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Time-Varying Pulmonary Resistance and Compliance in Human

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INTRODUCTION

An inverse relationship between the pulmonary resistance and the lung volume was reported in the forced oscillation experiments(Macklem and Mead, 1967; Vincent et al., 1970; Hoppin et al., 1978) and the plethysmographic tests (Briscoe and DuBois, 1958; Butler et al., 1960; Blide et al., 1964; Guyatt and Alpers, 1968). This relation was also reported to have a useful diagnostic value in obstructive disease (Briscoe and DuBois, 1958).

The above experimental results were obtained using time-invariant analytical technique of the linear model of respiratory mechanics. After fixing the mean lung volume at a specific level, the resistance corresponding to that volume was measured, and the measurements were repeated at other various volume levels. Thus, for an accurate determination of the resistance values at various volumes from these discrete measurements, it requires a long experimental period. Furthermore, these discretely measured resistance parameters may not provide actual physiological state, since the lung volume change is occurring as a continuous variation during one respiratory cycle.

In the present paper, a time-varying system analysis and the inverse relations of the resistance and compliance against the lung volume were used to compute the continuous changes of the pulmonary resistance and the lung compliance from the measured esophageal pressure and respiratory flow in one forced respiratory cycle. Using the present technique and least-square-error computation method, the characteristic parameters of the resistance and compliance were estimated in two patients.

THEORY

In the time-varying analysis of the linear respiratory mechanics model, consisting of the series resistance and compliance, the pressure and volume are related as follows(Mead and whittenberger, 1952; Kim and Meadows, 1971)

$$P(t)=R(t)\dot{V}(t)+D(t)V_a(t)$$
$$D(t)=1/C(t) \tag{1}$$

where

- $P(t)$ is the instantaneous pressure difference between the mouth and the intrapleural space,
- $\dot{V}(t)$ is the instantaneous airway flow rate,
- $V_a(t)$ is the alternating component of the instantaneous lung volume,
- $R(t)$ is the time-varying resistance,
- $C(t)$ is the time-varying compliance, and
- $D(t)$ is the time-varying elastance.

Using the reported hyperbolic relation between the resistance and lung volume(Jordan et al., 1981), $R(t)$ can be expressed as follows;

$$R(t)=\frac{B}{V(t)-D}+A \tag{2}$$

where A, B, D are constants and $V(t)$ is the instantaneous total lung volume.

Expressing $V(t)$ as the sum of the mean component, V_0, and the varying component, $V_a(t)$,

$$V(t)=V_0+V_a(t) \tag{3}$$

Then from eq.s (2) and (3),

$$R(t) = \frac{B}{V_a(t) - R_1} + A \quad (4)$$

where $R_1 = D - V_0$.

Also, using the reported result of inverse relation between compliance and lung volume (Hoppin et al., 1978), the instantaneous lung elestance can be related to the lung volume as follows;

$$D(t) = K_1 + K_2 V(t) \quad (5)$$

where K_1, K_2 are constants.

From eq.s (3) and (5),

$$D(t) = D_1 + D_2 V_a(t) \quad (6)$$

where $D_1 = K_1 V_0 + K_2$

$D_2 = K_2$

Substituting eq.s (4) and (6) to eq. (1),

$$P(t) = \left[\frac{B}{V_a(t) - R_1} + A\right] V(t) + (D_1 + D_2 V_a(t)) V_a(t) \quad (7)$$

The least-square-error method (Slutsky et al., 1979; Jordan et al., 1981) can be used to estimate the characteristic parameters (A, B, R_1, D_1, D_2) of the resistance and the elastance from the measured pressure and flow during the forced expiration and inspiration.

EXPERIMENTS AND METHODOLOGY

Experiments

Preliminary clinical experiments were performed on two patients after obtaining the written permission. Subject 1 (35 yrs old, Female) was a patient with pulmonary hypertension, and Subject 2 (18 yrs old, Male) had tubeculosis, and both patients could complete the whole experiment with only minor discomfort at the time of the esophageal balloon insertion.

The pressure difference between the mouth and the esophagus was measured using an esophageal balloon (Hyatt type, 10cm length, 3.5 cm perimeter, Youngs Rubber CO.) and a strain gauge type differential pressure transducer (270, Hewlett-Packard), and the respiratory flow rate was measured using a Fleisch pneumotachography (21073B, H.P.) and a respiratory flow transducer (47304A, H.P.). The volume signal was obtained from the flow signal after electronic integration. All the signals were amplifid to the ± 2.5V level using the amplifiers (8802A, 8805C, 8816A, H.P.), recorded on an FM magnetic tape recorder (3964A, H.P.), converted to digital signal at a sampling rate of 40 samples/sec, and processed using DEC-MINCll computer.

