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Short communication

# Respiratory inductive plethysmography to assess respiratory variability and complexity in humans

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**Abstract**

Human ventilation is aperiodic, exhibiting a breath-by-breath variability and a complexity of which the characteristics may be interesting physiologically and clinically. In the present study, we tested the ability of respiratory inductive plethysmography (RIP) to describe these properties. Indeed, RIP does not have the effects on ventilation described with mouthpiece measurements. We compared the ventilatory flow recorded with a pneumotachograph ($V'_{PNT}$) and the ventilatory flow derived from the mathematical treatment of the thoracoabdominal motion signals obtained from a particular type of RIP ($V'_{RIP}$, Visuresp®, Meylan, France) in 8 freely breathing normal subjects. Using the $Z$ correlation coefficient, Passing–Bablock regressions and Bland and Altman graphical analyses, we compared the coefficients of variation of the main discrete respiratory variables determined with $V'_{PNT}$ and $V'_{RIP}$ and a set of nonlinear descriptors including the noise limit (chaotic nature of the signal), largest Lyapunov exponent (sensitivity to initial conditions), the Kolmogorov–Sinai entropy (unpredictibility) and the correlation dimension (irregularity). When the recordings were obtained with the two techniques simultaneously, all the measurements were correlated and interchangeable. RIP can be safely used to quantify the breath-by-breath variability of ventilation and to study the complexity and the chaotic behavior of the ventilatory flow.


*Keywords:* Control of breathing; Respiratory variability; Respiratory complexity; Chaos; Respiratory inductive plethysmography

## 1. Introduction

At first glance, tidal ventilation resembles a periodic phenomenon. However, deeper analyses demonstrate that there is a breath-to-breath variability of discrete ventilatory variables, such as tidal volume or the ventilatory period, and that the trajectory of ventilatory flow exhibits complexity. Ventilatory complexity can be described using nonlinear descriptors such as the largest Lyapunov exponent (LLE, sensitivity to initial conditions), the Kolmogorov–Sinai entropy (KSE, unpredictability) or the correlation dimension (CD, irregularity, complexity). Recently, the chaotic nature of the ventilatory flow has been demonstrated using the noise titration technique (Wysocki et al., 2006). Studying the variability and the complexity of ventilation may prove useful physiologically or even clinically, to better describe the control of breathing and identify certain related abnormalities or risk factors (e.g. Miyata et al., 2004). The technique used to record ventilation can have a strong influence on the observations. For example, measuring the ventilatory flow through a mouthpiece is known to modify the breathing pattern (Perez and Tobin, 1985) and respiratory variability (Rameckers et al., 2007). Respiratory inductive plethysmography, a technique that measures tidal volume from rib cage and abdominal motions, may not have such a caveat (Perez and Tobin, 1985). In the present study, our aim was to examine the ability of the ventilatory flow signal mathematically reconstructed from a thoracoabdominal respiratory inductive plethysmography device (Eberhard et al., 2001), to provide nonlinear descriptors of ventilation and indexes of variability that would match those obtained with the flow recorded at the mouth with a pneumotachograph.

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## 2. Methods

### 2.1. Subjects

Eight healthy subjects (six men, two women, age 26.5 ± 2 years), naïve about respiratory physiology, participated in the study after legal and ethical clearance (Comité de Protection des Personnes se prêtant à des Recherches Biomédicales Pitié-Salpêtrière, Paris, France). The subjects received detailed information about the study and gave written consent.

### 2.2. Recordings of ventilatory flow

#### 2.2.1. Pneumotachograph (PNT)

The subjects wore a nose clip and breathed through a mouthpiece attached to a heated pneumotachograph (Hans Rudolph, 3700A series, Kansas City, MO, USA), connected to a ±2 cm $H_2O$ linear differential pressure transducer (DP-45-18, Validyne, Northridge, CA, USA). The flow signal ($V'_{PNT}$) was digitized at a 40 Hz sampling rate (MacLab/16, AD Instruments, Castle Hill, Australia) and recorded in the form of data files (Chart® version 4, AD Instruments, Castle Hill, Australia).

