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On-line monitoring of lung mechanics during spontaneous breathing: a physiological study

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Summary

Background: Monitoring the mechanics of breathing in patients with advanced chronic obstructive lung diseases prior to lung transplantation is useful to characterize changes in the mechanical properties of the lungs. On-line methods of monitoring immediately process the data for clinical decisions. However, the few available methods are so far limited to monitor respiratory mechanics in ventilator-dependent patients. We investigated whether on-line monitoring of the lung mechanics, including intrinsic PEEP, was feasible in spontaneously breathing patients.

Methods: In 9 stable patients with chronic obstructive pulmonary disease (COPD) and 11 with cystic fibrosis (CF) undergoing the procedure for the lung transplantation waiting list, we applied 2 methods of on-line monitoring (modified recursive least squares, RLS and modified multiple linear regression methods, SLS) of intrinsic PEEP (P_0), dynamic lung elastance (E_{Ldyn}) and inspiratory resistance (R_{Linsp}), and compared them with an off-line graphical analysis (GA), our reference technique.

Results: In CF patients, there was no difference between methods, while in COPD, the median values of E_{Ldyn} and R_{Linsp} were significantly different between GA/SLS and GA/RLS, respectively (Dunn's, $p < 0.05$). However, the correlation was very high for all comparisons, particularly for

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E_{Ldyn} ($R > 0.98$) and R_{Linsp} ($R > 0.93$). Moreover, Bland–Altman plots showed that the mean differences were consistently low and the intervals of agreement reasonable.
Conclusions: Our study suggests that on-line methods are reliable for monitoring lung mechanics in spontaneous breathing patients with severe lung diseases and could help clinicians in their decision-making process.

Introduction

In patients with advanced chronic obstructive pulmonary disease (COPD) or cystic fibrosis (CF), the normal structure of the lungs is completely and irreversibly deranged.[1–4] Gas exchange is profoundly impaired and lung mechanics is severely abnormal.[5,6] The patients need long-term oxygen therapy and, in some instances, chronic home ventilatory support.[7–9] In most patients dyspnea becomes unbearable even for the simplest daily activities.[10] Measurement of respiratory mechanics could be important to gain an insight into the pathophysiology of the diseases, as well as to assess the evolution and effects of treatments.[11–14] For example, inspiratory lung resistance is a useful measure to select patients with emphysema for lung volume reduction surgery.[15,16] However, the measurement of lung mechanics in actively breathing patients requires the esophageal balloon-catheter technique.[17,18] This well standardized technique has been used for many years for research purposes,[18–20] but it has failed to penetrate the clinical settings. Firstly, it is commonly considered uncomfortable for the patients and poorly suitable for the clinical practice. Secondly, the conventional off-line methods for measuring lung mechanics require time to provide the results such that the data are not available in due time for the decision-making process. By contrast, on-line methods can be implemented in the data acquisition software to get real-time monitoring of key physiologic variables such as resistance, elastance and intrinsic positive end-expiratory pressure (PEEPi).[21,22] In particular, PEEPi reflects the magnitude of dynamic pulmonary hyperinflation, a key event in the pathophysiology of obstructive pulmonary disease.[23–25]

The few available methods for on-line monitoring of the mechanics of breathing were limited so far to ventilator-dependent patients without respiratory muscle activity.[12,26,27] In spontaneously breathing (SB) patients, non-invasive assessment of respiratory mechanics can be performed using the forced oscillation technique (FOT).[28,29] However FOT is not suited to measure PEEPi.

This study aimed to investigate whether on-line monitoring of lung mechanics, including PEEPi, was possible in SB patients. We adapted two methods [21,22] and compared their results with a traditional off-line graphical analysis,[30,31] which was our reference method. We thought that the availability of on-line methods to measure and monitor the mechanical properties of the lungs might help the clinicians in the difficult decisions for the therapeutic strategies in those severe patients.

Table 1 Patients' anthropometrics data and lung volumes. Mean values (±SD).

		COPD $n = 9$	CF $n = 11$
Age (yrs)		57.9 (±7.9)	28.4 (±6.6)
Height (cm)		167.8 (±6.3)	165.4 (±12.3)
Weight (kg)		70.6 (±12.0)	54.0 (±10.7)
BMI		25.0 (±3.5)	19.6 (±1.9)
VC (L)	abs	2.36 (±0.52)	1.92 (±0.56)
	%pr	64 (±11)	46 (±9)
FEV_1 (L)	abs	0.66 (±0.24)	0.94 (±0.31)
	%pr	23 (±9)	26 (±6)
FEV_1/VC (%)	abs	28 (±9)	48 (±7)
	%pr	36 (±12)	58 (±8)
IC (L)	abs	1.63 (±0.33)	1.41 (±0.44)
	%pr	62 (±10)	49 (±8)
FRC (L)	abs	4.38 (±1.21)	2.38 (±1.50)
	%pr	139 (±43)	81 (±38)
RV (L)	abs	3.62 (±1.04)	1.90 (±1.47)
	%pr	171 (±55)	125 (±77)
TLC (L)	abs	5.98 (±1.31)	3.82 (±1.88)
	%pr	101 (±23)	66 (±19)