System calibration was performed using a constant flow generator and a water manometer at the intervals of 0.5 l/s for flow and 1cmH_2O for pressure. After calibration was completed, an esophageal ballon was inserted and located at the lower third level of the esophagus, and the ballooning was produced with 12cc of air. After the pneumotachography was connected, the patients took a few minutes of tidal breathing in sitting position to get used to the procedure. Two cycles of forced inspiration-expiration-inspiration procedure were performed, and repeated once more after two minutes' rest of tidal breathing. Then the N_2 multiple breath test (Sackner, 1976) was performed to measure the functional residual capacity (FRC).

Data Analysis and Computation

The mean components during the tidal breathing were used as the zero levels in pressure, flow, and volume data. Then the conventional method was used to compute the time-invariant resistance and compliance using the least-squre-erroe method (Roy et al., 1974).

The resistance and compliance parameters of eq. (7) were estimated using the following two algorithms. The first algorithm is for determination of the estimated values of A, B and R_1 of the resistance using Jordan et al.'s method (1981) for various of D_1 and D_2. The second algorithm is for computing the optimal of D_1 and D_2 with the minimal standard error between the measured and the computed pressure, which is based upon

Slutsky et al.'s method (Slutsky and Drazen, 1979). A summary of the algorithms is shown in the flow-chart of Fig. 1.

Table 1 shows the values of the pulmonary resistance and lung compliance of the time-invariant model, as computed using a conventional method. Table 2 shows the estimated values of the present time-varying model. Estimated values of D_1 of the present method are shown to be comparable to the conventional method data in both patients. Also, other estimated values are similar in both patients except the B value. The reproducibility of the estimation in each patient was satisfactory, as the standard deviation was less than 10% for both cases. Especially the data of Subject 2 show a high curve fitting result with the standard error of 0.16cm H_2O, where the maximal pressure is about 25cm H_2O. The original measured signals are shown in Fig. 2. Figs. 3 and 4 show the computed time-varying profiles of the conductance, compliance, and the volume signal. These figures show the monoto nically varying conductance and compliance with the volume change during one respiratory cycle. Fig. 5 shows the relation between the changes of the lung volume and the resistance,

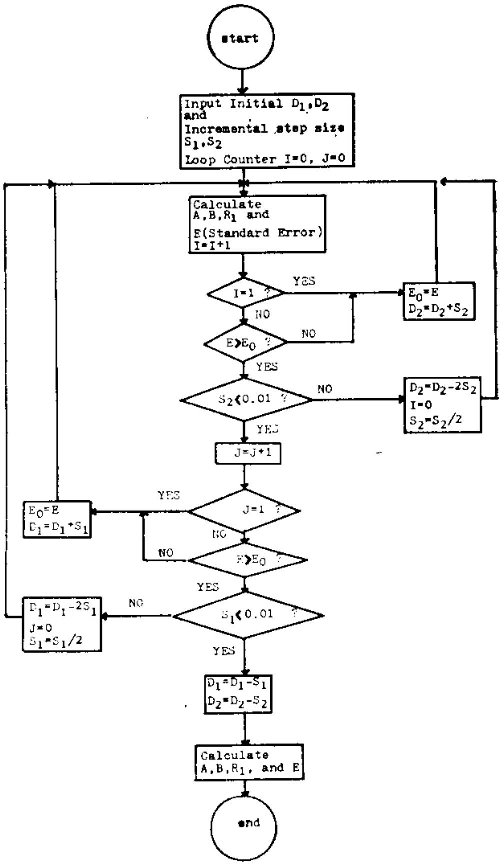

Fig. 1. A flow-chart for computation.

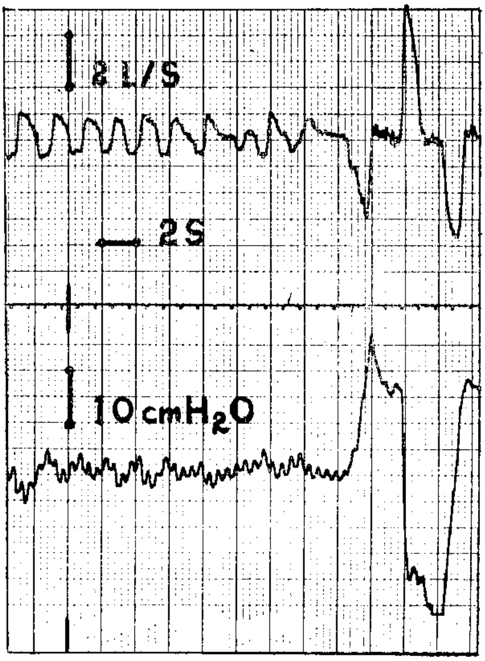

Fig. 2. The measured flow rate (upper) and the mouth-to-esophageal pressure (lower).

