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Accuracy of ventilatory measurement employing ambulatory inductive plethysmography during tasks of everyday life

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ABSTRACT

Ambulatory inductive plethysmography (AIP) has recently been introduced to permit monitoring of ventilation outside the clinic and laboratory. It provides a method for nonintrusive assessment of both timing (e.g. respiration rate; RR) and volumetric parameters (e.g. tidal volume and minute ventilation volume; V_T and V'_E, respectively). Although inductive plethysmography has been validated in laboratory investigations, quantitative validation during ambulatory, naturalistic conditions has not yet been assessed. Should AIP yield accurate estimation of ventilatory parameters, real-life monitoring of breathing pattern may provide new insights into respiratory functioning in health and disease. We examined the accuracy of AIP for assessing RR, V_T and V'_E during a 90-min protocol simulating activities of everyday life. A mobile backpack metabolic cart with integrated flowmeter was employed as the reference standard. Within- and between-participant minute-by-minute comparisons were made for each ventilatory measure among 9 healthy adults. Average within-participant minute-by-minute correlations between reference method and AIP were 0.96, 0.91 and 0.92 for V'_E, V_T and RR, respectively. Average correlations across participants yielded r's of 0.98, 0.98 and 1.0. Analysis of mean task levels across participants revealed, in all cases, very close correspondences between both methods of measurement, with only a significant but minor deviance during a period of supine posture. Additionally, results indicated that within-individual variations in oxygen consumption were highly correlated with AIP-estimated V'_E, suggesting that ambulatory assessment of V'_E may provide a reliable index of metabolic activity during everyday life.

1. Introduction

Normative data is scarcely available concerning how people breathe in the real world under varying physical, behavioral or psychological demands. In fact, measurement of human respiration, or ventilation, has only rarely occurred outside the clinic or laboratory (Anderson et al., 1992; Grossman et al., 2004; Martinez et al., 1996; Pfaltz et al., 2009; Wilhelm and Roth, 1998). Because most clinical knowledge of ventilatory function is based upon tests of forced or manipulated breathing, naturalistic information about ventilation may provide new insights into respiratory functioning in health and disease. Paucity of information regarding ventilatory patterns in daily life may be a consequence of the fact that nonintrusive ambulatory monitoring of ventilation has until very recently been difficult to achieve and unavailable commercially. The few field investigations that monitored breathing pattern beyond the clinic or laboratory have provided only tentative evidence of the reliability of measurement (Anderson et al., 1992; Martinez et al., 1996; Wilhelm and Roth, 1998). Nevertheless, new evidence suggests that the methodology of inductive plethysmography may provide a useful and accurate means by which to assess volumetric and temporal parameters of ventilation during natural conditions of life (Grossman et al., 2004, 2006; Wilhelm et al., 2006).

Respiratory inductive plethysmography (RIP) has long been accepted as a standard, well-validated and accurate estimation procedure for both timing and volumetric variables in the laboratory (Chadha and Sackner, 1983; Clarenbach et al., 2005; Rodenstein et al., 1985; Sackner et al., 1980; Tobin et al., 1983a,b; Zimmerman et al., 1983). It is nonintrusive and enables monitoring of naturally occurring breathing parameters, without the distortions of face-mask or mouthpiece and noseclip, necessary for direct estimation Askanazi et al. (1980), Han et al. (1997), Hirsch and Bishop (1982), Perez and Tobin (1985) and Weissman et al. (1984). Other non-invasive methods, such as thoracic impedance or piezo-electric (or different type) strain gauges, are also available but often do not provide linear signals of chestwall displacement that are constant over time and physiological range, and these methods have not been validated as well as RIP. Characteristic for RIP are elastic abdominal

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and thoracic inductance bands that derive respiratory timing and volumetric parameters from linear, respiration-related changes in chest wall circumference. In a recent laboratory study of respiratory function across a wide range of exercise intensities, RIP appeared to yield only minor inaccuracy of breath-to-breath measurement (within 7%) of tidal volume (V_T), minute ventilation volume (V) and breathing frequency (RR), as compared to direct flowmeter derived assessment, whereas average measurements over many breaths were essentially identical to directly measured parameters (Clarenbach et al., 2005).

Current evidence suggests that this method can also be used to assess volumetric variations within individuals during the naturalistic conditions of everyday life (Grossman et al., 2004): normal exertion-related variations in heart rate and cardiac autonomic activity were very closely related to changes in minute ventilation, measured by ambulatory inductive plethysmography (AIP; using the LifeShirt, Vivometrics, Ventura, CA, USA). Thus the relations between ventilation and cardiac activity in real life were similar to those during which ventilation was directly measured in the laboratory under exercise conditions. Furthermore, in another study with this method, repeated measurement of V'_E, V_T and RR indicated reliability of AIP to assess stable individual differences of those respiratory parameters over consecutive weeks during ambulatory conditions (Grossman et al., 2006). Nevertheless, no study has so far determined whether AIP consistently provides accurate absolute levels of V'_E, V_T and RR during typical conditions of everyday life. The availability of mobile ergospirometry (also called spiroergometry), in which respiratory volumes and gas exchange are directly monitored under freely active situations, now permits such an evaluation (Attinger et al., 2006; Deboeck et al., 2005; Huynh et al., 2006; Perret and Mueller, 2006; van Helvoort et al., 2007; Verges et al., 2006).

