text{sEMG} - K_2 \cdot \text{sEMG}^2 + P_0. \qquad (5)$$

A reconstruction of P_{mus} can then be achieved by inserting the estimated parameters into a) model eq. (3) or b) model eq. (4). Another fusion model combining eq. (1) and (2) was evaluated analogous, but inserted in eq. (1) and (2) as a performance baseline:

$$P_{\text{aw}} = R \cdot V + E \cdot \dot{V} - K \cdot \text{sEMG} + P_0. \qquad (6)$$

II.II. Evaluation

For all recordings included, parameters were estimated using ordinary least squares. For parameter estimation of the pneumatic and sEMG model P_{mus} was derived from P_{es} as reference. Model performance and constructed signals were evaluated using coefficient of determination R^2, mean absolute error (MAE) and Spearman's rank correlation coefficient ρ. Possible multicollinearity was assessed using condition numbers as well as variance inflation factors (VIF) for sEMG, V and $\dot{V}$.

III. Results and discussion

For both pneumatic and sEMG models, the most complex models showed best model performance with R^2 = 0.87, MAE = 1.45 mbar, ρ = 0.54 for the pneumatic and R^2 = 0.41, MAE = 1.62 mbar, ρ = 0.46) for the sEMG model, as displayed in fig. 1. Interestingly, the extension to a two-compartment pneumatic model as described in [6] did not improve performance, the simpler single-compartment model might capture lung mechanics in ARDS patients sufficiently. However, the rather low correlation coefficients (< 0.6) for either model reveal that neither model describes the underlying data reliably. Combining the two best performing models (eq. (5)), did not improve P_{mus} reconstruction compared to the individual models (R^2 = 0.73; a): MAE = 2.4 mbar, ρ = 0.22; b): MAE = 1.91 mbar, ρ = 0.38). This indicates that adding model characteristics does not automatically improve performance, which aligns with results from Perrin et al. for hydrological models [7] highlighting the estimation challenges introduced with increasing model complexity.

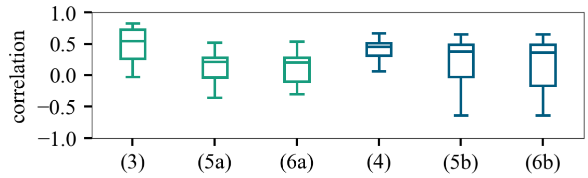

Figure 1: Correlation coefficients. Isolated models (3)-(4) vs. fusion models (5)-(6) using corresponding a) pneumatic or b) electromyographic eqs. for P_{mus} reconstruction.

One factor that must be taken into consideration is the possibility of multicollinearity. Fig. 2 depicts two measures indicating collinearity, namely VIF and condition number.

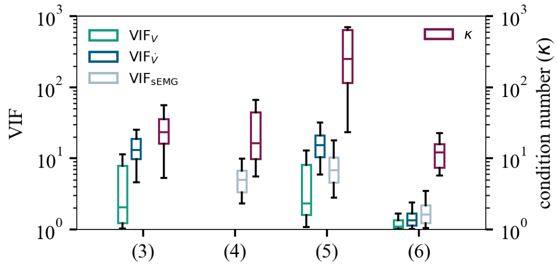

Figure 2: VIFs for V, $\dot{V}$, sEMG and condition numbers (κ) for selected models (3) and (4) and fusion models (5) and (6).

When comparing the results of the fusion model of eq. (5) to the simplest fusion model of eq. (6), despite the more complex model better describing the data, the simple model suffers less from multicollinearity and therefore achieves similar performance (R^2 = 0.7; a): MAE = 2.62 mbar, ρ = 0.2; b): MAE = 1.86. mbar, ρ = 0.37).

With moderate correlation (ρ > 0.5) the most complex pneumatic model shows great promise of describing the underlying data. Correlation in sEMG models was slightly lower due to low SNR. Performance decreases for complex fusion models which might be because of multicollinearity.

IV. Conclusions

Pneumatic and sEMG models enable estimation of lumped parameter lung mechanics. While more complex models show higher flexibility to fit the data, they may lead to multicollinearity. Thus, estimation with simpler fusion models preserves identifiability and may often be preferable for calculating respiratory effort in ARDS patients.

AUTHOR'S STATEMENT

This work resulted as part of the project "Verbundprojekt: Protektive Beatmungstherapie basierend auf Elektromyographie (PreVent)" funded by the Federal Ministry of Research, Technology and Space (BMFTR), Funding code: 13GW0717B. Conflict of interest: Jan Graßhoff and Philipp Rostalski hold patents with Drägerwerk AG & Co. KGaA and have received research grants and speaking fees from Drägerwerk AG & Co. The study was approved by the local ethics committee (EA4/005/19) and registered at the German Clinical Trials Register (DRKS00017138).

REFERENCES

[1] E. C. Goligher et al., *Clinical challenges in mechanical ventilation*, The Lancet, vol. 387, no 10030, 2016.

[2] E. C. Goligher et al., *Lung- and Diaphragm-Protective Ventilation*, American Journal of Respiratory and Critical Care Medicine, vol. 202, no. 7, 2020.

[3] A. H. Jonkman et al., *The oesophageal balloon for respiratory monitoring in ventilated patients: updated clinical review and practical aspects*, European Respiratory Review, vol. 32, no. 168, 2023.

[4] J. Grasshoff et al., *Model-Based Estimation of Inspiratory Effort Using Surface EMG*, IEEE Transactions on Biomedical Engineering, vol. 70, no. 1, 2023.

[5] J. Sauer et al., *Automated characterization of patient–ventilator interaction using surface electromyography*," Annals of Intensive Care, vol. 14, no. 1, 2024.

[6] J. H. T. Bates, *Lung Mechanics: An Inverse Modeling Approach*, Cambridge University Press, 2009.

[7] C. Perrin et al., *Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments*, Journal of Hydrology, vol. 242, no 3-4, 2001.