ORIGINAL ARTICLE

Lung function measured by impulse oscillometry and spirometry following eucapnic voluntary hyperventilation

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BACKGROUND: The efficacy of impulse oscillometry (IOS) to measure airway calibre change is not fully established.

OBJECTIVES: To evaluate lung function change after eucapnic voluntary hyperventilation (EVH), and to compare IOS indices with spirometric maximal expiratory flow measurements.

METHODS: Twenty subjects (10 airway hyperresponsive [AHR+] and 10 normal [AHR–]) underwent IOS and spirometry before and for 15 min after 6 min EVH (inhaling 5% CO_2, 21% O_2, balance N_2) at a target ventilation of 30 times the baseline value of the forced expiratory volume in 1 s (FEV$_1$) at 20°C. AHR+ was defined by a fall in FEV$_1$ of 10% or greater from baseline after a provoking challenge. Airway resistance at 5 Hz (R_5), reactance at 5 Hz, resonant frequency (F_{res}), area of reactance integrated from 5 Hz to F_{res} (AX), and FEV$_1$ were determined.

RESULTS: No baseline spirometry values correlated with falls in FEV$_1$. Baseline R_5 and AX values correlated with peak falls in FEV$_1$ (r=–0.51 and –0.46, respectively; $P<0.05$). AHR+ subjects demonstrated greater per cent peak falls in FEV$_1$ than did AHR– subjects following EVH (30.6±14.0% versus 7.5±2.6%, respectively; $P<0.05$). Changes in R_5, F_{res}, reactance and AX were greater for AHR+ subjects than for AHR– subjects and correlated with a fall in FEV$_1$ (r=–0.74, –0.70, 0.69 and –0.73, respectively; $P<0.05$). At a designated specificity of 80%, the per cent change in R_5 (50% or greater) and post-EVH AX (12 cm H_2O/L or greater) yielded sensitivities to a 10% fall in FEV$_1$ of 90%.

CONCLUSION: IOS is an acceptable measure to determine AHR and can supplement spirometry in lung function evaluation.

Key Words: *Airway hyperresponsiveness; Dry air; Eucapnic voluntary hyperpnea; Exercise-induced bronchoconstriction; Forced oscillation*

Fonction pulmonaire mesurée par oscillométrie à impulsion et spirométrie après hyperventilation volontaire eucapnéique

HISTORIQUE : L'efficacité de l'oscillométrie à impulsion pour mesurer les changements de calibre des voies respiratoires est plus ou moins bien établie.

OBJECTIF : Mesurer les changements de fonction pulmonaire après hyperventilation volontaire eucapnéique (HVE) et comparer les indices d'oscillométrie aux débits expiratoires de pointe obtenus par spirométrie.

MÉTHODES : Vingt sujets (10 aux voies respiratoires hyperréactives [VRHR+] et 10 normaux [VRHR–]) ont subi une oscillométrie et une spirométrie avant, puis 15 minutes après 6 minutes d'HVE (inhalation de CO_2 à 5 %, d'O_2 à 21 %, N_2 équilibré) à une ventilation cible de 30 fois la valeur de départ du VEMS à 20 °C. Les sujets VRHR+ étaient définis par une chute du VEMS de 10 % ou plus comparativement au départ, après le test de provocation. La résistance respiratoire à 5 Hz (R_5), la réactivité à 5 Hz, la fréquence de résonance (F_{res}), la surface de réactivité intégrée de 5 Hz à F_{res} (AX) et le VEMS ont été déterminés.

RÉSULTATS : Aucune valeur de spirométrie de base n'était en corrélation avec les déclins du VEMS. Les valeurs R_5 et AX de base étaient en corrélation avec les déclins de pointe du VEMS (r = – 0,51 et – 0,46, respectivement; p < 0,05). Les sujets HRVR+ ont présenté un pourcentage de déclin de pointe du VEMS plus marqué que les sujets HRVR– après l'hyperventilation (30,6 ± 14,0 % versus 7,5 ± 2,6 %, respectivement; p < 0,05). Les changements de R_5, de F_{res}, de réactivité et d'AX ont été plus marqués chez les sujets HRVR+ que chez les sujets HRVR– et ont été en corrélation avec un déclin du VEMS (r = – 0,74, – 0,70, 0,69 et – 0,73, respectivement; p < 0,05). À une spécificité désignée de 80 %, le changement de pourcentage du R_5 (50 % ou plus) et l'AX post-hyperventilation (12 cm H_2O/L ou plus) ont donné des sensibilités de 90 % pour ce qui est d'une baisse de 10 % de VEMS.