Previous validations of inductive plethysmography in the laboratory have tended to examine the accuracy of inductive plethysmography measures across a very wide range of exercise levels (e.g. Clarenbach et al., 2005). This procedure is, of course, likely to enhance the degree of correlation between methods and does not specifically address the extent of correspondence of methods during the more limited range of normal daily activities. Therefore, our investigation compared assessments of ventilatory parameters, based on both AIP and a mobile backpack flowmeter-derived ergospirometry system employing a closed facemask (Oxycom Mobile, Jaeger), during a more restricted scope of metabolic activity. In addition, we were interested in how much the precision of measurements is affected by variation in posture and mental effort typical for daily activities. Thus, we employed a 90-min protocol aimed at capturing the range of variation of behavioral activities characteristic of everyday life. Tasks varied from highly sedentary (quiet reading) conditions to levels of brisk walking typical of daily life. Other more moderate conditions included normal periods of walking, a housekeeping routine, working at the computer, a fine-motor task, a mental task, watching a movie segment and talking. Postures were also varied and comprised standing, sitting and lying.

2. Methods

2.1. Participants

Nine adult volunteers, recruited from hospital and university staff, participated in the study (5 female and 4 male). Their mean age was 37.3 years (range 29–58, S.D. 10.2) with a mean body-mass index of 22.3 (range 19.0–25.1, S.D. 1.98). All participants were physically healthy and had no history of respiratory disease.

2.2. Measurements

AIP signals were continuously measured via a multi-channel ambulatory monitor (LifeShirt System; Vivometrics Inc., Ventura, CA), capable of registering respiration, electrocardiogram, accelerometry and O_2 saturation for up to 24 h. Data was processed in a portable recording device, approximately the size of a personal digital assistant (PDA; 17.3 cm × 7.9 cm × 3.8 cm; weight, 382 g). Respiratory pattern was monitored using the thoracic and abdominal inductance plethysmography bands integrated in the LifeShirt garment, located respectively at the levels of nipples and umbilicus. The LifeShirt system contains different sizes of Lycra vest garments, and the appropriate size was chosen to fit snugly to the participant, but without discomfort or the sensation of restriction of chest wall displacement. Data was stored on a flash memory card inserted in the LifeShirt recorder.

Mobile ergospirometry (Oxycon Mobile, Jaeger/VIASYS Healthcare, Hoechberg, Germany) was employed as reference standard. This system employs a tightly fitting facemask covering nose and mouth with a lightweight integrated flowmeter (Triple V volume sensor; 45 g) with a deadspace of 30 ml. It monitors ventilatory parameters, oxygen uptake and CO_2 production on a breath-by-breath basis. The processing, recording and battery system is comprised of two units (12.6 cm × 9.6 cm × 4.1 cm, each; weight of entire system, 950 g) attached to a belt and worn on the back during testing. Data were stored on memory cards. Calibration of this instrument was performed prior to each recording according to the manufacturer's manual employing the automatic volume- and gas-calibration functions. A flow-volume sensor calibration procedure assures that the Oxycom quantification system (including the amplifier, Triple V sensors, and pressure transducer) is functioning correctly. The gas analyser and delay time calibration was also automatic, as provided by the manufacturer: a calibration gas at 180 kPa (16.25% O_2, 4.13% CO_2 and 79.62% N_2) was introduced to the Oxycon to attain gain, offset and delay times within 1%.

2.3. Protocol

The experimenter first fitted participants to the appropriately sized LifeShirt vest and attached the electrocardiogram electrodes and cable connector to the ambulatory monitor. After instruction about the procedure to adjust gains of the thoracic and abdominal AIP bands, the monitor was turned on. In line with standard volumetric adjustment procedure with AIP (e.g. Wilhelm and Roth, 1998; Grossman et al., 2004), participants were asked to breathe six times in and out of an 800 ml plastic-bag attached to a mouthpiece tube while the nose was clipped, filling and emptying the bag completely with each breath. This procedure was conducted in sitting and standing posture after appropriate pauses, twice for each posture. It was repeated if participants did not adhere to instructions (e.g. incomplete filling or emptying of bags, leakage of air around the mouthpiece or excessive bloating of cheeks) until successfully performed. The phase of controlled breathing was marked on the recordings and later analyzed to derive a single multiplicative factor to adjust the AIP signal to absolute volumetric parameters (see Section 2.5).

The mobile ergospirometry unit was subsequently attached to the participant, and the mask was carefully fitted to preclude air leakage. Simultaneous time stamps were made on each system before the following fixed order of conditions were performed during measurement: (1) initial quiet baseline sitting (6 min; BASE); (2) walking at a pace similar to everyday fast walking for the individual (6-min; FWALK); (3) post rapid-walking quiet sitting (5 min; POST); (4) Walking outside to other unit (lab) at normal pace (5 min; WALK2); (5) quiet standing still (6 min; STAND); (6) manual housework consisting of the following sequence of tasks, filling a bucket of water at a sink to brimming level, walking 14 m, setting the bucket down on a platform, then wiping the water off the floor that had spilled from the overfilled bucket, walking back to the sink, emptying the bucket, filling it again and repeating the previous steps to conclusion (6 min; WORK); (7) viewing a film segment on a video monitor in sitting posture (6 min; FILM); (8) talking about any aspect of the film with the facemask in place (6 min; TALK); (9) fine-motor task of cutting out a figure with a pair of scissors while sitting (6 min; SCIS); (10) typing a document on a PC (6 min; TYPE); 11) silently reading a document while sitting (6 min; READ); (12) performance of the timed paper-and-pencil D2 mental task of selective attention (6 min; D2; (Brickenkamp and Zillmer, 1998)); (13) quiet lying right-lateral supine (3 min; LIE); (14) Normal walking from lab (5 min; WALK3). We attempted to approximate the normal proportion of sedentary and non-sedentary activity of daytime daily life we had found in an earlier study (Grossman et al., 2004).

This study was part of a larger investigation into validation of ambulatory monitoring systems approved by the local institutional review board.

