RELIABILITY OF RESPIRATORY TIDAL VOLUME ESTIMATION BY MEANS OF AMBULATORY INDUCTIVE PLETHYSMOGRAPHY

Paul Grossman[1,2], Monika Spoerle[2] and Frank H. Wilhelm[3]

[1] Psychosomatic and Internal Medicine, University of Basel Hospital, Basel, Switzerland
[2] Freiburg Institute for Mindfulness Research, Freiburg, Germany
[3] Institute for Psychology, University of Basel, Basel, Switzerland

KEYWORDS

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ABSTRACT

Ambulatory monitoring of ventilatory parameters in everyday life, field research and clinical situations may offer new insights into respiratory functioning in health and disease. Recent technological advances that employ ambulatory inductive plethysmography could make monitoring of respiration outside the clinic and laboratory feasible. Inductive plethysmography provides a method for nonintrusive assessment of both timing (e.g. respiration rate) and volumetric parameters (e.g. tidal volume and minute ventilation), by which tidal volume is initially calibrated to direct measures of volume. Estimates of tidal volume assessed by this technique have been validated in laboratory investigations, usually examining within-individual relations to direct measures over a large range of tidal volume variation. However, the reliability of individual differences in tidal volume or other breathing parameters has not been tested under naturalistic measurement conditions using inductive plethysmography. We examined the test-retest reliability of respiration rate, tidal volume and other volumetric parameters of breathing over a period of six weeks of repeated measurements during baseline conditions and breathing exercises with 16 healthy freely moving volunteers in a Yoga course. Reliability of measurement was evaluated by calculating the average week-to-week between-subject correlation coefficients for each physiological measure. Additionally because body-mass index has been previously positively correlated to tidal volume, we also assessed this relationship as an external criterion of validity of tidal volume estimation. Regarding the latter, similar correlations to those previous studies were found ($r = 0.6$). Furthermore, reliability estimates were high and consistent across respiratory measures (typically r's = 0.7–0.8). These results suggest the validity of ambulatory inductive plethysmographic measurement of respiration, at least under relatively sedentary conditions. Findings also point to the stability of individual differences in respiratory parameters over consecutive weeks.

INTRODUCTION

Measurement of human respiration, or ventilation, has only rarely occurred outside the clinic or laboratory [1-4]. Although many ventilatory parameters can often easily be discerned both by the breathing individual and by visually observant others, the absence of naturalistic investigation has, ironically, led to the situation that we have almost no normative data about how people breathe in the real world under varying behavioral and psychological demands. Such information may provide new insights into respiratory functioning in health and disease. A likely explanation for the lack of knowledge regarding naturalistic ventilatory patterns is that nonintrusive ambulatory monitoring of ventilation has been difficult to perform and has not until very recently been commercially available. Furthermore, the few field investigations that did monitor breathing pattern provided only very tentative evidence of the reliability of measurement [1, 2, 4]. These studies have employed joint monitoring of abdominal and thoracic inductive plethysmography, attaching stretchable bands around the chest wall and the abdomen.

Inductive plethysmography has long been found to be a standard, well-validated and accurate estimation procedure of both timing and volumetric variables in the laboratory [5-11]. In a recent laboratory study of tidal volume (Vt) and minute ventilation volume (V) during a wide range of exercise, compared to direct assessment, this method appeared to induce only minor inaccuracy of breath-to-breath measurement (within 7 %), whereas average volumetric measurements over many breaths were essentially identical to directly measured respiratory volumes [11]. Furthermore, inductive plethysmography is nonintrusive and enables monitoring of naturally occurring breathing parameters, without the distortions of facemask, or mouthpiece and noseclip, that are necessary for direct estimation [8, 12-16].