CONCLUSION : L'oscillométrie à impulsion est une mesure acceptable pour déterminer l'hyperréactivité des voies respiratoires et peut compléter la spirométrie lors d'évaluation de la fonction pulmonaire.

Although exercise-induced bronchoconstriction (EIB) has received much attention over the past decade, its mechanisms remain elusive (1-3). The response to EIB is most likely multimediated and dependent on the precise stimulus. For example, the pathophysiology of cold air-induced bronchoconstriction (4-6) involves different mediators than high particulate matter exposure (7,8) or allergen-mediated bronchoconstriction (9). Likewise, there are differences of opinion concerning the most appropriate provoking challenge for diagnosis and what cutoff criteria should be employed for specific populations. Some studies have proposed a sports-specific challenge (10,11), while others have suggested eucapnic voluntary hyperventilation (EVH) (12-16) or osmotic (17-19) challenges. Pharmacological challenges (20,21) have been found to be less sensitive for identifying EIB in athletes (15). The measurement most often used to determine airway hyperresponsiveness in athletes, regardless of the specific challenge, is a postchallenge 10% or greater fall in the forced expiratory volume in 1 s (FEV$_1$), which is determined using spirometry from 5 min to 20 min after provocation (10,22,23).

Impulse oscillometry (IOS) has been used to measure short-term changes in bronchial tone in bronchodilator tests (24), and has been shown to correlate with FEV$_1$ (25-33) and airway resistance, which is determined by body plethysmography (34,35). IOS applies brief, random pressure pulses of 5 Hz to 35 Hz generated by a small loudspeaker mounted in series or parallel to a pneumotachometer. The pressure impulses are superimposed to tidal breaths, and real-time recordings are

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TABLE 1
Subject demographics and per cent fall in forced expiratory volume in 1 s after eucapnic voluntary hyperventilation (mean ± SD)

	AHR–	AHR+
n	10	10
Age (years)	21.3±4.37	25.5±8.73
Weight (kg)	76.1±9.64	80.6±16.12
Height (cm)	174.8±7.16	173.0±6.71
Fall in FEV_1 (%)	7.5±2.59	30.6±14.03

AHR Airway hyperresponsive

used to estimate total respiratory impedance. The two components of impedance are resistance and reactance. Bisgaard and Klug (25) have shown that reactance (X) at 5 Hz has the lowest intra- and between-individual variability, and has a sensitivity equal to that of airway conductance. Others have suggested that airway resistance at 5 Hz (R_5) is sensitive to obstruction (24,26,32). Goldman et al (36) demonstrated that the area of X integrated from 5 Hz to resonant frequency (F_{res}), otherwise known as AX, is sensitive for detecting changes in bronchomotor tone in adolescent asthmatics. Schmekel and Smith (31) found that the response in F_{res} has the most discriminative capacity to correctly diagnose asthma. Although the clinical efficacy of measuring respiratory impedance using IOS has been demonstrated, its use has not been widespread in assessing airflow obstruction (32).

In the present study, we compared airway responses with a 6 min EVH challenge using IOS and forced expiratory flow (FEF) manoeuvre values in airway hyperresponsive (AHR+) athletes and normal (AHR–) athletes and assessed the sensitivity and specificity of IOS to spirometry measures for identifying airway hyperresponsiveness. We correlated R_5, F_{res}, X and AX to FEV_1, and suggested cutoff criteria for these IOS measurements for determining airway hyperresponsiveness.

METHODS

Twenty subjects (five women and 15 men) volunteered to participate in the present study, which was approved by the Marywood University Institutional Review Board (Pennsylvania, USA). Table 1 provides subject demographic data. Ten subjects (four women and six men) were considered AHR+ by a 10% or greater fall in FEV_1 following EVH, and 10 subjects (one woman and nine men) were considered AHR– by EVH.

The EVH protocol required subjects to breathe a compressed dry gas mixture (21% O_2, 5% CO_2, balance N_2) at a predetermined rate (30 × FEV_1) for 6 min (12,14-16). Gas flowed from a cylinder through a calibrated rotameter (1110 Series Flowmeter, Brooks Instruments, USA) to three 300 g reservoir bags via high-pressure tubing. From the reservoir bags, the gas was directed to the subject via a 35 mm breathing tube, two-way breathing valve and mouthpiece (Hans Rudolf, USA). Expired gas passed through a flow sensor and minute ventilation was recorded (Vmax Spectra, SensorMedics, USA). Inhaled gas during EVH was at laboratory temperature but completely dry. Ambient temperature, relative humidity and barometric pressure in the laboratory were 19.4±0.61°C, 16.1±3.22% and 722±7.8 mmHg, respectively.