Abbreviations: SD: standard deviation; COPD: chronic obstructive pulmonary disease; CF: cystic fibrosis; *n*: number of patients; BMI: Body Mass Index; VC: vital capacity; FEV_1: forced expiratory volume in 1 s; IC: inspiratory capacity; FRC: functional residual capacity; RV: residual volume; TLC: total lung capacity. Abs: absolute value; %pr: percentage of predicted value.

Materials and methods

Patients

Twenty-three patients, 10 with a diagnosis of severe COPD and 13 with severe CF, were initially enrolled in this study. The patients were evaluated in the Pulmonary Division of the Bergamo General Hospital enter the waiting list for lung transplantation. Two patients (1 COPD and 1 CF) were excluded because of technical problems with the measurement equipment (balloon-catheters or A/D converter). Another CF patient asked to stop the study because of personal discomfort. Table 1 shows the mean values of anthropometric data and lung volumes (MS-PFT Analyzer Unit, Erich Jaeger GmbH, Germany) of the 20 patients who completed the procedure. The patients' clinical respiratory conditions were stable at the time of the examination.

Measurements

Pressure at the airway opening (Pao) and flow (V') were recorded during spontaneous breathing by a heated pneumotachograph coupled to a pressure transducer (pediatric, Hans Rudolph Inc., Kansas City, MO) and connected to a mouthpiece. The pneumotachograph was calibrated using

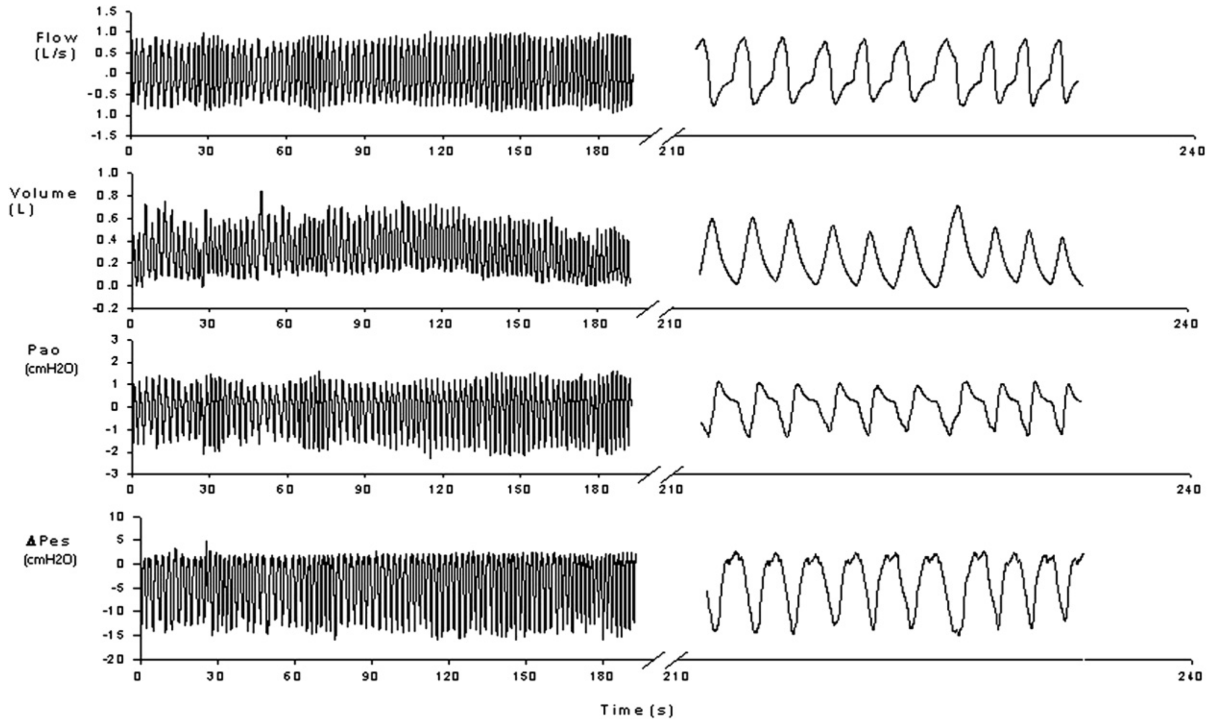

Figure 1 Plots of flow, volume, pressure at airways opening (Pao) and esophageal pressure (ΔPes) in a patient with CF, in spontaneous breathing.