Recent evidence also suggests that this method can be used to assess volumetric variations within individuals during the naturalistic conditions of everyday life [3]: Normal exertion-related variations in cardiac autonomic activity were very closely related to changes in minute ventilation, measured by ambulatory inductive plethysmography (using the LifeShirt, Vivometrics, Ventura, CA, USA); thus the relations between ventilation and cardiac activity in real life were similar to those when ventilation was directly measured in the laboratory under exercise conditions. However, these associations were examined within individuals and mean levels were determined by averaging degree of correlation across subjects. Therefore, we do not yet know the extent to which inductive plethysmography can accurately and reliably assess absolute differences in Vt and V between individuals, as well as across multiple measurement sessions within individuals. Additionally the range of within-individual Vt and V variation in previous studies has been large, and, therefore, levels of association may not reflect the degree of relationship when the range of the volumetric parameter is significantly smaller. Hence, the question remains whether inductive plethysmography can reliably detect relatively small variations in Vt and V.

This study addresses issues of reliability and accuracy of inductive-plethysmographic Vt, and other volumetric parameter estimation, over a six-week period of repeated measurements under ambulatory field conditions during baseline breathing conditions. Because we did not have an independent direct assessment of Vt to compare accuracy of measurement, we examined the week-to week stability of baseline Vt across subjects using correlational analyses. Additionally, it is well known that parameters of body size, including weight and body-mass index (BMI), are significantly correlated with directly measured Vt, typically on the order of r's = 0.5-0.7 [17-19]. Therefore, in order to provide an external, independent criteria for nonintrusive Vt estimation, we determined whether anthropometric variables were associated with Vt derived from inductive plethysmography,. We assumed that if body size was correlated to a similar extent in direct clinical vs. ambulatory plethysmographic measures of Vt, this would support the use of ambulatory inductive plethysmography for estimation of Vt and other volumetric ventilatory parameters under field conditions. Finally, we also monitored the ECG in order to derive measures of heart rate and respiratory sinus arrhythmia, in order to compare the week-to week stability of these measures to respiratory volumetric parameters.

METHODS

Participants. Sixteen adult volunteers participated in the study (eight male and eight female). Their mean age was 21.8 (range, 18.2-25.7). All participants were physically healthy and had no history of respiratory or cardiac disease.

Procedure. The results of this methodological study are based on a six-week group training of Yoga breathing exercises led by a qualified female Yoga teacher. Group session were once per week and approximately 60 min in duration. Groups included between six and nine participants who were each instrumented at the same time with separate ambulatory devices (LifeShirt, Vivometrics Inc., Ventura, CA, USA). Subjects arrived in the clinic in the evening before Yoga class. After the procedures were fully explained during the first session, all participants signed an informed consent form. Subjects were then asked to put on the LifeShirt garments with embedded sensors

(Vivometrics Inc., Ventura, CA). Thus, there were as many ambulatory units as participants. The experimenter assisted subjects by attaching the electrocardiogram electrodes and the cable connector to the multi-channel ambulatory monitor. Then after adequate instruction about the calibration procedure, the monitors were started and subjects were asked as a group to follow the instructions on the LCD screen of the device to calibrate the chest- and abdominal-band respiratory sensors by breathing in and out of an 800 ml bag seven times, filling and emptying it completely. This procedure was conducted in sitting and standing posture, repeated twice for each posture. Then subjects were asked to sit quietly with eyes open (baseline 1, 10 min), before starting the Yoga course. The Yoga exercises (Yoga phase) consisted of slow deep breathing and were followed by another quiet breathing period (baseline 2, 10 min), during which participants were asked to pay attention to their breathing pattern without attempting to consciously modify it.

Data acquisition. Physiological signals were continuously registered via a multi-channel ambulatory monitor (LifeShirt System; Vivometrics Inc., Ventura, CA) and stored on compact flashcards. Placement of electrodes and sensors and data recording followed established conventions. Electrocardiogram lead-II was measured from the thorax using 3 spot electrodes. Respiratory pattern was measured using the thoracic and abdominal inductance plethysmography bands integrated in the LifeShirt garment. Data was stored on a flash memory card inserted in the LifeShirt recorder.