#### 2.2.2. Respiratory inductive plethysmography (RIP)

Rib cage and abdomen displacements were recorded with two coils coated in a sleeveless jacket allowing horizontal wiredrawing only. The signal was digitized at a 40 Hz sampling rate and processed (Visuresp®, RBI, Meylan, France) to provide a measurement of the ventilatory flow as described previously in details (Eberhard et al., 2001). In brief, the coefficients of the linear combination of the rib cage and abdomen signals best fitting the integrated PNT flow signal were obtained by the least squares method. The combination provided the RIP volume signal, of which the derivation provided the RIP flow signal ($V'_{RIP}$). Text data files were generated for subsequent analysis.

### 2.3. Procedure

The subjects were instructed to keep their eyes open during the recordings. They could listen through earphones to music of their choice that was emotionally and rhythmically neutral. No particular instructions regarding breathing were given. $V'_{RPNT}$ and $V'_{RIP}$ were recorded during 10 min epochs following a 15 min stabilisation period, under the following conditions, in random order: (i) simultaneous acquisition of $V'_{RPNT}$ and $V'_{RIP}$; (ii) consecutive acquisition of $V'_{RPNT}$ and $V'_{RIP}$ (also in random order). In each subject this set of three recordings was performed in the sitting and in the supine position (also in random order).

### 2.4. Analysis

#### 2.4.1. Breath-by-breath variability of ventilation

The $V'_{PNT}$ signal was integrated to get tidal volume that was directly obtained from the respiratory inductive plethysmograph. Total instantaneous ventilation ($V'_I = V_T/T_{TOT}$), tidal volume ($V_T$), mean inspiratory flow ($V_T/T_I$), total cycle time ($T_T$), inspiratory time ($T_I$), expiratory time ($T_E$) and duty cycle ($T_I/T_T$) were determined by use of macros developed with Chart® 5.2.2 and Excel (Microsoft® Office for Windows® XP Pro) software. The breath-by-breath variability was assessed in terms of the coefficient of variation (standard deviation to mean ratio).

#### 2.4.2. Ventilatory complexity and chaos

This was studied as previously described (Wysocki et al., 2006). Ventilatory chaos was first assessed with the noise titration technique, a robust way to detect and quantify chaos in short and noisy time series (Poon and Barahona, 2001). Very briefly, the quantity of white noise that must be added to a time series for it to be better fitted by a linear than by a nonlinear model defines the "noise limit" NL. A positive NL evidences chaos, of which the NL value quantifies the intensity. After subsampling the ventilatory flow data at 5 Hz (Dataplore®, Datan, Teltow, Germany) – a frequency previously shown to provide optimal results (Wysocki et al., 2006) – we performed the noise titration using a specific routine developed under Matlab® V.6.5 R13 (MathWorks Inc, Natick, MA 01760-2098, USA), If the signal was chaotic we calculated its largest Lyapunov exponent (LLE, an index of the sensitivity of the system to its initial conditions) and its correlation dimension (CD, a fractal dimension reflecting the complexity or irregularity of the system) (Dataplore®).

### 2.5. Statistical analysis

After normality checks (Kolmogorov–Smirnov test, Prism® software, Graphpad, San Diego, CA, USA), the analysis was performed on the seated and supine data first separately and then pooled. Correlation between PNT and RIP measurements was looked for using the $Z$ coefficient of correlation. If the correlation was significant ($p < 0.05$), the agreement between PNT and RIP measures was assessed using the graphical analysis of Bland and Altman (1986) and the specific regression method described by Passing and Bablok (1983) (MedCalc Software® 8.0, Mariakerke, Belgium). Changes in $V_T$ and $T_T$ induced by the recording devices or by posture were assessed using a two-way analysis of variance followed, when appropriate ($p < 0.05$), by the Fisher PLSD post-hoc test (StatView® version 5.0, SAS Institute Inc, Abacus Concepts, San Francisco, CA, USA).

## 3. Results

### 3.1. Breath-by-breath variability of ventilation

During the separate $V'_{PNT}$ and $V'_{RIP}$ recordings, the mean values of $V_T$ were significantly higher when the subjects breathed through a PNT ($p < 0.0002$), $T_T$ being unaffected. During both the simultaneous and the separate $V'_{PNT}$ and $V'_{RIP}$ recordings, $V_T$ was significantly lower in the supine posture ($p = 0.0052$), $T_T$ also being unaffected.