a super-syringe and had to be linear over the experimental range of flow (0—160 L/min). Volume (V) was obtained by the numerical integration of flow. Esophageal pressure was recorded using standard balloon-tipped catheters (Microtek Medical B.V., Zutphen, NL) connected to internal pressure transducers and was used as index of changes in pleural pressure (ΔPes). As demonstrated by Milic-Emili et al.,[18] based on dynamic occlusion test, it appears that in general, during spontaneous breathing and sitting position, the dynamic changes of Pes closely reflect the corresponding changes in Ppl. So, during occluded breaths, ΔPao should closely reflect ΔPpl, and hence a concordance between ΔPao and ΔPes should indicate that the dynamic changes of Pes are a valid index of overall ΔPpl. A single length of standard noncompliant tubing (80 cm long) was used.[18] All signals were recorded on a personal computer via a 16-bit analog-to-digital converter (Direc/NEP model 201A, Raytech Instruments, Canada) at a sample rate of 100 Hz.

Minute ventilation (V'_E), tidal volume (V_T) and respiratory frequency (f) were calculated from the flow and volume signals. Transpulmonary pressure (Ptp) was computed as the difference between Pao and ΔPes. Fig. 1 illustrates a few minutes of V', V, Pao and ΔPes recorded in a patient with CF. The tidal inspiratory muscle effort, estimated as the maximal variations of Pes (swingPes), was also measured. The neuromuscular drive was estimated by the decrease in airway opening pressure at 0.1 s ($P_{0.1}$) after the onset of an inspiratory effort against an occluded airway (Rapid valve, Direc/NEP model 201A, Raytech Instruments, Canada).[32] Lung mechanics (dynamic PEEPi (PEEPi,dyn), inspiratory lung resistance (R_{Linsp}) and inspiratory dynamic lung elastance ($E_{L,dyn}$)) were estimated from Ptp, V and V', by three different methods, as described below.

Procedure

The patients were studied in the sitting position. After topical anesthesia, the catheter was introduced through the nose into the esophagus, and the ''occlusion test'' was performed to ensure the correct positioning.[17,20] Once the

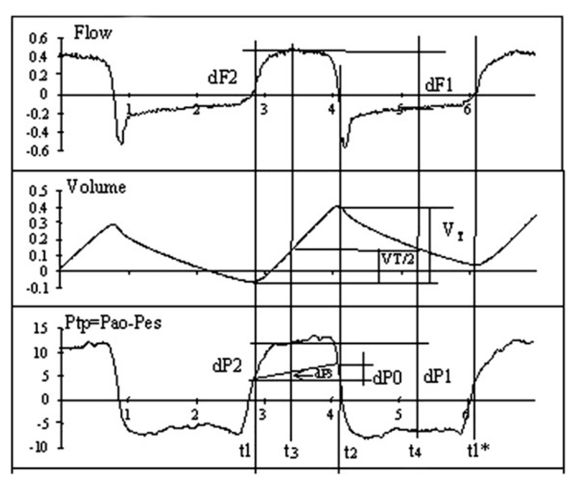

Figure 2 Reference points and parameters of the graphical analysis (GA). t1: beginning of inspiration; t2: end of inspiration; t1∗: end of expiration; t3 and t4: times at inspiratory and expiratory mid-tidal volume ($V_T/2$), respectively; dF1: difference of flow between flows measured at t3 and t4; dF2: difference of flow between flows measured at t1 and t3; dP0: difference of pressure between pressures measured at t1 and t2; dP1: difference of pressure between pressures measured at t3 and t4; dP2: difference of pressure between pressures measured at t1 and t3; dP3 = dP0/2.

patient relaxed and well accustomed to the experimental setting, we collected about 5 min of physiologic signals after at least 10 min of quiet breathing. Afterwards, measurement of $P_{0.1}$ was performed. Oxygen saturation (SpO_2) was monitored by a pulse oximeter (Pulsox-3iA, MINOLTA, Osaka, Japan). Supplemental oxygen was delivered, if necessary, to maintain $SpO_2 > 92\%$.

Data analysis

Three methods were used to estimate lung mechanics on the inspiratory part of breathing cycle.

Off-line method

The graphical analysis (GA), a well established experimental technique, computes the lung mechanics only once the signals are recorded and stored (Fig. 2).[8,30,31] PEEPi,dyn is calculated as the change in ΔPes preceding the start of the inspiratory flow.[33] Ptp was used to calculate $E_{L,dyn}$ according to Mead and Whittemberger[34] and $R_{L,insp}$ at mid-inspiratory volume according to the Neergaard-Wirtz elastic subtraction technique.[12] We considered GA our reference technique.

