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VALIDATION OF A RECRUITMENT MODEL WITH EIT IMAGING

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Abstract— Mechanical ventilation is a standard and necessary treatment at lung injuries like the acute respiratory distress syndrome. But ventilator induced injuries are possible consequences especially at patients with long time ventilation or mislead settings. The prevention of such injuries can be optimized by finding an optimal model for the patients lung and identify the patients specific parameters of such models. In focus is the patients' resistance, compliance and threshold opening pressure (TOP - which represents the ideal pressure for opening and holding collapsed alveoli open for better oxygenation). In this study the so called "pressure recruitment model" (PRM) which is a combination of alveoli recruitment and static as well as dynamic effects of lung tissue implemented by C. Schranz, should be pre-validated.

The algorithm is based on a combination of Hickling's lung layer model and Salazar's pressure-volume relationship of alveoli and here tested with six patient datasets. Every patient underwent a Low-Flow maneuver with 4ml/min which is the necessary input for the PRM-calculations. Identified parameters of the PRM are compared with the first order lung model (FOM) and an electrical impedance tomography (EIT) method.
The PRM is showing a up to ten times better fitting quality compared to the FOM. Although the results in part of lung compliance is illogically higher in the PRM than in the FOM. Accordance between the EIT method and the algorithm from Schranz in case of TOP could not be found. In both comparisons further studies must be done to exclude influence factors for the different models and improve the performance.

Keywords— Validation, recruitment, lung model, EIT, ARDS

I. INTRODUCTION

Mechanical ventilation in intensive care units is a common and necessary treatment in lung injuries like the acute respiratory distress syndrome (ARDS). But mechanical ventilation is not only an support of the human lung, it can cause ventilator induced lung injuries especially in long time ventilated patients. [1,2]To avoid such induced injuries is related with a better understanding of the lung and adaption of the treatment strategy to the patient situation. But this situation is not only correlated to the present reason of ventilation like ARDS. Another task is the individualization of ventilator settings corresponding to the patients' state and properties. Finding these properties can be made by trial and error, experiences, and scanning techniques or by mathematical models. Scanning techniques and models become more important in the last years because they are more gently to the patients and didn't need prior knowledge (particularly for young inexperienced doctors). Different kinds of models and techniques are exist which are all valid in their specific fields of application and needing therefore different measurement devices and data. We are concentrating here on patients which are suffered from ARDS.

ARDS patients are suffered by stiff lung alveoli which are partly collapsed. Open such lung-regions are a standard procedure to improve oxygenation. Buta periodic reopening and collapse of these alveoli can cause inadvertent stress and further damage; therefore a positive-end-expiratory-pressure (PEEP) is applied to hold them open. Health care staff partly using ventilation settings out of the pressure-volume diagram to find optimal settings. This diagram can be split in an alveoli opening-, a linear relationship- and an over distension-part of the lung. In the area of the linear shape it was assumed that no further reopening of alveoli is happening and ventilation it this range is optimal. Deductive it seems logical to set the PEEP to the start of the linear shape. But due to the work of Hickling these assumption can be partly revised.

He showed that anoverall PEEP to avoid collapse of anyalveoli isn't exist and eachalveolus needs a different value partly corresponding to its position.[3] Additionally Salazar found that the compliance of the lung (which represents the elasticity of lung tissue) is changing related to the pressure applied to the lung units. [4] So the optimal range in the pressure-volume-diagram and resulting ventilator settings can be hidden or mislead by such effects.

So finding an optimal threshold opening pressure (TOP) to avoid too much cycling is not as easy. Computer tomography (CT) scans are a common method to make out TOP's. But high radiation doses for patients are reluctantly effects of this method. Another radiation free possibility can be the use ofelectrical impedance tomography (EIT) images. Such EIT images are based on in the impedance change of lung tissue while a breath. Such a change can be used to determine the TOP's by the assumption that the opening pressure of each unit is 10% of the maximum change of this lung unit while the breath. [7] Though this method is still in validation.

Not only the TOP's have an influence in the optimal ventilation settings of a patient. The patient specific parameters like the overall compliance and resistance of lung tissue are factors which must be additionally involved to find the optimal treatment strategy.

So a further method without the necessity of an EIT or CT device could be lung-models. Such a model was recently proposed by C. Schranz [5] called the pressure recruitment model (PRM). It combines static relationships as well as dynamic relationship of the lung. The aim of this study is to validate the PRM algorithm compared to the first order lung model (FOM) in patient specific parameters and compared to the EIT method to find TOP.