Respiratory and autonomic data reduction. The data stored on the memory card was downloaded to a personal computer and loaded into the VivoLogic analysis and display software accompanying the LifeShirt. The calibration periods marked on the recordings were analyzed to derive multiplication gain factors for the thoracic and abdominal inductance plethysmography sensors by a multiple regression analysis [20]. These were then automatically applied to the signals to compute the calibrated respiratory lung volume curve (in liters). The VivoLogic software then computed a variety of parameters for each breath across the entire recording. The electrocardiogram was analyzed to detect R-waves and calculate consecutive RR intervals. Beat-by-beat values were edited for outliers due to artifacts or ectopic myocardial activity by computer algorithm and visual inspection. Respiratory sinus arrhythmia (RSA; high-frequency heart-rate variability) was detected using the peak-valley algorithm [3] and quantified as the amplitude of RR interval change (ms) in phase with the respiratory cycle, then converted to the natural logarithm of ms^2. We also calculated RSA normalized for Vt (RSA/Vt; ms/l). This measure is frequently employed as an index of cardiac vagal activity (see [3, 21]) and therefore of particular relevance for this investigation assessing the reliability of noninvasive estimation of Vt.

Statistical data analysis. Pearson product-moment correlations were employed to characterize the between-sessions reliability of individual differences in the specific physiological measures across sessions. Correlations were performed only between adjacent weeks. The rationale for this was that the Yoga intervention was designed to gradually alter parameters of the breathing pattern, and these effects were presumed to be least disturbing to estimates of stability across adjacent weeks. However, later examination of average correlations across all possible comparisons, unreported here, yielded very similar results.

RESULTS

Mean physiological data for respiratory and cardiac measures are provided in Table 1.

Table 1. Mean and standard error (SE) levels averaged across each experimental phase over six weeks

Mean (SE)	Base1	Base2	Yoga
Tidal Volume (ml)	477.7	549.8	1268.8
	(66.1)	(71.2)	(129.1)
Minute Ventilation (l/m)	6.1	5.3	6.6
	(0.5)	(0.5)	(0.5)

Respiration Rate (c/m)	14.5 (1.3)	11.0 (1.3)	6.2 (0.7)
Heart Rate (b/m)	75.6 (2.2)	72.0 (1.9)	73.1 (1.8)
Respiratory Sinus Arrhythmia (ln ms2)	6.5 (0.4)	7.1 (0.4)	8.5 (0.3)
Normalized Respiratory Sinus Arrhythmia (ms/l)	219.2 (42.7)	253.1 (44.9)	196.8 (27.7)

Association with body size

Baseline Vt was associated with both body weight ($r = 0.54$, $p < .03$) and body-mass index ($r = .63$, $p < 0.01$); Figure 1 depicts the scatterplot of the latter relationship.

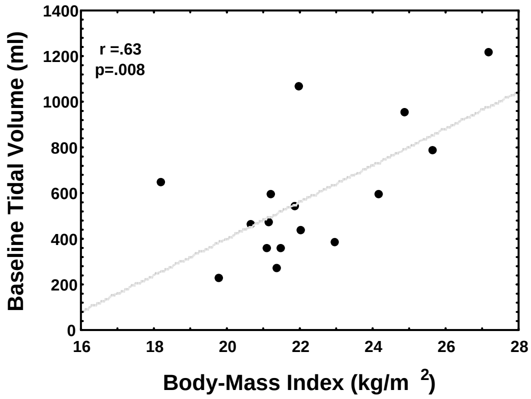

Figure 1. Scatterplot of the association between body-mass index and baseline tidal volume.

Stability and reliability of volumetric parameters across weeks

Values for each physiological measure were correlated across subjects for the six adjacent weeks, resulting in five correlation coefficients for each variable. Correlations for each condition were transformed from means of the corresponding variances (which provided normal distributions) and then averaged across five comparisons (Table 2). Stability of volumetric measures (Vt, V and normalized RSA) tended to be highest during the initial baseline and the Yoga phase and somewhat lower during the last baseline condition. However all correlations were significant, with p's < .02-.001. Similar week-to-week stability was found for respiration rate and unnormalized RSA. Individual week-to-week (test-retest) correlation coefficients (i.e. r's) for Vt ranged between 0.6 and 0.9. Stability of heart rate across weeks was notably less, although still significant (all p's < .05). However, a difference test comparing the highest and lowest correlations coefficients in Table 2 indicated that no coefficient was significantly different from any other. Figure 2 presents scatterplots of typical week-to-week relations of individual levels of tidal volume during a baseline Yoga phase.