On-line methods

The two selected methods [21,22] are based on the first-order lumped visco-elastic model, previously used in the first attempts of on-line monitoring respiratory mechanics.[35,36] We adapted the methods to compute inspiratory lung mechanics Eq. (1):

$$\mathrm{Ptpi}(t) = P_0 + E_{L,dyn}.\mathrm{Vi}(t) + R_{L,insp}.\mathrm{Vi}'(t) \quad (1)$$

where Ptp_i, Vi and Vi′ are inspiratory Ptp, tidal volume and airflow, respectively; P_0 accounts for the residual value of transpulmonary pressure at zero flow and zero volume, i.e. at the beginning of each inspiration, and t is time.

Recursive Least Square (RLS): the RLS method provides weighted means and standard deviations for the estimated parameters and recursively updates estimation at each new sampling time.[35,36] A forgetting factor determines the memory of the estimation procedure. An appropriate value for this factor (between 0 and 1) is crucial.[37] Nucci et al.[11,22] modified the RLS algorithm to monitor PEEPi and respiratory mechanics on an inspiration-by-inspiration basis, in ventilator-dependent patients. We tested this method on SB patients.

Modified Selective Least Square (SLS): Eberhard et al.[21] proposed a program for continuous estimation of respiratory mechanics in ventilated patients. They modified the classical multiple linear regression method[38–40] in order to select the most reliable parts of the breathing cycles, such that transition phases at the beginning of inspiration and expiration and the pauses were eliminated. Their mathematical model included a non-linear resistive pressure, as the authors believed it would better represent the resistive component in intubated patients, such that Eq. (1) becomes:

$$\mathrm{Ptpi}(t) = P_0 + E_{L,dyn}.\mathrm{Vi}(t) + (R_0 + \alpha.|\mathrm{Vi}'(t)|)\mathrm{Vi}'(t) \quad (2)$$

with $R_{L,insp} = R_0 + \alpha.|\mathrm{Vi}'(t)|$, where R_0 and α are the constant and slope of the inspiratory resistance-flow relationship, respectively.

In our study, we included the beginning of inspiration in the fit, as we believed it could improve the estimation of P_0. This parameter is determined as the value of Ptp at zero flow.

Statistics

We manually discarded erroneous values prior to compute the means, standard deviations (SD), medians and interquartiles of variables. Comparisons between methods were done using the non-parametric Friedman Repeated Measures Analysis of Variance on Ranks and Pairwise Multiple Comparison Procedures (Dunn's Method), with significance set at $p < 0.05$ (SigmaStat v.3.00). We used Spearman Rank Order correlation test to measure the strength of the association between pairs of parameters of lung mechanics for the whole subjects. Bland and Altman plots were constructed to determine the agreement between pairs of parameters.

Results

Table 2 shows the mean (±SD) of ventilatory variables, swingPes and $P_{0.1}$ over 5 min of breathing pattern, in both groups. Fig. 3 shows the time course of lung mechanics estimated by the three methods, in one patient with CF. For RLS method, the tracking algorithm was tuned according to a forgetting factor of 0.95, which corresponds to a weighted data window of about 0.2 s. Mean, SD, median and interquartiles values of lung mechanics estimated by each method are presented in Table 3. In the CF group, the medians of the 3 parameters were not significantly different between methods (ANOVA, $p > 0.05$). In COPD, the medians of P_0 were not significantly different between methods (ANOVA, $p > 0.05$). In contrast, the values of E_{Ldyn} and R_{Linsp} were significantly different between GA/SLS and GA/RLS (Dunn's, $p < 0.05$), respectively. However, all pairs of parameters significantly and positively correlated ($p < 0.05$) (Table 4). The coefficients of correlation were very high. Bland–Altman analysis shows that differences between pairs of parameters followed an unbiased distribution, meaning that the fits were good for the three methods (Fig. 4). Globally, data were well under the 95% limit of agreement. For P_0, mean differences between all pairs were very low (<0.5 cmH_2O, in absolute value) and the intervals of agreement were very small. For $E_{L,dyn}$, the mean differences and intervals of agreement were very similar between GA/RLS and GA/SLS, when considering all patients, but also considering COPD patients only. Finally, for R_{Linsp}, the mean differences were small in the 3 pair comparisons. When considering only COPD, mean differences and intervals of agreement were very similar between GA/RLS and GA/SLS.

Discussion

We validated two methods for monitoring lung mechanics in SB patients with advanced chronic pulmonary diseases. The methods are not intrinsically new, however the setting of the application is new. To our knowledge, no previous study addressed the issue of monitoring lung mechanics, including PEEPi, in SB patients. The validity of the on-line

Table 2 Breathing pattern, ventilatory drive and inspiratory effort. mean values (±SD).