2.4. Respiratory data reduction

The data stored on the memory card was downloaded to a personal computer and loaded into the VivoLogic analysis and display program (Vivometrics, Ventura CA USA) accompanying the LifeShirt. The software program provides both full disclosure of the original digitized signals and the derived parameters in a strip-chart graphic display. Raw and derived data were routinely inspected to assure proper quantification. The software computes a variety of parameters for each breath across the entire recording, including measures of accelerometry activity and cardiac R–R intervals. However, only the following ventilatory measures derived from the LifeShirt recording are presented here, V_T (ml) V'_E (l/min) and RR (breaths/min).

Similarly the reference ambulatory ergospirometry system measured these respiratory parameters, as well as oxygen uptake ($V'O_2$, ml/min) and CO_2 production ($V'CO_2$, ml/min) on a breath-by-breath basis using data analysis software provided by the manufacturer; data was routinely evaluated for accuracy. Timestamps at the start and end of measurement were used to synchronize the two measurement systems. Guidelines have suggested presenting ventilatory data as averages of 30- or 60-s values (American Thoracic Society, 2003). Therefore, breath-by-data were converted to minute-by-minute median values for later comparisons. Medians were employed because they are statistically robust against isolated extreme outlier values.

2.5. Calibration procedure

Calibration included two steps after collection of data: first a standard qualitative diagnostic calibration (QDC) was performed for each individual participant to estimate proportional relations of ribcage vs. abdominal displacements to V_T (Sackner et al., 1989). We then performed an additional calibration procedure for volumetric parameters, based upon regressing the summed AIP abdominal and thoracic signal (QDC-adjusted) upon the reference standard, ergospirometric signal during 10-min of sitting and walking. Individual regression coefficients for each participant were employed as adjustment factors.

Because calibration is frequently made by performing a fixed-volume procedure of breathing in and out of a 800-ml plastic-bag system (e.g. Wilhelm and Roth, 1998; Grossman et al., 2004), we also separately carried out this procedure, as mentioned in the protocol, in order to evaluate its degree of accuracy for estimation of volumetric parameters. The average summed V_T of the two respiratory bands (after QDC adjustment) per breath was calibrated to 800 ml. Furthermore, because this procedure applies a simple single multiplication factor based upon the QDC method, comparisons of ergospirometry-calibrated measures with either the fixed-volume adjustments or merely the QDC adjustment factor are equivalent (i.e. the only difference being the multiplication factor). To distinguish between the above-described methods, we call the latter approach "fixed-volume adjustment" throughout this paper, whereas the method using mobile ergospirometry values is termed "reference calibration."

2.6. Statistical data analysis

Pearson product-moment correlations of individual and group minute-by-minute data for each ventilatory measure were employed to characterize the degree of correspondence between methods. Paired *t*-tests contrasted all conditions for each method of estimation of RR, V_T and V'_E, and the degree of concurrence between methods in terms of significant differences between conditions was examined. Because of the validation nature of this study and the fact that we were interested in similarity of patterns of statistical significance and non-significance between methods, we did not correct for multiple comparisons, and significance level was set at $p < 0.05$, providing a sensitive test of deviation between methods.

Bland–Altman plots were made to assess the extent of bias (mean difference between methods) and of agreement (±95% confidence around the bias; Bland and Altman, 1986). This is a statistical approach that allows quantitative and visual comparison of two measurements techniques by plotting the differences between two techniques against the average of the two methods. It supplements correlational analyses by determining the limits of agreement between methods (in which the mean level ±1.96 S.D. represents bias ±95% confidence interval range of agreement).

Additionally, for each variable and method, we calculated the average levels for each condition and performed multivariate repeated-measures analyses of variance (RMANOVA's) with two repeated measures, measurement method (AIP [reference-calibrated or fixed-volume-adjusted] vs. ergospirometry) and Condition. Greenhouse-Geisser corrections were made to adjust for nonsphericity of multiple comparisons, and all significance levels were corrected.

3. Results

3.1. Minute-by-minute within-individual and pooled analyses

Participant characteristics and mean levels for respiratory measures during the experimental protocol are presented in Table 1. Within-participant correlations (individual numbers of observations (m) = 80–100) between ergospirometry values and reference-calibrated AIP estimates are presented in Table 2. Mean levels of correlation were similar for all variables, with V'_E showing the highest levels. For V'_E, correspondence between methods were very consistent for all participants (r's (80–100) = .89–.97). Examples of correspondence between methods for V'_E median minute data are displayed in Fig. 1a and b for the participant with the poorest association and for an average participant; Fig. 1c illustrates typical correspondence of RR between methods. Associations were also highly consistent for both V_T and RR, except for one participant's greater deviation for V_T (Participant 8, $r(92) = .63$; see Table 2); nevertheless this did not greatly compromise correspondence between methods for estimation of V'_E for this person ($r(92) = 0.89$). When the individual minute-by-minute data of all participants were pooled, reference and AIP estimated measures showed good correspondences (r's(821) = 0.95 V'_E, 0.93 V_T and 0.96 RR).

Bland–Altman plots (Fig. 2a–c) show the extent of bias and agreement between ergospirometry and reference-calibrated AIP for RR, V_T and V'_E. There was a 0.4-breath/min underestimation bias for RR and a 0.4-l/min underestimation bias for V'_E. There was no bias for V_T. Although the degree of correlation both within individuals and pooled across participants was generally very high, the 95% prediction confidence intervals (shown in the Bland–Altman plots) was substantial, indicating that reference-calibrated AIP minute-by-minute data can sometimes be quite divergent from the ergospirometric, reference, values.

Table 1
Mean and standard deviation (in parentheses) for participant characteristics and average levels[a].

	Mean (S.D.)
Age, years	36.1 (11.2)
Height, cm	173.4 (6.9)
Weight, kg	66.4 (9.6)
BMI, kg/m^2	22.0 (2.1)
Respiration rate, breaths/min	15.8 (6.1)
Tidal volume, ml	775.3 (243.4)
Minute ventilation, l/min	11.3 (2.6)

[a] Ventilatory measures are from the reference standard (ergospirometry) during baseline.