Airway resistance and X were determined by IOS (MS-IOS, Jaeger, Germany) using the manufacturer's recommended techniques. Real-time recordings of mouth pressure and flow signals pulsed through the 5 Hz to 35 Hz spectrum were superimposed and displayed on a computer screen. Fast fourier transformation analysis calculated R_5 (cm H_2O/lps [litres per second]), X (cm H_2O/lps), F_{res} (Hz) and AX (cm H_2O/L).

Pulmonary function response to EVH was determined using spirometry immediately following the IOS manoeuvre. Forced vital capacity (FVC), FEV_1, FEV_1 to FVC ratio, and FEF through the middle portion of the vital capacity ($FEF_{25–75}$) were measured pre- and post-EVH. The procedure for all pulmonary function tests involved the following steps: three normal tidal volume breaths; maximal inhalation; forced maximal exhalation; and maximal inhalation as previously performed (16). All testing was completed using a calibrated, computerized pneumotachograph spirometer (Masterscope PC, Jaeger, Germany). Baseline pulmonary function was established by selecting the best of three resting pulmonary function tests. An individual measurement of maximum voluntary ventilation was obtained using a 12 s manoeuvre. Postchallenge pulmonary function was measured at 5 min, 10 min and 15 min after a challenge. If any postchallenge time point measurement was technically unacceptable, it was repeated.

Descriptive statistics for resting lung function were calculated for IOS and spirometry lung function measurements. Repeated measures ANOVA was used to analyze differences between post-EVH lung function measurements and between AHR+ and AHR– groups. Pearson Product Moment correlations were used to evaluate relationships between resting measurements and between postchallenge falls in FEV_1, airway resistance and X measurements (determined using IOS). $P \leq 0.05$ was considered significant.

RESULTS

Baseline lung function

Resting lung function variables obtained using IOS and maximal expiratory flow volume manoeuvres performed by 10 AHR+ and 10 AHR– subjects are presented in Table 2. Mean values for FVC, FEV_1, the FEV_1 to FVC ratio and $FEF_{25–75}$ were within normal limits for both groups. The FEV_1 values of two AHR+ subjects were 80% or below the values that were predicted. The $FEF_{25–75}$ values of five AHR+ subjects and two AHR– subjects were 70% or below the predicted values. One subject demonstrated an FEV_1 to FVC ratio of 66%.

No resting spirometric measures were related to post-EVH falls in FEV_1. Resting R_5 and AX values were significantly correlated with peak post-EVH falls in FEV_1 (r=–0.51 and –0.46, respectively; $P<0.05$). No significant correlations were identified between peak fall in FEV_1 and resting F_{res} or X values (r=–0.30 and 0.41, respectively). Presented in Table 3 are correlation coefficients to post-EVH peak falls in FEV_1, as well as baseline cutoff criteria, sensitivity and predictive values for 80% specificity.

Airway response to EVH

Peak post-EVH measurements from IOS were significantly greater than baseline values for AHR+ and AHR– subjects ($P<0.05$). Baseline IOS measurements were not different between AHR+ and AHR– subjects; however, postchallenge peak IOS values were different between subject groups (Figure 1; $P<0.05$). Per cent changes for AHR+ and AHR– subjects in R_5, F_{res}, X and AX were 70.3 versus 37.9, 82.6 versus 48.6, 175.9 versus 70.8, and 567.8 versus 267.0, respectively. When computed as a per cent change from baseline, only the per cent change in peak R_5 was significantly greater for AHR+ subjects ($P<0.05$); F_{res}, X and AX per cent changes were not