When $V'_{PNT}$ and $V'_{RIP}$ were recorded simultaneously, the mean values of $V'_I$, $V_T$, $V_T/T_I$, $T_T$, $T_I$, $T_E$ and $T_I/T_T$, were significantly correlated (seated: $R$ values always above 0.75, with $p$

always below 0.0324; supine: $R$ above 0.83, with $p$ below 0.0114; pooled: $R$ above 0.81, with p values below 0.0001). The coefficients of variation of $V'_I$, $V_T$, $V_T/T_I$, $T_T$, $T_I$, $T_E$ and $T_I/T_T$ were also significantly correlated ($R$ above 0.75 and $p$ below 0.0311). In all cases, the 95% confidence interval of the intercept of the Passing–Bablock regression included zero and the 95% confidence interval of the slope included one, indicating the absence of a systematic differences.

In contrast, the comparison of the $V'_{PNT}$ and $V'_{RIP}$ signals gathered separately during two consecutive recordings (see above, Section 2.3) showed that the mean values of $V'_I$, $V_T$, $V_T/T_I$, $T_T$, $T_I$, $T_E$ and $T_I/T_T$ were not significantly correlated, with the exception of weak $R$ values for the supine $T_I$ and the pooled $T_I$ ($R = 0.74$, $p = 0.036$ and $R = 0.54$, $p = 0.032$, respectively). The coefficients of variation were also uncorrelated, with the exception of weak $R$ values for the supine $V_T$ and the pooled $V_T$ ($R = 0.71$, $p = 0.048$, and $R = 0.52$, $p = 0.04$, respectively).

### 3.2. Ventilatory complexity and chaos

The noise limit was above zero with PNT and RIP in all conditions, evidencing chaos. When both $V'_{PNT}$ and $V'_{RIP}$ were

Table 1
Values of noise limit (NL), largest Lyapunov exponent (LLE) and correlation dimension (CD) recorded simultaneously with a pneumotachograph (PNT) and respiratory inductive plethysmograph (RIP)