Table 2
Within-individual correlation coefficients between reference standard and reference-calibrated AIP measures. V'_E, minute ventilation (l/min); V_T, tidal volume (ml); RR, respiration rate (breaths/min).

Participant	V'_E	V_T	RR
1	0.97	0.94	0.88
2	0.97	0.91	0.95
3	0.94	0.82	0.92
4	0.96	0.92	0.98
5	0.97	0.95	0.92
6	0.96	0.89	0.87
7	0.97	0.97	0.96
8	0.89	0.63	0.96
9	0.94	0.97	0.84
Mean (S.D.)	0.95 (0.03)	0.89 (0.11)	0.92 (0.05)

3.2. Analyses of average conditions levels

Two-factor (Method of Estimation × Condition) repeated-measures analyses of variance were performed to assess the extent of concordance of task effects between these two methods for V'_E, V_T and RR (see Fig. 3a–c). Significant effects for Condition were confirmed for all three variables (F's [13,104] = 25.4–66.3, p's < 10^{-7}). There were no main effects for Method of Estimation for either V'_E or V_T, although there was one for RR ($F[1,8] = 7.4$, $p < 0.03$): RR was slightly higher (0.4 breaths/min) for the reference standard, *post hoc* tests reaching significant differences for the walk, read and scissor conditions. There was also a significant Method × Condition interaction effect only for V_T ($F[13,104] = 3.15$, $p = 0.03$); in *post hoc* analyses, ergospirometric and reference-calibrated AIP methods significantly differed solely for the lying condition (698 vs. 602 ml, respectively). As illustrated by the figures, both levels and confidence intervals are highly in agreement between methods for each measure.

3.3. Comparison of individual condition differences between methods

Paired *t*-tests were performed comparing all conditions with each other for each method (ergospirometry and reference-

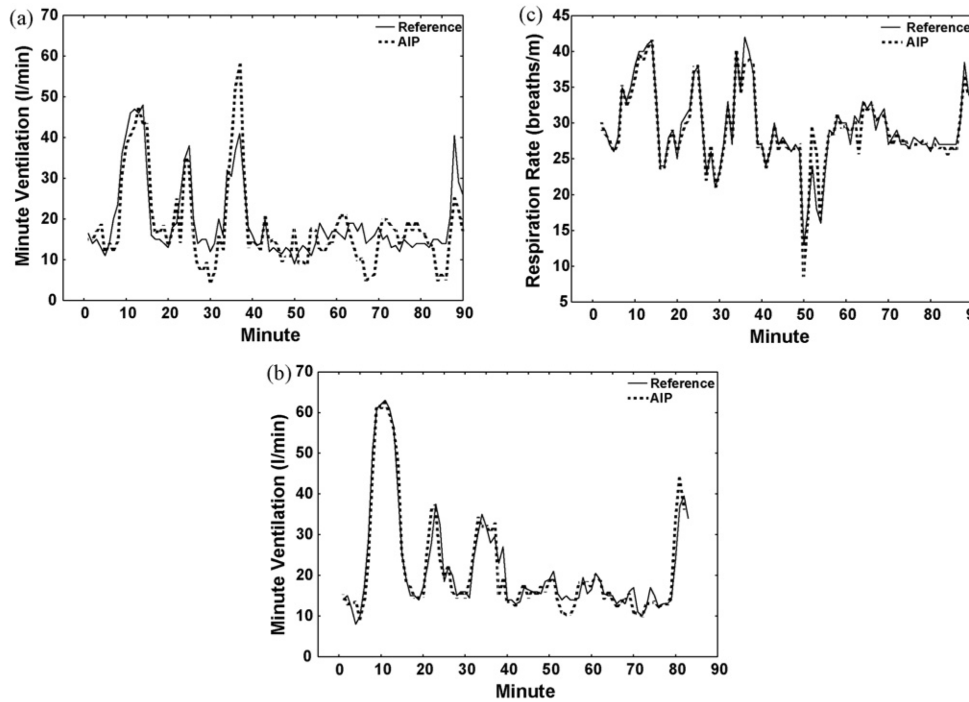

Fig. 1. Correspondence between methods for minute ventilation (V'_E) and respiration rate (RR): (a) V'_E for the participant with the poorest correspondence between methods; (b) a typical example of correspondence between methods for estimating V'_E; (c) a typical example of correspondence between methods for estimating RR.

calibrated AIP) and for all three criterion variables. The findings are presented in Table 3a–c. As can be seen, there were many significant differences between conditions for each of the ventilatory parameters. Patterns of significant and nonsignificant differences between methods was most similar for RR, with correspondence in 89/91 contrasts, and the remaining two discrepancies were very minor. Deviations between methods were somewhat more marked for both V_T and V'_E. However, there was generally still good correspondence between methods for each variable, a corresponding pattern of significance and non-significance in 77/91 comparisons