II. MATERIALS & METHODS

A.Models & Parameters

The FOM is one of the simplest models in lung simulation and lung identification. It is based on an electrical circuit with a resistor and a capacitor. In this analogy the volume flow $\dot{V}$ is represented by the floating current, the bronchial tree by an electrical resistor R_{FOM} and the sum of all alveoli, including all other elastic effect, by a capacitor as the overall compliance C_{FOM}. The airway pressure p_{aw}can be illustrated as overall voltage [6]:

$$p_{aw} = R_{FOM} \cdot \dot{V} + \frac{1}{C_{FOM}} \cdot \int \dot{V}\, dt \qquad (1)$$

The PRM can be easily described as a FOM with a variable capacitor which values are depending on pressure. It is based on the recruitment model of Hickling considering a lying patient and Salazars compliance-pressure relationship as described.[4] In the Hickling model the lung is spit in 30 layers with distributed opening pressures in each layer [3] This PRM was implemented by Schranz [5] in Matlab (The Mathworks, Massachusetts, USA). The FOM and the PRM parameter identification is based on patient data which underwent a Low-Flow-manoeuvre.

The FOM and the PRM are combined as hierarchical parameter identification. The result of the FOM is used as initial values for the PRM. The K value was here fixed to 0.03 whereas the other parameters were free for the identification. The PRM algorithm consists of the equation:

$$p_{aw} = R_{PRM} \cdot \dot{V} + \int \frac{\dot{V}}{(C_{init} + C_{rec})} dt \qquad (2)$$

With

$$C_{init} = C_{FRC} \cdot e^{-K \cdot p_a} \qquad (3)$$

$$C_{rec} = C_L \cdot \sum_{n=1}^{30} H_n \cdot e^{-K \cdot (p_a - SP_n - TOP)} \qquad (4)$$

Whereas C_{FRC} is the initially compliance of the alveoli, C_L representing the recruited alveolar units, K describes the decreasing speed of the compliance by increasing pressure, R_{PRM} equals the resistance in the PRM, H_n denotes if the set of alveoli units are recruited ($H_n = 1$) or not recruited ($H_n = 0$), SP_n equals the superimposed pressure described by Hickling.

The algorithm calculates the patient parameters by minimizing the sum of squared errors (SSE) between the measured and the simulated p_{aw} from the models using a gradient based method:

$$SSE = \sum (p_{aw,meas} - p_{aw,sim})^2 \qquad (5)$$

To make a clear statement over the fitting quality the coefficient in determination (CD) is calculated which represents the goodness of a fit. A CD of 1 means perfect fit whereas a CD of 0 means no relationship between fit and simulation:

$$CD = 1 - \frac{SSE}{\sum (p_{aw,sim} - \bar{p}_{aw,meas})^2} \qquad (6)$$

With $\bar{p}_{aw,meas}$ is the mean value of all measured airway pressures in the dataset.

The identification shows small changes in the SSE of the TOP. [5] To prevent identification error due to that flat local minima. The algorithm is run multiple with initial TOP values between 2 up to 12 in increment steps of 2.

B. Comparison between EIT and PRM

The EIT images were analyzed for determining the opening pressures according to Pulletz et al. [7] taking the 10% value of the maximum impedance change.

All EIT lung-unit opening pressures are evaluated in a histogram to the most popular value and compared with the PRM-TOP.

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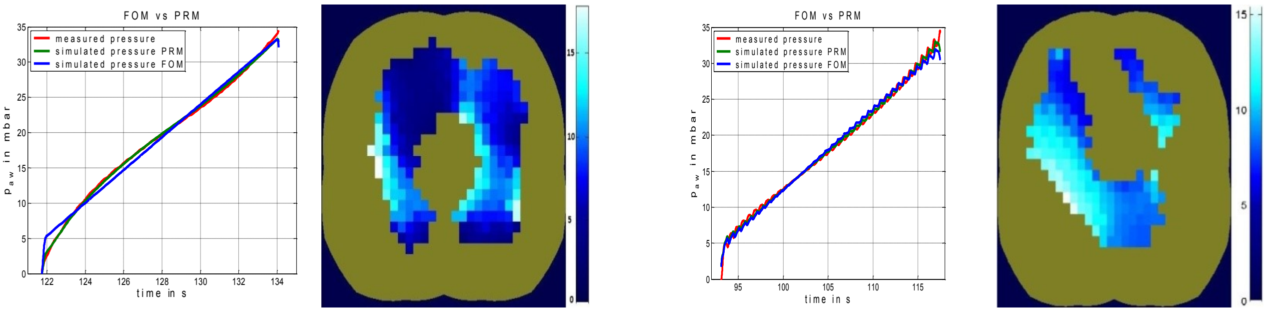

a b b d

Figure 1: Pressure while Low-Flow manoeuvre and corresponding model fits of FOM and PRM of patient 1 (a) and patient 2 (c). EIT images of opening pressures while inspiration of patient 1 (b) and patient 2 (d).