	COPD	CF
V'_E (L/min)	9.3 (±1.9)	10.1 (±2.9)
V_T (L)	0.56 (±0.12)	0.51 (±0.19)
f (b/min)	17 (±4)	22 (±8)
swingPes (cmH_2O)	11.2 (±2.7)	15.3 (±4.5)
$P_{0.1}$ (cmH_2O)	1.9 (±0.4)	2.2 (±0.7)

Abbreviations: V'_E: minute ventilation; V_T: tidal volume; f: respiratory frequency; swingPes: maximal variation of transpulmonary pressure on a breath cycle; $P_{0.1}$: pressure generated in the first 100 ms of inspiration against an occluded airway. COPD: chronic obstructive pulmonary disease; CF: cystic fibrosis.

methods for their application in the clinical setting is supported by the excellent correspondence of our data with the traditional reference graphical method.

Intrinsic PEEP

The meaning of P_0 calculated by the three methods is different. Indeed, for GA, P_0 represents dynamic PEEPi, i.e. the end-expiratory positive alveolar due to the elastic recoil of the lungs because of the incomplete expiration. While for on-line methods, P_0 represents dynamic PEEPi plus the change in Pao preceding the start of the inspiratory flow. However, we did not find any significant difference in PEEPi values between methods. This is probably due to the fact that, in spontaneously breathing subject, variations of Pao are very small such that it does not significantly influence the value of P_0.

The coefficients of correlation were high, from 0.605 to 0.887. Furthermore, our values of PEEPi are similar to those

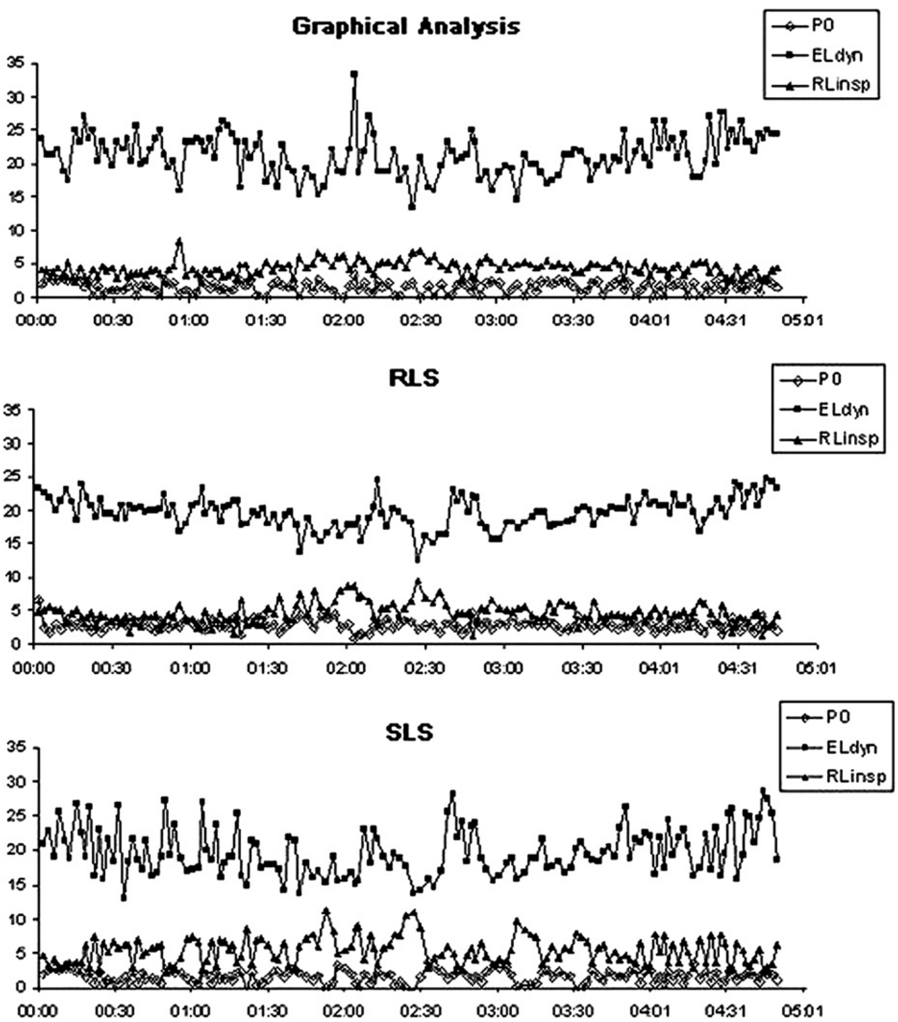

Figure 3 Estimation of lung mechanics parameters by the three methods. The figure represents the results of the estimation of parameters by the 3 methods, in the patient with CF, whom recorded signals are presented on Fig. 1. For GA and SLS methods, each point represents the value of parameters calculated for the inspiratory part of one breath cycle, while for RLS method, each point is the weighted mean of the parameters recursively estimated throughout the inspiratory part of one breath cycle. P_0 is the residual pressure at zero flow and zero volume, in cmH_2O, E_{Ldyn} is the dynamic inspiratory lung elastance, in $cmH_2O\,L^{-1}$, R_{Linsp} is the inspiratory lung resistance, in $cmH_2O\,L^{-1}\,s$. The time is in minutes.