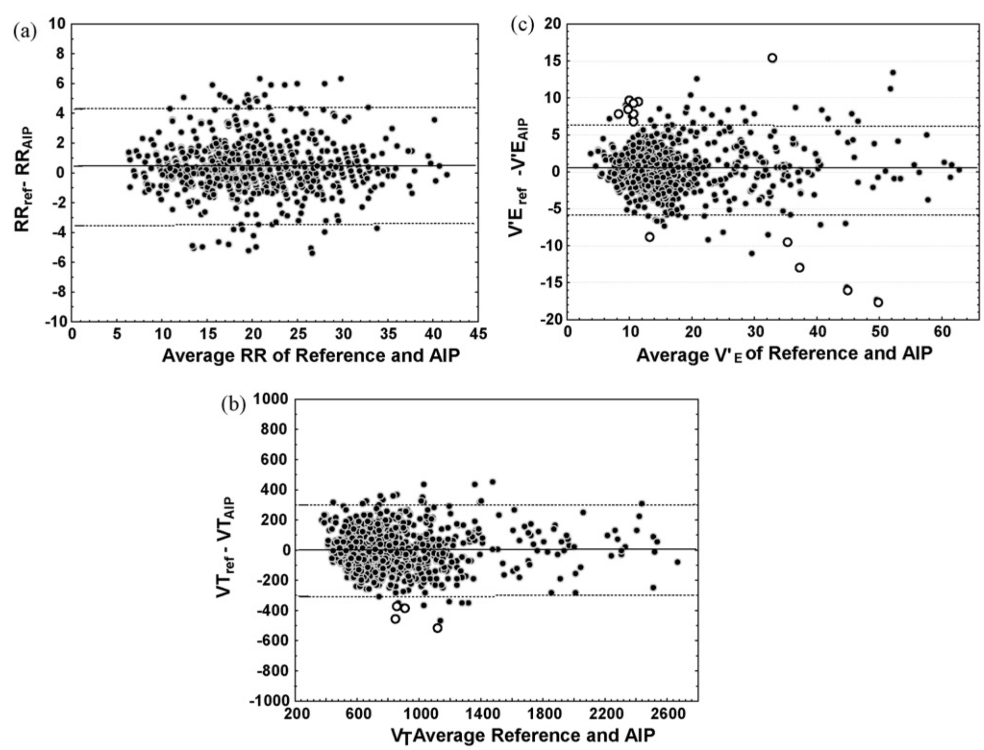

Fig. 2. Bland–Altman plots for minute-by-minute data (a–c) show the extent of bias and agreement between reference standard (ref) and ambulatory inductive plethysmography (AIP) for (a) respiration rate (RR, breaths/min); (b) tidal volume (V_T, ml) and (c) minute ventilation (V'_E, l/min). Center horizontal line indicates mean level of bias, and outer lines 95% confidence intervals. The open circles in b and c indicate points beyond the 95% confidence interval contributed by one participant with poorest volumetric relations between reference and AIP methods (see Table 2 and Fig. 1a).

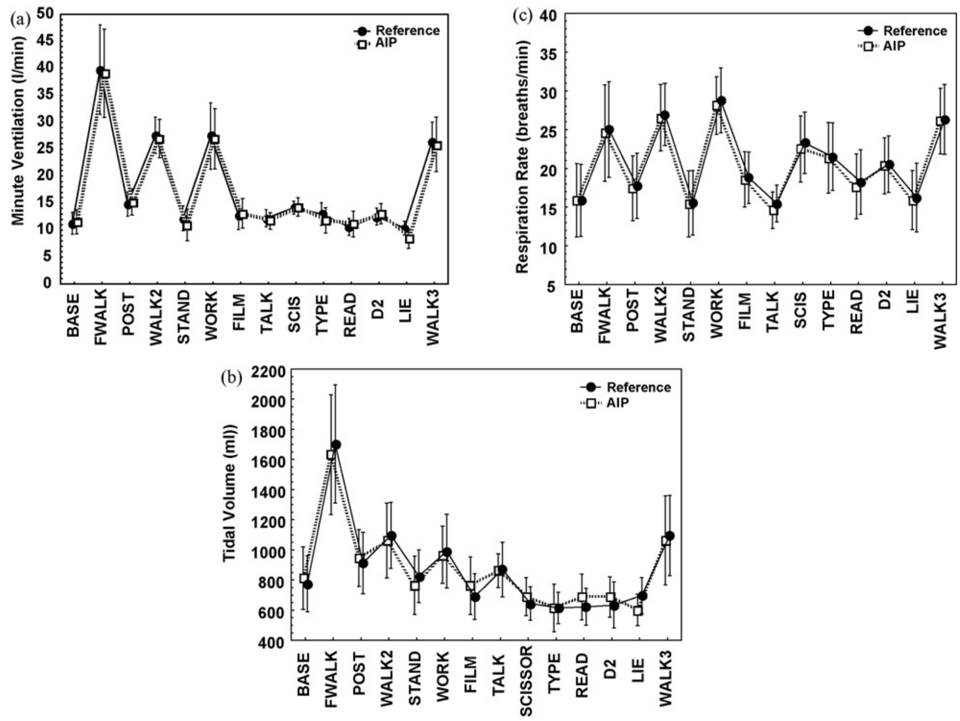

Fig. 3. Extent of concordance of task effects between the two methods for minute ventilation (V'_E), tidal volume (V_T) and respiration rate (RR). Each point represents the mean levels for each condition across participants. Solid lines, reference method; dashed lines, ambulatory inductive plethysmography (AIP).

for each, with the mean differences between conditions most often small. Nevertheless, the number and extent of deviation were typically most marked for comparisons of conditions of differing postures, and patterns were not identical between ergospirometry and reference-calibrated AIP estimations of volumetric measures.

3.4. Comparison of average between-participant variations

Correlation coefficients between methods were calculated using mean levels of RR, V_T and V'_E over the entire measurement period ($n = 9$). Calculated from the ergospirometric method measurements, across all conditions, mean RR was 20.7 breaths/min (4.6 S.D., 15.4–29.3 range); V_T, 855 ml (218 S.D., 631–1315 range); V'_E, 17.2 l/min (3.5 S.D. 12.3–21.8 range). Between-participant r's(9) = 1.0, 0.98 and 0.98, respectively (p's < .00001). Mean reference-adjusted AIP values varied from ergospirometric levels by 1.8%, 0.2%, and 2.2%, respectively.