| | Seated and supine | | Seated | | Supine | |
|---|---|---|---|---|---|---|
| | NL PNT | NL RIP | NL PNT | NL RIP | NL PNT | NL RIP |
| Noise limit (NL) | | | | | | |
| Minimum value (%) | 10 | 8 | 10 | 8 | 18 | 16 |
| Maximum value (%) | 47 | 48 | 47 | 44 | 41 | 48 |
| Mean (%) | 32.06 | 32.25 | 30.38 | 31.00 | 33.75 | 33.50 |
| S.D. (%) | 10.08 | 10.93 | 12.50 | 11.96 | 7.42 | 10.46 |
| $R$ | 0.88 | | 0.94 | | 0.81 | |
| 95% Confidence interval | 0.68–0.96 | | 0.69–0.99 | | 0.24–0.96 | |
| $P$ | 0.0001 | | <0.0005 | | 0.0153 | |
| Mean difference between RIP and PNT (%) | 0.2 | | 0.6 | | −0.3 | |
| Lower limit of agreement (%) | −10.0 | | −7.8 | | −12.5 | |
| Upper limit of agreement (%) | 10.4 | | 9.1 | | 12 | |
| Confidence interval of the intercept | −14.00 to 7.53 | | −8.70 to 16.75 | | −5.13 to 35.50 | |
| Confidence interval of the slope | 0.73 to 1.43 | | 0.50 to 1.30 | | 0.00 to 1.21 | |
| | LLE PNT | LLE RIP | LLE PNT | LLE RIP | LLE PNT | LLE RIP |
| Largest Lyapunov exponent | | | | | | |
| Minimum value (bit/it) | 0.17 | 0.18 | 0.17 | 0.19 | 0.18 | 0.18 |
| Maximum value (bit/it) | 0.31 | 0.30 | 0.28 | 0.24 | 0.31 | 0.30 |
| Mean (bit/it) | 0.23 | 0.22 | 0.22 | 0.21 | 0.24 | 0.22 |
| S.D. (bit/it) | 0.04 | 0.03 | 0.04 | 0.02 | 0.05 | 0.04 |
| $R$ | 0.72 | | 0.74 | | 0.72 | |
| 95% Confidence interval | 0.36–0.90 | | 0.08–0.95 | | 0.04–0.95 | |
| $P$ | 0.0015 | | 0.0351 | | 0.0435 | |
| Mean difference between RIP and PNT (bit/it) | −0.013 | | −0.012 | | −0.014 | |
| Lower limit of agreement (bit/it) | −0.069 | | −0.052 | | −0.078 | |
| Upper limit of agreement (bit/it) | 0.043 | | 0.037 | | 0.051 | |
| Confidence interval of the intercept | −0.03 to 0.15 | | −0.02 to 0.16 | | −0.23 to 0.16 | |
| Confidence interval of the slope | 0.26 to 1.05 | | 0.20 to 1.06 | | 0.20 to 2.02 | |
| | CD PNT | CD RIP | CD PNT | CD RIP | CD PNT | CD RIP |
| Correlation dimension (CD) | | | | | | |
| Minimum value (unitless) | 2.60 | 2.15 | 2.60 | 2.77 | 2.63 | 2.15 |
| Maximum value (unitless) | 3.33 | 3.32 | 3.32 | 3.32 | 3.33 | 3.32 |
| Mean (unitless) | 3.07 | 2.99 | 3.10 | 3.06 | 3.04 | 2.92 |
| S.D. (unitless) | 0.27 | 0.36 | 0.27 | 0.24 | 0.29 | 0.45 |
| $R$ | 0.69 | | 0.72 | | 0.72 | |
| 95% Confidence interval | 0.31–0.89 | | 0.03–0.94 | | 0.02–0.94 | |
| $P$ | 0.0027 | | 0.0439 | | 0.0454 | |
| Mean difference between RIP and PNT | −0.08 | | −0.04 | | −0.12 | |
| Lower limit of agreement (unitless) | −0.59 | | −0.42 | | −0.75 | |
| Upper limit of agreement (unitless) | 0.42 | | 0.34 | | 0.50 | |
| Confidence interval of the intercept | −6.05 to 0.83 | | −9.72 to 1.05 | | −55.58 to 3.05 | |
| Confidence interval of the slope | 0.74 to 2.94 | | 0.67 to 4.00 | | 0.02 to 19.00 | |

S.D.: standard deviation; $R$: coefficient of correlation; $P$: statistical significance of $R$; bit/it: bit/iteration. The CD is dimensionless. The lower and upper limits of agreement were determined with the Bland and Altman analysis. The confidence intervals of the intercept and the slope refer to the Passing and Bablock regression.