Table 3 Mean, standard deviation (SD), median (Med) and interquartiles values of estimated lung mechanics.

		GA					RLS					SLS				
		Mean	SD	Med	25%	75%	Mean	SD	Med	25%	75%	Mean	SD	Med	25%	75%
COPD	P_0	2.56	1.58	2.04	1.89	2.58	2.66	1.35	2.51	1.79	2.82	2.47	1.44	2.09	1.62	2.57
	$E_{L,dyn}$	8.87[a]	3.38	8.19	6.61	11.86	6.29	2.27	6.34	4.24	8.48	5.57[a]	2.23	6	3.89	6.92
	R_{Linsp}	9.01[a]	3.35	8.81	6.04	11.05	10.72[a]	3.9	11.02	6.74	13.33	10.17	3.86	9.88	6.4	13.11
CF	P_0	1.25	0.82	0.99	0.34	1.62	2.03	1.37	1.75	1.03	2.85	1.44	0.91	1.03	0.7	1.9
	$E_{L,dyn}$	24.96	13.27	21.51	15.22	27.13	24.65	13.27	20.18	15.17	28.21	23.73	11.54	20.67	15	27.9
	R_{Linsp}	10.14	4.64	8.7	6.84	14.93	11.28	4.65	9.57	8.71	14.4	10.31	5.68	7.98	5.4	14.2

P_0: dynamic PEEPi in cmH_2O; $E_{L,dyn}$: inspiratory dynamic lung elastance in $cmH_2O\,L^{-1}$; R_{Linsp}: total pulmonary inspiratory resistance in $cmH_2O\,L^{-1}\,s$; GA: graphical analysis; RLS: modified recursive least square method; SLS: modified selective least square method.

[a] Significantly different ($p < 0.05$).

Table 4 Spearman Rank Order Correlation coefficients.

	GA/RLS	GA/SLS	RLS/SLS
P_0	0.605	0.887	0.726
$E_{L,dyn}$	0.979	0.98	0.995
R_{Linsp}	0.973	0.938	0.929

All pairs of variables significantly correlated ($p < 0.05$).
P_0: dynamic PEEPi in cmH_2O; $E_{L,dyn}$: inspiratory dynamic lung elastance in $cmH_2O\,L^{-1}$; R_{Linsp}: total pulmonary inspiratory resistance in $cmH_2O\,L^{-1}\,s$; GA: graphical analysis; RLS: modified recursive least square method; SLS: modified selective least square method.

reported in SB patients with severe stable COPD[8,33] and CF.[25,41] The values are rather small. However, these data confirm that dynamic hyperinflation already exists during quiet breathing providing the condition for the rapid rise of PEEPi to much higher values during exacerbation[42] and exercise.[43,44]

It is noteworthy that PEEPi calculated with RLS was slightly greater than with GA (Table 3). This is in agreement with the finding in ventilator-dependent patients.[22] In fact, the esophageal pressure at the point of zero flow, i.e. PEEPi,dyn, reflects the minimum pressure needed to start inspiration, which is the pressure that counterbalances the lowest PEEPi. In GA and SLS, P_0 reflects the value of PEEPi,dyn, while RLS calculates a weighted mean value of the time course of PEEPi,dyn throughout inspiration. Hence, with RLS, the value of P_0 is affected not only by the initial lowest PEEPi but also by the subsequent higher values of PEEPi within the lung units, which are recruited all over inspiration.[22] Therefore, the higher PEEPi,dyn obtained by RLS may better reflect the inspiratory threshold load that the patient's inspiratory muscle must counterbalance to start inspiration.