C. Patient Data & manoeuvre description

The Low-Flow manoeuvre is used in volume controlled ventilation. A constant flow is applied to the patient till a maximal pressure or the target volume is achieved. During the manoeuvre the pressures as well as the volume are continuously recorded.
Clinical data of six patients ventilated with an Evita XL ventilator (Draeger medical, Luebeck, Germany) were taken for this study. Corresponding lung diagnosis for each patient is described in table 1
.

Table 1: Patient data

No.	Diagnosis
1	Sepsis: moderate ARDS
2	Sepsis: moderate ARDS
3	Trauma: moderate ARDS
4	Sepsis: mild ARDS
5	Lung healthy
6	Lung healthy

Every patient underwent a Low-Flow-Manoeuvre with 4 L/min. The inspiration part of each manoeuvre were cut out and smoothed twice for suppressing noise (*smooth*-function using Matlab). Smoothing filtering was done by using of a moving average filter with a filter length of 20 samples.

III. RESULTS

The obtained results of the PRM algorithm are showing an increase in fit quality compared with the FOM in every patient. The PRM showing a 2 - 10 times better result in the SSE and an increase in CD from mean CD_{FOM} = 0.9944 to CD_{PRM} = 0.9983. An example can be seen in fig. 1-a and table 2 at patient 1. But the usage of the FOM in some patients is still sufficient whereas PRM only fits the noise to get a better result as shown in fig1-c. The PRM results in every patient in a higher compliance.

Table 2: Parameter comparison FOM, PRM and EIT

	FOM		PRM			EIT
	C	R	C	R	TOP	TOP
Patient 1	25	0.086	43	0.042	4	4
Patient 2	51	0.080	79	0.085	0	11
Patient 3	84	0.073	129	0.057	0	5
Patient 4	49	0.079	80	0.067	3	7
Patient 5	116	0.029	173	0.024	0	3
Patient 6	73	0.113	121	0.080	2	7

C in ml/cmH_2O; R in cmH_2O/l/s; TOP in mbar

The TOP values out of the PRM compared with the EIT data coincide only at one of six patients as illustrated in table 2, with high accordance in TOP at patient 1 (fig1-b) and no accordance in patient 2 (fig1-d).

IV. DISCUSSION

The PRM improves the model-to-patient fit quality especially in the SEE compared to the FOM. But in fact these improvements are most due to the better fitting of the resistance and resulting that increasing the compliance. But such increase, especially in ARDS patients, is not deceptive because a stiffer lung is generally assumed. This mislead could be influenced by three reasons. The SSE-function of the resistance $R_{PRM}$is very flat which influences the result of the other parameter.

Due to that it could be sufficient to hold the R-value from the FOM model by calculation the PRM or using more strict criteria to such value. Another reason could be the holding of the K value. This value was held cause of negative results after the tries of gradient search. Giving the possibility of varying this value (in a strict range) could lead to more logical results. The last influence factor could be the decision making by searching the lowest SSE. The variation in different initial TOP's and comparison of the SSE can be the solution. Maybe the next slight higher SSE (resulting in another TOP) leads to more accurate parameterisation.

Another possibility of the high compliance values in the PRM can be that some patients are so called: non-recruiters. Such patients cannot be recruited by ventilation in any way. The PRM assumed to have recruiters and is not possible to change this. Especially in the healthy patients the results were predictable.

The comparison between EIT- and PRM-TOP endsin the conjecture that the PRM is totally wrong. But with a detailed view to the EIT images areas of high necessary TOP's can be observed. Such high values lead to the assumption of being artefacts. This would suppose that lung tissue movement was happened which therefore let doubt about the validity of each other EIT-pixel. To check such movement a deeper look through all EIT-images of each patient should be done to exclude or weight such artefacts in the algorithm. Furthermore the choice of 10% of the maximal impedance change for calculating the TOP's could be not the universal solution. A patient's specific adaption of this percentage would be an additional idea. But to find factors for this adaption, further studies have to done. Another possibility of the mismatch between EIT and PRM could be the present of noise still in the smoothed data at 4 of 6patients. Such noise like heartbeats influences the algorithm to detect wrong TOP values and is ending in noise fitting.

In general either the EIT as well as the PRM algorithm could be wrong. Both methods for determining the TOP are still not totally validated. Further studies like a comparison with CT-imaging methods to prove the PRM (as well as the EIT-method) should be done.

Summarized the PRM has the possibility to support medical stuff in decision making if a patient is a recruiter or not. This has further influence of the ventilator settings and can therefore help to avoid ventilator-induced lung injuries.

V. CONCLUSION

The PRM algorithm improves the fitting quality compared to the FOM. Neither the less the results especially in the compliance are unrealistic. In the TOP values accordance to the EIT method could not be seen. Further studies and adaption of the algorithm must be done.

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