Table 1. Time-invariant pulmonary resistance, the lung compliance, and the elastance of conventional method

Subject	Resistance[cmH_2O]	Elastance
1	2.94±0.25	7.69±0.77
2	2.02±0.36	5.65±0.63
Mean±S.D.	2.48±0.46	6.67±1.02

Subject	Compliance[1/cmH_2O]
1	0.130±0.012
2	0.177±0.022
Mean±S.D.	0.154±0.024

Table 2. The estimated parameters of the resistance (A, B, R_1) and the elastance (D_1, D_2).

Subject	A	B	R_1
1	1.912±0.010	1.054±0.012	1.462±0.013
2	3.802±0.040	0.109±0.054	1.591±0.016
Mean±S.D.	2.857±0.945	0.582±0.473	1.527±0.065

Subject	D_1	D_2	Standard error
1	7.875±0.089	1.269±0.212	0.695±0.542
2	5.063±0.070	1.788±0.275	0.160±0.121
Mean±S.D.	6.469±1.406	1.529±0.260	0.428±0.268

which is comparable to other previous results (Briscoe and DuBois, 1958; Butler et al., 1960; Blide et al., 1964; Macklem and Mead, 1967; Guyatt and Alpers, 1968; Vincent et al., 1970; Hoppin et al., 1978; Jordan et al., 1981).

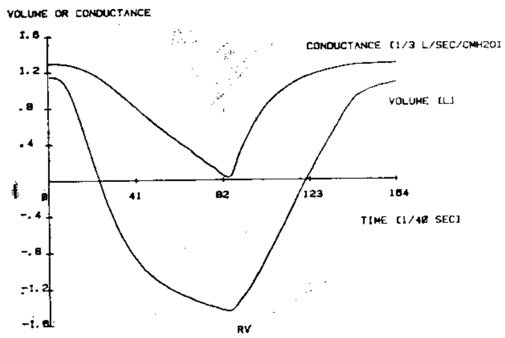

Fig. 3. Relation between the instantaneous pulmonary conductance and the lung volume in one respiratory cycle(Subject 1).

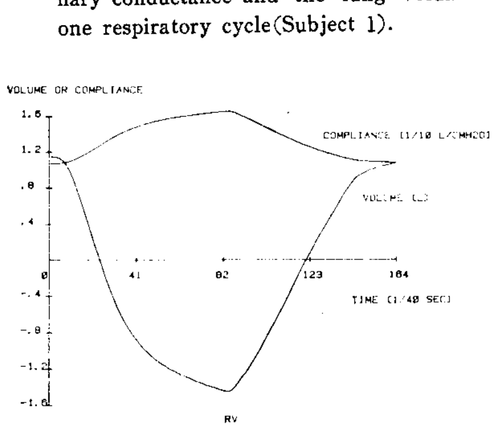

Fig. 4. Relation between the instantaneous pulmonary compliance and the lung volume in one respiratory cycle(Subject 1).

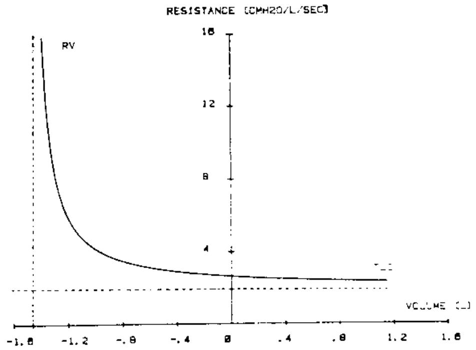

Fig. 5. The computed inverse relation between the pulmonary resistance and the lung volume (Subject 1).

DISCUSSION

In this paper, the characteristic parameters of the pulmonary resistance and the lung compliance were determined using a single forced ventilation test in two patients. The computation method is based upon two least-square-error estimation techniques for a time-varying model of the respiratory mechanics, using a measurements from the mouth-to-esophageal pressure, the airway flow rate, and the volume data.

While the results are from only a preliminary study with two patients, the computed values are comparable to other results obtained with complicated procedures. As an example, the D_1 values, constant terms of time-varying elastance model, were computed to have almost the same values as the conventional method's elastance values in both patients in Tables 1 and 2. Also, the curve fitting could be accomplished with smaller standard errors in time-varying case, compared with time-invariant analysis of the conventional methods. Furthermore, when we plot the relation between the instantaneous resistance and the instantaneous lung volume at each point of the ventilation, the previously reported inverse relation between the resistance and volume could be reproduced.