Dynamic lung elastance

The analysis of variance showed that values of E_{Ldyn} obtained with the three methods were not different in CF patients but slightly dissimilar in COPD. This difference was essentially due to the greater value found with GA compared with SLS. However, the coefficients of correlation were excellent, over 0.98. Moreover, Bland–Altman analysis does not show a great difference between GA/RLS and GA/SLS. Some authors[25,41] measured dynamic lung compliance, the reciprocal of elastance, in stable CF patients. The mean elastance calculated from Pradal et al.,[25] 8.3 $cmH_2O\,L^{-1}$, is about three times lower than ours (Table 3). However, they examined less severe patients, as documented by the FEV_1 of 59%pred. in their patients vs. 23%pred. in our patients. The elastance calculated from Hart et al.[41] is similar to ours, and their patients' mean FEV_1 averaged 28%pred. In COPD patients, E_{Ldyn} was lower than in CF patients. Our values were similar to the mean elastance found in severe stable COPD patients by Purro et al.[8] (9.1 $cmH_2O\,L^{-1}$) and higher than the data by Dal Vecchio et al.[33] in less severe COPD (5 $cmH_2O\,L^{-1}$). Scott et al.[45] reported a low preoperative E_{Ldyn} (4.4 $cmH_2O\,L^{-1}$) in candidates to lung transplantation with severe pulmonary emphysema (FEV_1 18%pred.). However, they did not describe the methods used to calculate lung mechanics.

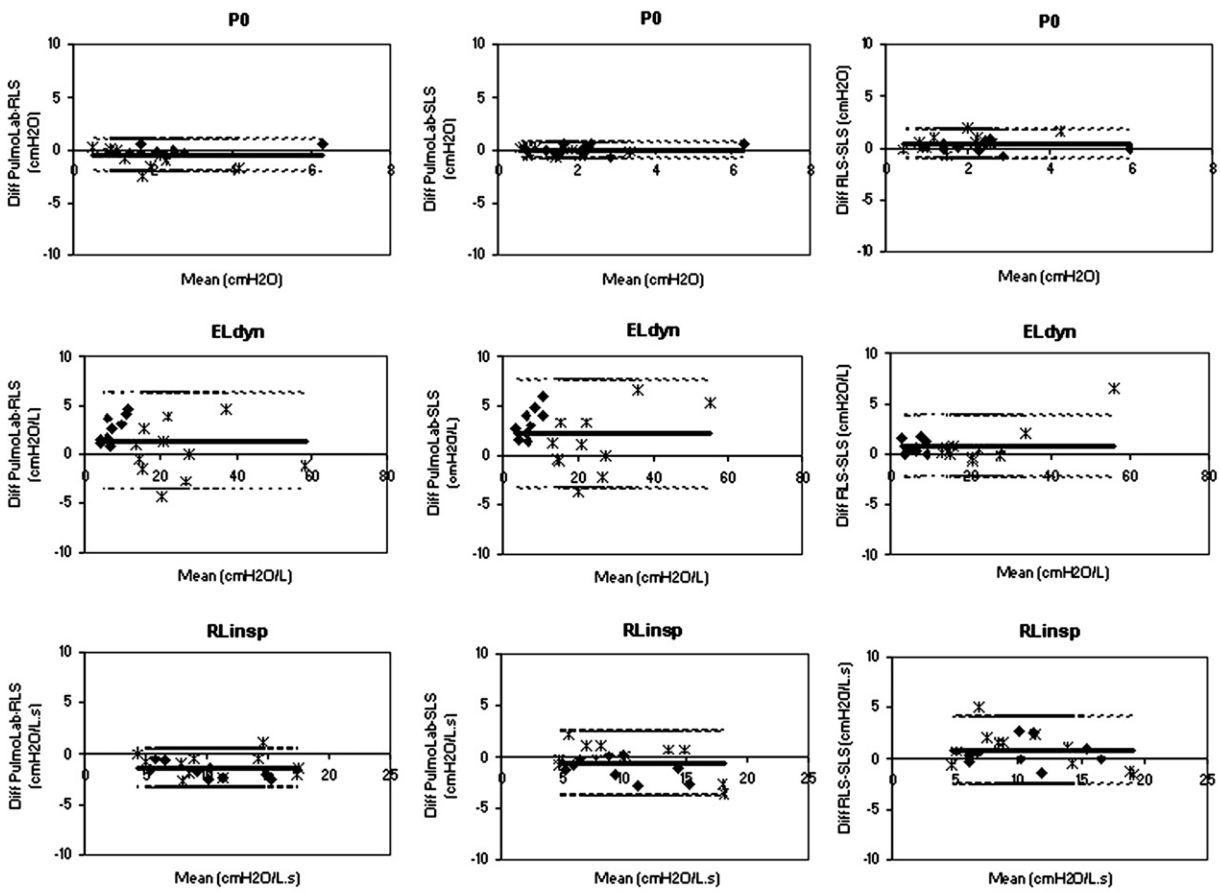

Figure 4 Bland—Altman plots. From left to right: the graphs represent the comparison between GA and RLS methods, GA and SLS methods, RLS and SLS methods, for the three parameters of lung mechanics (P_0 in cmH_2O, E_{Ldyn} in $cmH_2O\,L^{-1}$, R_{Linsp} in $cmH_2O\,L^{-1}\,s$, respectively from top to bottom), for all the patients. Each point represents the difference between the values of parameter estimated by the pairwise methods in function to the mean of the pairwise values. The solid line is the mean value of the differences, and the dashed lines are the mean $\pm$ 2 standard deviation (2SD) intervals. Note that the difference of the value of the three parameters estimated by the different methods is globally very low between methods. Diamonds: COPD; stars: CF.