We also examined differences between genders because of the well known larger lung volumes of men in comparison with women. Although, even with this very small sample, males did differ from females in terms of larger V_T and V'_E (t's[7] = 3.14 and 2.65, respectively; p's < .05), there was no significant difference in average correlations between methods for either V_T or V'_E (p's > .25). Nevertheless, the average correlation coefficients for each parameter were somewhat smaller for females than for males (V_T, .94 vs. 0.97; V'_E, .87 vs. .94).

3.5. Comparison of fixed-volume-adjusted AIP and reference ergospirometry techniques

Because AIP V_T and V'_E are often only assessed after a fixed-volume adjustment for gains of the AIP bands (employing the fixed-volume 800-ml plastic breathing bags), we also computed paired t-tests of V'_E and V_T, comparing the reference ergospirometric method with the fixed-volume adjustment procedure (i.e. not reference-calibrated). The fixed-volume-adjusted AIP procedure underestimated reference V'_E by 5.5 l (±4.4 S.D.), $t(819) = 35.8$, $p < 10^{-7}$. Similarly, fixed-volume-adjusted AIP values of V_T underestimated average ergospirometric level by 265.7 ml (±123.3 S.D.), $t(819) = 61.7$, $p < 10^{-7}$.

3.6. Comparison of relative change between uncalibrated AIP and reference ergospirometry techniques

We also performed similar repeated-measures analyses, as above, comparing percentage change from initial baseline for V_T and V'_E for ergospirometry and the QDC-adjusted (but not reference-calibrated) method. This analysis examined whether condition-related change in V'_E and V_T – only adjusted for QDC, and not calibrated against the reference technique – reflected similar levels of responses to those of ergospirometric estimates. Condition effects were significant for both measures ($F[12,96] = 70.0$ and 46.8, respectively; p's < 10^{-7}). Fig. 4a and b indicates the level of agreement between methods.

3.7. Relations between O_2 consumption and V'_E

Because minute volume is normally closely tied to metabolic processes, we examined the degree of within-participant correlation between oxygen consumption and estimates of V'_E derived from ergospirometry and the reference-calibrated AIP method. Average r's were 0.95 and 0.92 for reference and AIP methods, respectively; ranges, 0.83–0.96 for both (see Fig. 5). Very similar results were also found for CO_2 production and the two V'_E methods. We also compared the degree of within-person correlation between oxygen consumption, on the one hand, and RR and V_T, on the other: average r's = 0.60 and 0.83, respectively; ranges, −0.03 to 0.86, and 0.49–0.96.

Table 3
Pairwise significant differences (p's < 0.05) between conditions for ergospirometry and reference-calibrated AIP methods calculated from paired t-tests of RR, V_T and V'_E parameters.

	BASE	FWALK	POST	WALK2	STAND	WORK	FILM	TALK	SCIS	TYPE	READ	D2	LIE
(a) Respiration rate (RR, breaths/min)[a]													
FWALK	**9.2**												
POST	1.9(1.5)	**−7.3**											
WALK2	**11.1**	–	**9.2**										
STAND	–	**−9.4**	–	**−11.4**									
WORK	**12.9**	**3.7**	**11.0**	–	**13.2**								
FILM	**2.9**	**−6.2**	–	**−8.2**	**3.2**	**−10.0**							
TALK	–	**−9.5**	–	**−11.5**	–	**−13.3**	**−3.3**						
SCIS	**7.4**	–	**5.6**	**−3.7**	**7.7**	**−5.5**	**4.5**	**7.8**					
TYPE	**5.6**	–	**3.8**	**−5.5**	**5.9**	**−7.3**	**2.7**	**6.0**	–				
READ	2.4(1.8)	**−6.8**	–	**−8.7**	–	**−10.5**	–	**2.8**	**−5.1**	**−3.2**			
D2	**4.7**	–	**2.8**	**−6.4**	**5.0**	**−8.2**	–	**5.1**	**−2.8**	–	**2.3**		
LIE	–	**−8.8**	–	**−10.7**	–	**−12.5**	**−2.5**	–	**−7.0**	**−5.2**	–	**−4.3**	
WALK3	**10.5**	–	**8.6**	–	**10.7**	–	**7.5**	**10.8**	**3.0**	**4.8**	**8.1**	**5.8**	**10.1**
	BASE	FWALK	POST	WALK2	STAND	WORK	FILM	TALK	SCIS	TYPE	READ	D2	LIE
(b) Tidal volume (V_T, ml)[b]													
FWALK	**927**												
POST	**138**	**−789**											
WALK2	**321**	**−606**	184(116)										
STAND	–	**−877**	**−88**	**−272**									
WORK	217 (155)	**−710**	–	−105(−95)	–								
FILM	–	**−1012**	**−223**	**−407**	−135 (−2.0)	**−302**							
TALK	–	**−833**	–	**−227**	–	–	180 (100)						
SCIS	*−131 (−121)*	**−1058**	**−268**	**−452**	−181 (−74)	**−347**	–	**−225**					
TYPE	**−161**	**−1088**	**−298**	**−482**	**−211**	**−377**	**−75**	**−255**	–				
READ	**−153**	**−1081**	**−291**	**−473**	−203 (−77)	**−370**	*−68 (−75)*	**−247**	–	–			
D2	**−141**	**−1068**	**−279**	**−463**	−191 (−78)	**−358**	–	**−236**	–	–	–		
LIE	*−78 (−210)*	**−1004**	**−215**	**−399**	*−127 (−163)*	**−294**	*−8.0 (−161)*	**−172**	–	–	–	–	
WALK3	**319**	**−608**	**182**	–	**270**	103(96)	**405**	225(200)	**450**	**480**	**473**	**461**	**397**
	BASE	FWALK	POST	WALK2	STAND	WORK	FILM	TALK	SCIS	TYPE	READ	D2	LIE
(c) Minute ventilation (V'_E, l/min)[c]													
FWALK	**28.5**												
POST	**3.6**	**−24.9**											
WALK2	**16.3**	**−12.2**	**12.7**										
STAND		**−27.5**	**−2.7**	**−15.4**									
WORK	**16.2**	**−12.3**	**12.6**		**15.2**								
FILM	–	**−26.9**	−2.0(−2.1)	**−14.8**	*−2.2 (−0.6)*	**−14.6**							
TALK	–	**−27.6**	**−2.7**	**−15.4**		**−15.3**	–						
SCIS	**2.9**	**−25.6**	–	**−13.4**	**2.0**	**−13.3**	–	**2.0**					
TYPE	1.7(0.2)	**−26.8**	**−1.9**	**−14.6**	–	**−14.5**	–	–	−1.2(−2.5)				
READ	–	**−29.2**	**−4.3**	**−17.0**	−1.6(0.2)	**−16.9**	−2.2(−2.0)	−1.6(−0.54)	**−3.6**	−2.4(−0.6)			
D2	*−1.3 (−1.5)*	**−27.2**	**−2.3**	**−15.1**	–	**−14.9**	–	*−1.4 (−0.4)*	**−1.6**	–	**1.9**		
LIE	*−0.9 (−3.2)*	**−29.4**	**−4.4**	**−17.2**	*−1.8 (−2.6)*	**−17.1**	*−2.4 (−4.7)*	*−1.8 (−3.3)*	**−3.8**	**−2.6**	*−0.2 (−2.8)*	**−2.1**	
WALK3	**15.3**	**−13.2**	**11.7**	–	**14.3**	–	**13.7**	**14.3**	**12.4**	**13.5**	**15.9**	**14.0**	**16.1**