TABLE 2
Baseline values for spirometry and impulse oscillometry*

	FVC	FEV_1	FEV_1/FVC ratio (%)	FEF_{25-75}	R_5 (cm H_2O/lps)	F_{res} (Hz)	X (cm H_2O/lps)	AX (cm H_2O/L)
AHR+ subjects								
1	4.49 (129.0)	2.99 (99.0)	66	1.76 (45.6)	9.29	22.78	–3.12	30.60
2	4.28 (89.0)	3.24 (79.0)	76	2.23 (45.2)	4.31	17.39	–1.56	7.50
3	5.20 (99.1)	4.08 (92.1)	78	3.20 (63.1)	3.83	15.26	–1.63	7.42
4	6.25 (122.6)	5.20 (120.4)	83	5.38 (107.0)	3.81	8.58	–0.68	1.25
5	3.93 (101.0)	3.60 (105.9)	92	4.75 (113.9)	4.3	12.70	–1.41	4.00
6	6.05 (122.0)	4.85 (115.2)	80	4.55 (91.4)	3.22	10.74	–0.96	2.12
7	4.33 (80.2)	3.63 (80.0)	84	3.52 (68.8)	7.14	19.79	–1.65	15.54
8	3.87 (115.2)	3.16 (109.0)	82	3.21 (89.4)	4.15	13.67	–1.53	5.66
9	4.60 (85.2)	3.85 (84.8)	84	3.59 (70.0)	4.20	14.84	–1.41	5.11
10	4.30 (105.9)	3.85 (109.4)	90	4.19 (110.0)	3.57	15.51	–0.70	3.81
Mean	4.73 (104.9)	3.85 (99.5)	81.5	3.64 (80.4)	4.78	15.13	–1.47	8.30
SD	0.835 (17.0)	0.713 (14.9)	7.3	1.121 (25.6)	1.91	4.161	0.689	8.786
AHR– subjects								
1	5.77 (113.1)	4.35 (100.7)	75	3.28 (65.2)	3.28	8.67	–1.07	1.70
2	4.92 (96.5)	3.91 (90.5)	79	3.17 (63.0)	4.03	15.99	–1.11	5.19
3	6.32 (108.2)	5.68 (116.6)	90	6.70 (127.1)	2.79	8.99	–0.79	1.46
4	4.22 (126.4)	3.68 (126.9)	87	8.31 (218.7)	3.84	11.79	–1.07	3.28
5	4.86 (110.0)	4.06 (111.2)	84	3.82 (93.2)	4.82	15.90	–1.61	6.99
6	4.81 (117.5)	4.10 (121.0)	85	4.93 (126.8)	3.12	7.89	–0.64	0.83
7	4.63 (109.5)	3.93 (112.3)	85	4.02 (101.5)	5.04	13.38	–1.32	4.74
8	6.04 (111.9)	5.01 (125.6)	83	6.81 (139.6)	3.47	13.43	–1.91	5.76
9	5.33 (114.1)	5.32 (114.4)	99	6.03 (116.6)	3.21	13.69	–0.49	1.93
10	6.08 (109.8)	4.68 (103.1)	77	3.70 (72.3)	3.44	9.43	–0.79	1.73
Mean	5.42 (110.0)	4.56† (110.6†)	84.0	4.72† (100.6†)	3.69	11.93	–1.08	3.37
SD	0.644 (5.8)	0.649 (10.9)	7.2	1.452 (28.9)	0.779	3.193	0.439	2.282

**Per cent predicted values are in parentheses.* †*Significant difference between airway hyperresponsive (AHR+) and normal (AHR–) subjects ($P<0.05$). AX Area of reactance integrated from 5 Hz to resonant frequency (F_{res}); $FEF_{25–75}$ Forced expiratory flow through the middle portion of the vital capacity; FEV_1 Forced expiratory volume in 1 s; FVC Forced vital capacity; R_5 Airway resistance at 5 Hz; X Reactance*

significantly different between AHR groups. The pattern of change in R_5 values at 10 min after EVH was similar to that observed for FEV_1 (Figure 2); however, resistance at 15 min after EVH was not different between groups.

Relationship between spirometry and IOS

Peak increase in R_5 was significantly correlated with peak increases in F_{res}, X and AX (r=0.79, –0.94 and 0.98, respectively; $P<0.05$). Peak increase in F_{res} was significantly correlated with peak increases in X and AX (r=–0.83 and 0.84, respectively; $P<0.05$). Peak increase in X was significantly correlated to peak AX (r=–0.96; $P<0.05$). Per cent peak fall in FEV_1 was significantly correlated with peak increases in R_5, F_{res}, X and AX expressed as raw values (r=–0.74, –0.70, 0.69 and –0.73, respectively; $P<0.05$) (Figure 3) and to per cent change (from baseline) in R_5, F_{res}, X and AX (r=–0.66, –0.47, –0.57 and –0.46, respectively; $P<0.05$) (Figure 4). Per cent peak fall in $FEF_{25–75}$ was significantly correlated with peak increases in R_5, F_{res}, X and AX as raw values (r=–0.57, –0.63, 0.58 and –0.57, respectively; $P<0.05$) and to per cent increases in R_5, F_{res}, X and AX (r=–0.58, –0.49, –0.56 and –0.4, respectively; $P<0.05$).