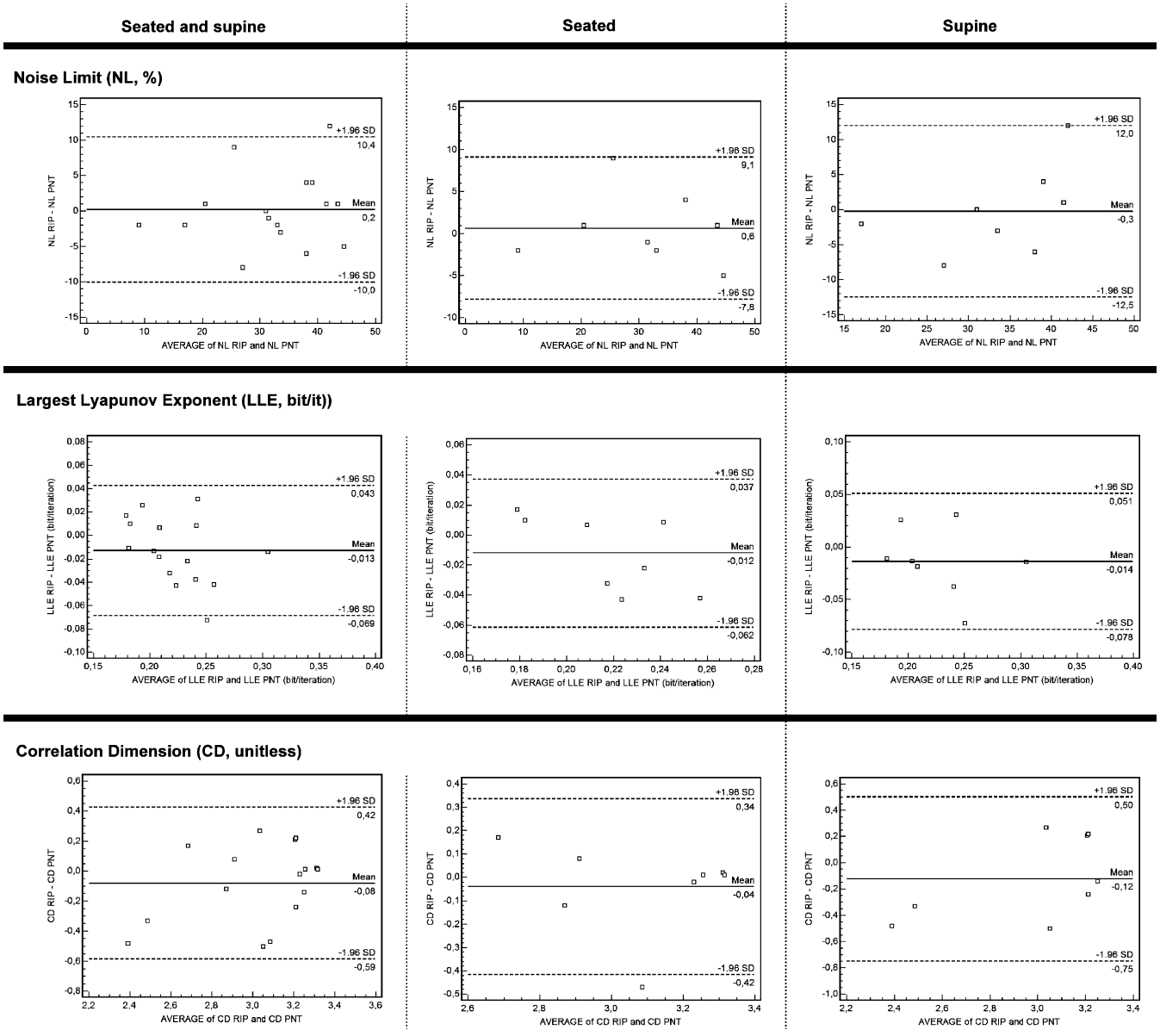


Fig. 1. Bland and Altman graphic analyses. *X*-axis: average of the values obtained from the recordings performed with the respiratory inductive plethysmograph (RIP) and with the pneumotachograph (PNT). *Y*-axis: difference between the values obtained from the recordings performed with the RIP and with the PNT. The solid horizontal line shows the mean difference between the two recording techniques. The dashed lines show the limits of agreement. The ventilatory flow was simultaneously recorded with PNT and RIP.

recorded simultaneously, NL, LLE and CD calculated from $V'_{PNT}$ were significantly correlated to NL, LLE and CD calculated from $V'_{RIP}$ (Table 1). The results of the Bland and Altman graphical analysis are provided in Table 1 and Fig. 1. The Passing–Bablock regressions indicated the absence of systematic differences between NL, LLE and CD calculated from $V'_{PNT}$ or $V'_{RIP}$ (Table 1, Fig. 2).

When $V'_{RIP}$ and $V'_{PNT}$ were recorded independently, the values of NL and CD were no longer correlated, but the LLE values remained so (seated: $R = 0.82$, $p = 0.0118$; supine: $R = 0.77$, $p = 0.0255$; pooled: $R = 0.78$, $p = 0.004$). The mean difference between the LLE calculated from $V'_{RIP}$ and $V'_{PNT}$ was 0.003 bit/iteration (bit/it) when all the data were pooled (lower limit of agreement −0.073 bit/it; upper limit of agreement 0.079 bit/it), 0.004 bit/it when the subjects were seated (lower limit of agreement −0.080 bit/it; upper limit of agreement 0.088 bit/it) and 0.002 bit/it when the subjects were supine (lower limit of agreement −0.072 bit/it; upper limit of agreement 0.076 bit/it). The Passing–Bablock regressions showed an absence of systematic LLE differences between $V'_{RIP}$ and $V'_{PNT}$ recordings.