Significant differences found for all cells with numbers (dashes indicate no significant differences). Values indicate mean differences of row variables minus column variable, intended to illustrate magnitude of difference; bold script = concurrent significant findings between AIP and reference; normal script = only reference method significant; and italic, underlined = only AIP significant. Values without parentheses are derived from the reference method, whereas values in parentheses represent AIP score differences. *Note*: BASE, quiet sitting baseline; FWALK, fast walking; POST, post-walking recovery; WALK2, walk to lab; STAND, brief standing; WORK, manual work; FILM, watching film segment; TALK, quiet conversational talking; SCIS, fine-motor cutting of paper forms with scissors; TYPE, typing a passage on a computer keyboard; READ, reading a general interest magazine article; D2, performing a paper-and-pencil cognitive task; LIE, brief lying supine; WALK3, walk from lab.

[a] 89/91 comparisons between methods match in terms of significant and nonsignificant differences between conditions. The largest method divergence in RR between mean differences between tasks was 0.6 breaths/min for BASE–READ contrast.

[b] 77/91 comparisons concurred on significance and non-significance. The largest method divergence in V_T between mean differences between tasks was 168 ml for LIE–READ contrast.

[c] 77/91 comparisons concur in terms of significance of findings (also in same direction of change). Where significant differences varied between methods, V'_E varied less than 2.6 l/min in all cases, and variations were generally less than 2 l/min. The largest method divergence in V'_E between mean differences between tasks was 2.3 l/min for the LIE–FILM contrast.

4. Discussion

Previous research indicated that inductive plethysmography can accurately estimate absolute levels of ventilatory parameters during exercise across a wide range of metabolic variation. Our study supplements those previous findings in two major ways. Unlike exercise validation studies in which ventilatory change occurs under a relatively constant movement pattern and posture, we examined accuracy of AIP measurement across changes of behavioral activities and posture that are typical of everyday life. Postures included both static and dynamically changing ones. Activities varied from rapid walking to talking, watching a film, speaking, and performing household-like work, mental tasks and fine-motor skills. Secondly, our range of ventilatory variation was much more restricted than in exercise studies (e.g. the range of V'_E in (Clarenbach et al., 2005) was 2.5 times that of ours). Nevertheless, agreement between the direct ergospirometry estimation and reference-calibrated AIP was good regarding within-individual variations, as well as with respect to group, condition-by-condition levels. Furthermore, no condition demonstrated a great amount of

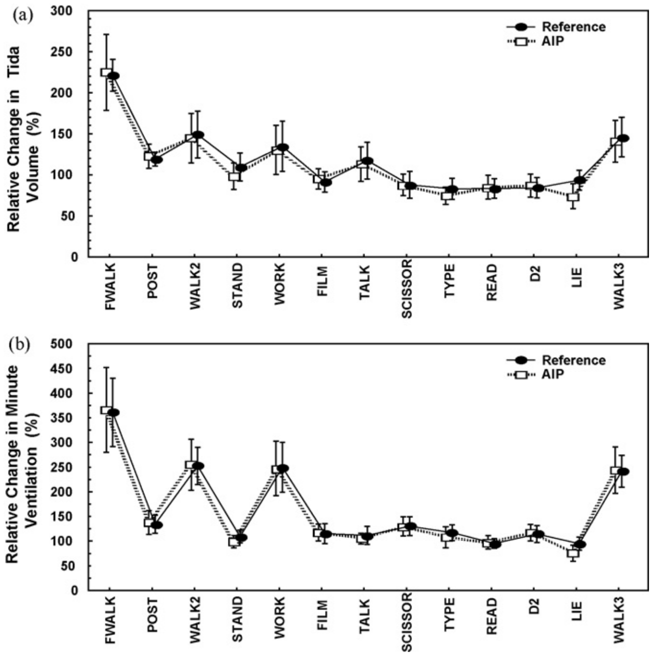

Fig. 4. Extent of concordance of task effects between the two methods for relative changes from baseline in tidal volume (V_T) and minute ventilation (V'_E). Each point represents the mean levels for each condition across participants. Solid lines, reference method; dashed lines, ambulatory inductive plethysmography (AIP).

mean bias for reference-calibrated AIP, despite large postural variations (e.g. housework) or direct modification of the respiratory apparatus (i.e. during speech). The one condition that did appear consistently to underestimate V'_E and V_T was lateral lying, but mean differences between the two methods were still quite small (i.e. about 2 l and 100 ml, respectively).