Table 2. Average week-to-week, between-subject correlations for each physiological parameter. High levels of correlation indicate both stability and reliability of individual differences over repeated weekly measurements.

	Base1	Base2	Yoga
Tidal Volume	0.82	0.65	0.78
Minute Ventilation Volume	0.76	0.70	0.81
Respiration Rate	0.83	0.73	0.78
Heart Rate	0.68	0.57	0.63
Respiratory Sinus Arrhythmia	0.81	0.81	0.77
Normalized Respiratory Sinus Arrhythmia	0.80	0.69	0.66

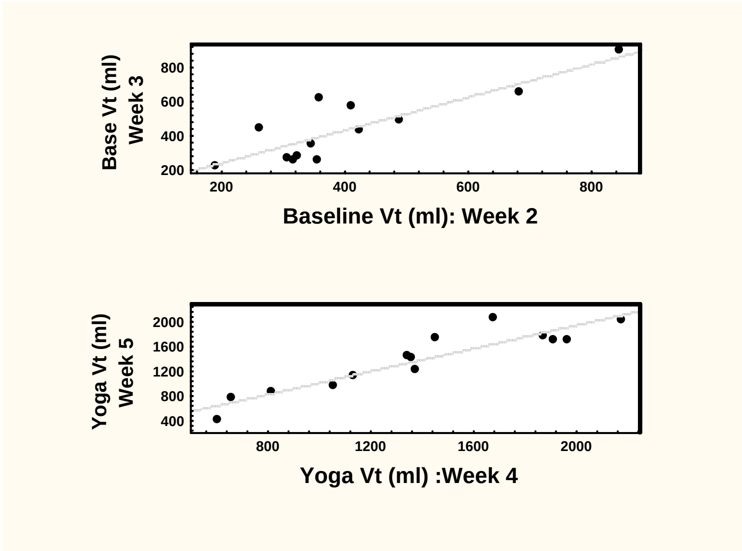

Figure 2. Sample scatterplots for week-to-week tidal volume (Vt) relations. Top, Baseline condition; bottom, Yoga.

DISCUSSION

The findings of this study suggest that nonintrusive estimation of ventilatory volumetric parameters is feasible under ambulatory, naturalistic conditions. Correlations between baseline Vt and BMI were similar to those found in other clinical studies employing direct measures of Vt. Additionally, individual differences in Vt, V and RSA normalized for Vt were all reliable from week to week, as indicated by the correlational analysis of relationships within each variable over adjacent weeks. Test-retest correlation coefficients of 0.7-0.8 are rarely surpassed when comparing the same physiological parameter on two similar occasions in time [22], and all correlations for volumetric parameters were within or very close to this range, suggesting accuracy of volumetric estimation. It is also noteworthy that the two parameters most closely tied to respiratory timing (respiration rate and RSA) demonstrated the greatest degree of stability of individual differences (albeit the lack of statistically significant differences among all correlation coefficients). Respiratory rate is certainly easier to accurately measure with inductive plethysmography, since it requires no calibration, and the method can very sensitively detect the frequency of cyclic chest wall and abdominal movements. However, it is also possible that central respiratory timing represents a more stable characteristic of individuality than volumetric parameters, as suggested by genetic investigations [23, 24] and long-term studies of respiratory individual differences [25]. In any case, the stability of individual differences in both timing and volumetric respiratory parameters not only indicates the validity of the ambulatory measures. These findings may be particularly remarkable because stable respiratory individuality was found during a course in which conscious control of the respiratory pattern was emphasized and behavioral and voluntary control of breathing was particularly active.

Limitations of this study are that no direct estimation of respiratory parameters were used for comparison, and the range of physical activity was relatively restricted, not permitting us to know whether ventilatory assessment might be compromised under more variable levels and types of activity.

CONCLUSIONS

Ambulatory inductive-plethysmography monitoring of ventilation provides reliable estimation of timing and volumetric components of the breathing pattern over time under naturalistic conditions of relatively sedentary behavioral activity. Future research should examine the reliability of this method under varied behavioral conditions in the field.

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