DISCUSSION

EVH is a widely accepted provocation challenge for EIB among high-level athletes. In fact, EVH is the challenge

TABLE 3
Relationship between impulse oscillometry variables and peak falls in forced expiratory volume in 1 s following eucapnic voluntary hyperventilation (EVH)

Variable	n	Cutoff	r	Sens (%)	Spec (%)	PPV (%)	NPV (%)	TA (%)
Baseline R_5	20	4.0 cm H_2O/lps	–0.51*	60	80	75	67	70
Baseline F_{res}	20	14 Hz	–0.30	60	80	75	67	70
Baseline X	20	–1.30 cm H_2O/lps	0.41	70	80	78	73	75
Baseline AX	20	5.5 cm H_2O/L	–0.46*	60	80	75	67	70
Post-EVH R_5	20	6.0 cm H_2O/lps	–0.74*	80	80	80	80	80
Post-EVH R_5 (% change)	20	50%	–0.66*	90	80	82	89	85
Post-EVH F_{res}	20	19 Hz	–0.70*	80	80	80	80	80
Post-EVH F_{res} (% change)	20	65%	–0.47*	50	80	71	62	65
Post-EVH X	20	–2.0 cm H_2O/lps	0.69*	80	80	80	80	80
Post-EVH X (% change)	20	90%	–0.57*	80	80	80	80	80
Post-EVH AX	20	12 cm H_2O/L	–0.73*	90	80	82	89	85
Post-EVH AX (% change)	20	300%	–0.46*	40	80	67	57	60

*Cutoff values, sensitivity (Sens), positive predictive value (PPV), negative predictive value (NPV) and test accuracy (TA) were calculated for impulse oscillometry parameters for a specificity (Spec) of 80%. *Indicates a significant correlation to post-EVH peak fall in forced expiratory volume in 1 s ($P<0.05$). AX Area of reactance integrated from 5 Hz to resonant frequency (F_{res}); lps Litres per second; R_5 Airway resistance at 5 Hz; X Reactance*