## 4. Discussion

This study shows that the ventilatory flow signal mathematically reconstructed from thoracoabdominal RIP signals gives access to valid estimates of respiratory variability and complexity. Indeed, in our subjects, the variability indexes, the noise limit, the LLE and the CD calculated from the $V'_{PNT}$ and $V'_{RIP}$

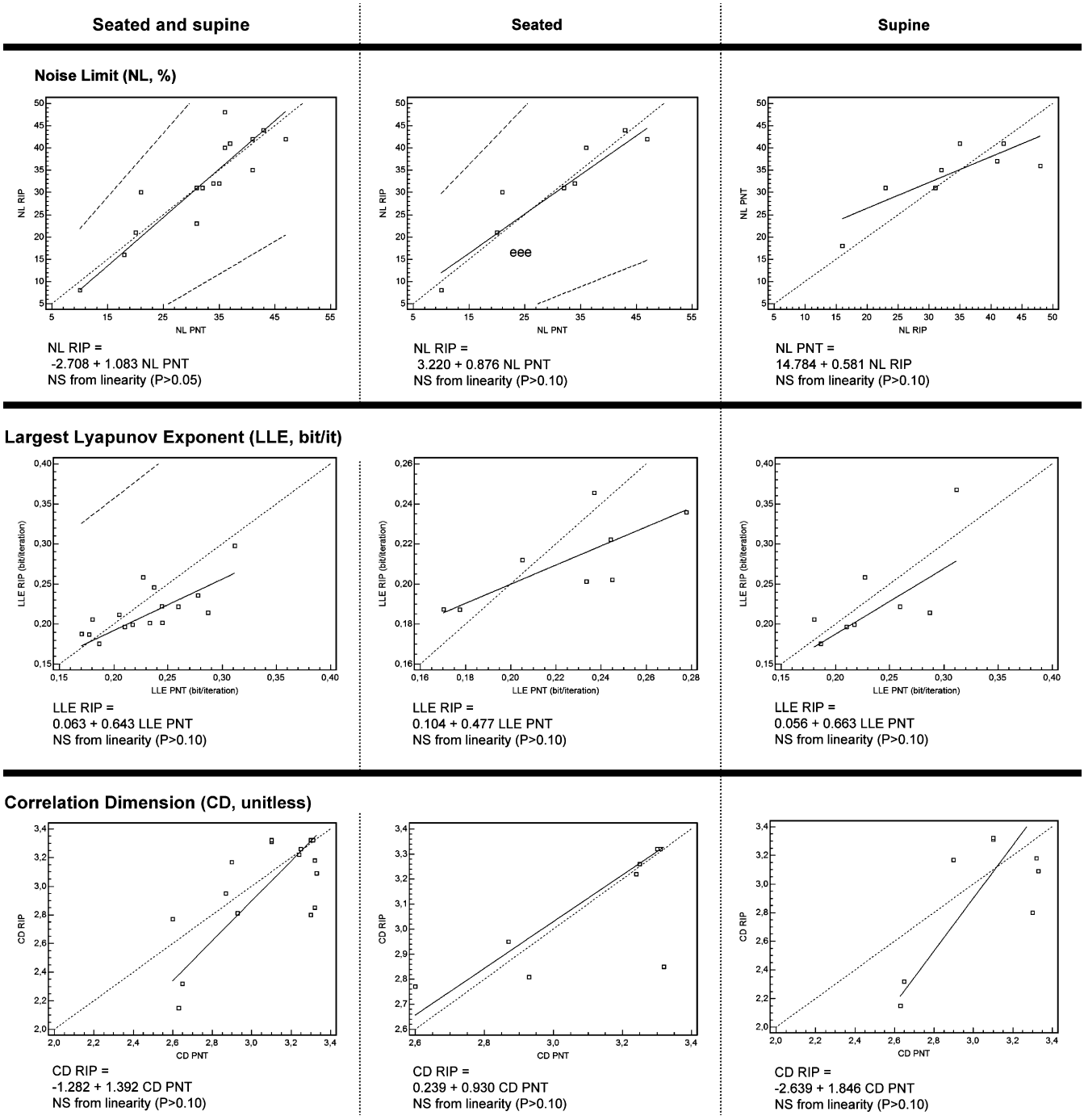


Fig. 2. Passing and Bablock regressions. *X*-axis: values measured with the pneumotachograph (PNT). *Y*-axis: values measured with the respiratory inductive plethysmograph (RIP). NS: no significant deviation from linearity. The ventilatory flow was recorded simultaneously with PNT and RIP.