Bland–Altman plots indicated that bias of estimation was very small, indicating that mean levels of V_T and V'_E derived from reference-calibrated AIP closely approximated direct ergospirometric levels across the entire range of values for each parameter.

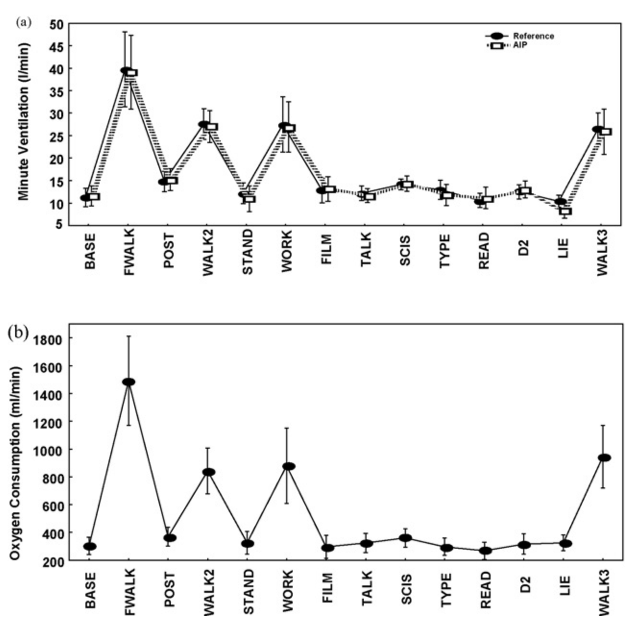

Fig. 5. Correspondence between oxygen consumption ($V'O_2$) and the two estimations of minute ventilation (V'_E). Solid lines, reference method; dashed lines, ambulatory inductive plethysmography (AIP).

However, the degree of agreement between methods, based on the Bland–Altman plots, was not as good as in earlier exercise studies, certainly to be expected given the dynamic postural and motion variations of everyday life. Confidence intervals were rather large for all parameters, demonstrating the possibility of significant discrepancies between methods. This indicates that assessment of individual ventilatory measurements will not always be precisely accurate using AIP in freely moving situations. These findings may have implications for the employment of the method for individual diagnostic or monitoring purposes. In such circumstances, it may be preferable to evaluate ventilation only under proscribed conditions of constant posture and sedentary activity, or to perform separate calibration procedures for each posture. On the other hand, our results do clearly suggest that AIP may be appropriate for research purposes in which average tendencies across groups and populations are sought. Indeed, we found near-perfect correspondence (approaching unity) between methods when estimating individual differences in mean levels of all ventilatory parameters across the measurement period. Furthermore, other analyses indicate that condition averages over several minutes may generally provide reliable indices of true absolute levels of V'_E and V_T. These results, therefore, suggest that AIP may be reliably employed to evaluate individual differences in respiratory function in everyday life, at least among healthy non-obese individuals without respiratory disease. Future research must determine the validity of this approach for patients with respiratory dysfunction, as well as obese populations. Also care must be taken that the LifeShirt vest is properly fitted to the participant: the one individual who could not be properly fitted (some slack in one of the respiratory bands) provided worst correspondence between methods for volumetric measures (participant 8 in Table 2 and Figs. 1a and 2b and c).

Proportional changes in V_T and V'_E were, nevertheless, very similar between ergospirometry and the QDC-adjusted but otherwise uncalibrated AIP. These data indicate that relative changes in ventilation across conditions can be reliably assessed without a detailed calibration procedure, although estimations of absolute levels of volumetric measures will be inaccurate and certainly require careful calibration.

We also found that the commonly employed fixed-volume-adjusted procedure systematically underestimated true levels of V_T and V'_E, and the level of misestimation was quite variable. These findings, therefore, indicate that this fixed-volume procedure is not sufficiently accurate to depict variations between individuals in V_T nor V'_E.

Finally, comparisons of ergospirometry derived O_2 consumption and the reference-calibrated AIP estimate of V'_E within individuals revealed generally high correlations. Thus AIP-estimated V'_E may serve as a reliable index of variations in metabolic activity across the day under many circumstances.

Several limitations of this study should be mentioned. Although the data from individual participants can be seen as multiple replications of within-individual validation, the overall sample size was small. Therefore, group analyses, as well as subgroup ones (e.g. gender) lacked sufficient power, and the sample size also precluded the possibility of more sophisticated statistical designs. Furthermore, our ergospirometric reference measurement of ambulatory ventilation may have somewhat affected the breathing pattern in an unnatural way due to the facemask and awareness of measurement. Hence, we cannot be sure that our findings always reflect normal breathing under naturalistic conditions. Nevertheless, we were primarily concerned with examining whether variations in ventilation under typical conditions of daily life are accurately estimated by AIP. It seems unlikely that any distortions produced by ergospirometry would be so large as to importantly alter our conclusions, especially since the baseline data (Table 1) are largely in line with nonintrusive studies of ventilation under resting conditions.

We conclude that, despite the above-mentioned caveats, monitoring of ventilation by means of ambulatory inductive plethysmography appears to provide reliable estimation of timing and volumetric components of the breathing pattern under naturalistic conditions of daily activity. Future research should examine the reliability of this method under more varied behavioral conditions, as well as its utility for ecological momentary assessment of emotion and related phenomena among normal and clinical populations, (Wilhelm and Grossman, 2010).

Conflict of interest

The authors have no conflicts of interest.

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