As compared with a recent study by Jordan et al.(1981), our present analysis has the following three differences; the pulmonary resistance was computed as compared with the total respiratory resistance, and a time-varying model of the elastance was used compared with the time-invariant elastance model. Most importantly, as compared with the several discrete measurements at various fixed lung volume levels in Jordan's forced oscillation method, we measured the continuous changes of the resistance in a single ventilation test. We have used Jordan et al.'s computation method in estimating the three hyperbolic parameters of the resistance, when the elastance values were given in the iterative method of Slutsky et al.(1979).

As we convert our data to the corresponding parameters of the Jordan's method (1981), using the measured FRC and Tidal volumes, we could obtain similar ranges of the parameters in Subject 1, as shown in Table 3. A lower value of the volume independent resistance parameter, A, may be due to the resistance component of the tissue and thoracic cage included in Jordan's method, as our method provides only the pulmonary resistance compared with the total respiratory resistance in Jordan's method (Ferris et al., 1964; Bachofen and Scherrer, 1967; Bachofen, 1968; Peslin et al., 1974). Also, the lower *D* values in our data, where *D* indicates the airway collapsing lung volume, is closer to other reported values (Briscoe and DuBois, 1958; Butler et al., 1960; Blidr et al., 1964; Guyatt and Alpers, 1968) than the Jordan's result. In Subject 2, the estimated values are comparable to Jordan's values, except the *B* value. As the value of $(1/B)$ indicates the specific lower airway conductance, a large difference in *B* value requires further study. This difference cannot be explained by the modeling or estimation error, as the standard error was smaller in Subject 2 than in Subject 1.

Table 3. Comparison of our results with Jordan et al.'s data.

Parameter	Jordan's data	Subject 1	Subject 2
A	2.50	1.912	3.802
B	0.99	1.054	0.109
D	2.25	1.538	1.809

To save the computation time, a combination of two least-square-error methods was used (Slutsky and Drazen, 1979; Jordan et al., 1981). Also, the initial estimation values were obtained from the conventional time-invariant measurements.

In this preliminary study, it is shown that the time-varying model and the volume dependency of the resistance and compliance can be used to estimate many useful physiological parameters of the respiratory mechanics, such as the specific lower airway conductance and the airway collapsing lung volume, in a single ventilation test. Thus, if the present results can be rigorously verified in further experiments, this new method may provide a useful diagnostic method in care of the respiratory patients.

SUMMARY

The objective of the present study was to compute the continuous changes of the pulmonary resistance and lung compliance in a respiratory cycle in human. A time-varying system analysis and the inverse relations of the pulmonary resistance and compliance against the lung volume were used to compute continuous changes of the resistance and compliance, as compared with the conventional discrete measurements in time-invariant model. In two patients, the measured mouth-to-esophageal pressure, the respiratory flow, and the volume data were used as the input data for the estimation by a combination of two least-square-error algorithms. The first algorithm is for estimation of the resistance

parameters for various compliance parameters, and the second algorithm is for computing the optimal values of compliance parameters with the minimal standard error between the measured and the computed pressure. The results show that the computed values of the present method were comparable to other results obtained with more complicated conventional forced oscillation method. Also, the curve fitting in the time-varying model could be accomplished with smaller standard errors, compared with time-invariant analysis.

=국문초록=

시변 임피던스 모델에 의한 폐기능 분석에 관한 연구

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본 연구의 목적은 사람의 한 호흡주기 내에서 폐저항 및 폐 compliance의 연속적인 변화를 계산하는데 있다. 종래의 시불변 모델을 이용한 이산적인 측정방식에 반해 시변모델과 이미 널리 알려진 이들(폐저항 및 폐 compliance)의 폐 부피와의 반비례 관계를 이용하여 이들의 시간에 따른 변화를 유도하였다. 두 환자에게서 측정한 식도내압, 호흡기류 및 폐부피 변화 신호를 입력자료로 하고 각기 다른 두 개의 최소자승오차방식으로 시변 특성매개 변수들을 추정하였다. 첫번째 알고리듬은 여러가지 compliance 매개변수들에 대한 저항 매개변수들을 추정하도록 고안되었고 두번째 알고리듬은 측정된 식도내압과 정해진 매개변수들로부터 계산된 식도내압간의 표준오차를 최소로 하는 compliance 특성 매개변수들의 최적치를 찾는데 사용되었다. 본 논문에 의거한 실험 및 계산결과는 종래의 보다 복잡한 forced cscillation method를 이용하여 산출된 결과와 유사하였다. 또한 시변모델을 사용한 결과 시불변 분석방식을 사용한 경우에 비해 더 작은 표준오차를 보였으므로 측정결과가 보다 정확하였음을 알 수 있었다.

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