signals were interchangeable when both signals were measured simultaneously. This study also shows that breathing through a mouthpiece not only modifies the ventilatory pattern but also ventilatory variability and the pattern of ventilatory complexity.

Respiratory inductive plethysmography has long been recognized as a reliable method to measure lung volume variations. The device used here consisted of a sleeveless jacket that has the advantage to maintain the coils in the right position whatever the position of the subjects. Compared to PNT and to full body plethysmography, it has proved to provide accurate recordings of the waveform of the spirogram (Carry et al., 1997). We calculated the flow signal as the first time derivative of the volume signal. Eberhard et al. (2001) demonstrated with the same device and same algorithm that this provides and adequate substitute for the flow measured with a PNT, in subjects breathing freely (seated, supine, or lying on a side) or against a resistance. Here, we confirm the results of Eberhard et al. (2001) since the mean values and coefficients of variation of the RIP $V_I'$, $V_T$, $V_T/T_I$, $T_T$, $T_I$, $T_E$, $T_I/T_T$ appeared to be interchangeable with the PNT ones, both in the seated and the supine position. In addition

and more importantly, the values of NL, LLE and CD calculated from $V'_{PNT}$ and $V'_{RIP}$ recorded simultaneously were not only significantly correlated but also interchangeable according to the Passing–Bablock and the Bland–Altman approaches (but of note the acceptable Bland–Altman limit of agreement is an arbitrary choice that will only be possible to make in the frame of particular applications). Therefore, the $V'_{RIP}$ signal that is produced by the Visuresp® device and the associated mathematical algorithm can be used as a substitute of the $V'_{PNT}$ to describe ventilatory complexity and chaos. Of note, in this study we chose to compare flow signals rather than volume ones, and therefore to differentiate the volume signal from the respiratory inductive plethysmography device rather than to integrate the flow signal from the pneumotachograph. That differentiation tends to be noisier than integration and provides thus robustness to our results.

When RIP and PNT recordings were not performed simultaneously, the above-described interchangeability was lost. Indeed, there was not even a significant correlation between most of the studied variables, be them volume or time ones. This is in line with the known effects on breathing pattern of the measurement of ventilation itself and of the breathing route (Perez and Tobin, 1985; Rameckers et al., 2007). During PNT recordings, our subjects were indeed obliged to breathe trough the mouth, which was not the case during RIP recordings. Our study adds to previous knowledge in demonstrating that measuring ventilatory flow during mouth breathing is not only liable to change tidal volume, but also respiratory variability and complexity. One important implication of our results is that caution will need to be exerted when comparing future results obtained with respiratory inductive plethysmography alone to previous results obtained with pneumotachography. The LLE was the only variable for which interchangeability was found not only during simultaneous $V'_{PNT}$ and $V'_{RIP}$ measurements, but also during separate ones. This could result from a too low sensitivity of the LLE to adequately characterize changes in ventilatory pattern. This could also suggest that LLE relates to a robust property of the ventilatory pattern, e.g. respiratory personality (Benchetrit, 2000).

Of significance, ventilatory chaos was evidenced by the positive noise limit in isolated RIP recordings. This confirms that mouth breathing is not a condition of ventilatory chaos, as previously suggested by facemask recordings (Wysocki et al., 2006). This also suggests that ventilatory chaos is not generated during the transformation of thoracoabdominal movements into flow.

In conclusion, respiratory inductance plethysmography is an adequate means to quantify the breath-by-breath variability of ventilation and study its complexity while avoiding the use of measurement devices known to interfere with ventilatory behaviour.

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