Inspiratory lung resistance

Inspiratory lung resistance was similar in our patients with CF and COPD. GA provides slightly smaller values. This could be explained by the fact that GA measured mid-inspiratory resistance and not total inspiratory resistance. In COPD, we found a significant difference between RLS and GA. However, the coefficients of correlation were very high in all pairs, over 0.93. Moreover the Bland—Altman analysis shows that mean differences between GA/RLS and GA/SLS were consistently low and the intervals of agreement were reasonable, considering the high values of resistance. The mean R_{Linsp} in our CF patients are slightly higher than the value of Pradal et al.[25] (7.3 $cmH_2O\,L^{-1}\,s$), but lower than the one reported by Hart et al.[41] (17.1 $cmH_2O\,L^{-1}\,s$), who measured total pulmonary resistance. Scott et al.[45] measured total pulmonary resistance in patients with emphysema but found values slightly lower than ours. While Purro et al.[8] and Ingenito et al.[15] reported similar R_{Linsp} values in patients with advanced stable COPD. In this connection it should be mentioned that in presence of expiratory flow limitation, which is common in patients with advanced obstructive diseases, total pulmonary resistance looses any physiological significance.[22,46]

Clinical interpretation

On the overall, the mean differences between methods for the measurement of lung mechanics are either negligible or small. The limits of agreement are small enough to be confident that the new methods can be used in clinical practice, providing immediate and continuous availability of data. Our results confirm that lung mechanics is severely abnormal in patients with advanced COPD or CF, indicating that the altered mechanics of breathing is one of the main determinants of the condition requiring lung transplantation. The stage of the disease in our patients was severe enough to indicate lung transplantation as the only possible therapeutic option.

Interestingly, our data show that COPD and CF determine similar mechanical abnormalities in terms of PEEPi and pulmonary resistance, while dynamic elastance is much higher in CF than in COPD. This is in line with the known pathology of the diseases. In fact, in CF secretions may occlude the airway and impede direct ventilation in some parts of the lung parenchyma.[3,4]

Limitations

Firstly, chest wall mechanics was not measured.[47,48] However, this should be accepted as a necessary boundary in actively breathing patients. Furthermore, it does not reduce the usefulness of measuring lung mechanics in patients with respiratory disorders, particularly when the disease affects mainly the lungs. Secondly, the esophageal balloon technique is considered invasive and of significant discomfort for the patients. However, it might be noted that an esophageal catheter is routinely inserted into the esophagus to monitor the changes in pH and diagnose gastro-esophageal reflux.[49,50] Moreover, the esophageal catheter is not more invasive than other techniques used during the clinical examinations that many patients have to complete prior to surgery. Finally, we did not measure the changes in abdominal pressure and hence the possible activity of the expiratory muscles. It is well-known that part of the swing in transpulmonary pressure, particularly at the beginning of inspiration, could be due to the relaxation of the expiratory muscles rather than to the contraction of the inspiratory muscles.[27,30,33,51] This issue could affect the interpretation of our values of P_0/PEEPi,[51] but not of elastance and resistance which express the passive mechanical properties of the lungs and are not influenced by the modality of generation of the distending pressure. This limitation can be overcome, only if an additional gastric catheter-balloon is used. However, it may also increase the discomfort of the patient.

In conclusion, our study provides evidence that on-line monitoring of lung mechanics is feasible in SB patients, in clinical practice. Further studies should be focused on the use of on-line monitoring in several clinical conditions such as during non-invasive ventilation, weaning or exercise, as well as to assess the effects of pharmacological or surgical treatments.[24,45]

Conflict of interest statement

Dr. Khirani was the recipient of an ERS fellowship and received a research grant from GlaxoSmithKline. Dr. Polese received money for patient enrollment for clinical studies from Altana Pharma Spa and Novartis Farma Spa. Dr. Aliverti has no conflict of interest to disclose. Dr. Appendini has no conflict of interest to disclose. Dr. Nucci was a former GlaxoSmithKline employee, and is actually working for Pfizer. Prof. Pedotti, Dr. Colledan, Dr. Lucianetti and Prof. Baconnier have no conflict of interest to disclose. Dr. Rossi received unrestricted educational grants from Altana Pharma Spa and Chiesi Farmaceutici. He participated to diverse speaking activities and industry advisory committees.

Ethics statement

The protocol has been approved by the local Research Ethics Committee. All patients provided written informed consent.

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