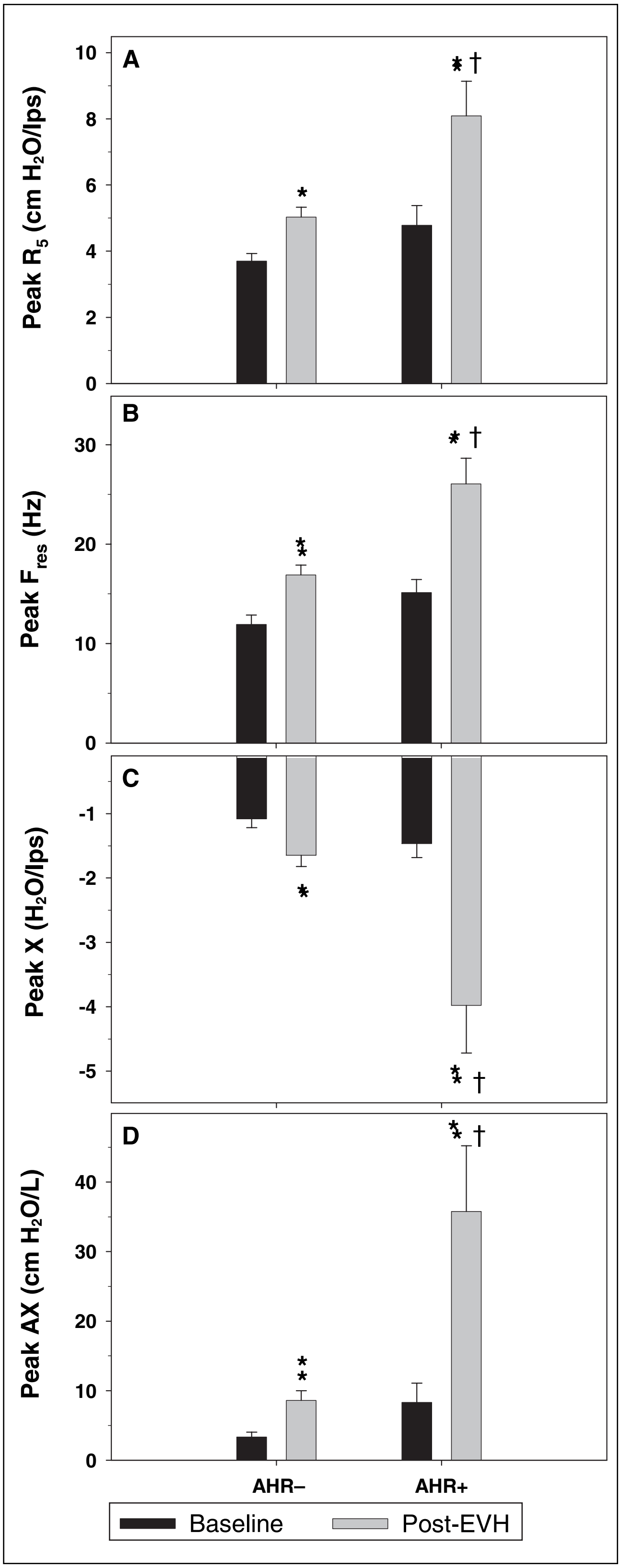

Figure 1) *Posteucapnic voluntary hyperventilation (EVH) values for airway resistance at 5 Hz (R_5), resonant frequency (F_{res}), reactance (X) and area of reactance integrated from 5 Hz to F_{res} (AX) were significantly greater for baseline values for both airway hyperresponsive (AHR+) and normal (AHR–) subjects (*P<0.05), and were greater for AHR+ subjects than for AHR– subjects (†P<0.05)*

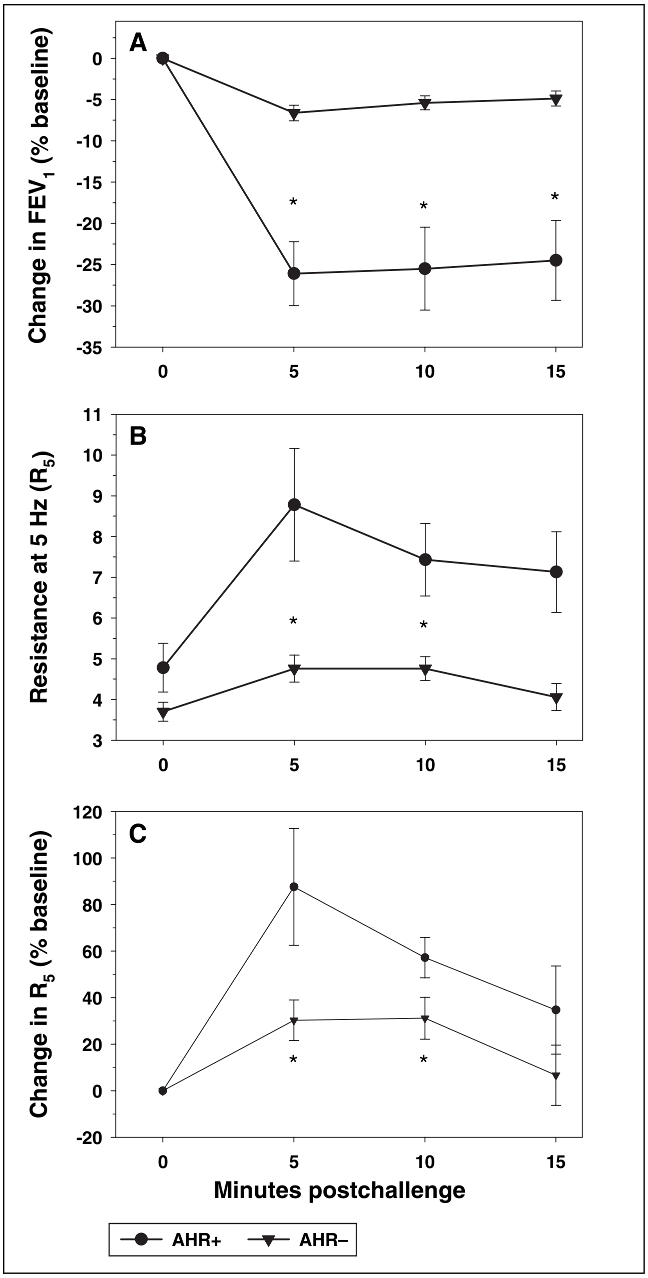

Figure 2) *The persistence of airway obstruction in airway hyperresponsive (AHR+) versus normal (AHR–) subjects over 15 min after the completion of eucapnic voluntary hyperventilation measured by per cent change in forced expiratory volume in 1 s (FEV_1; panel* **A***), airway resistance at 5 Hz (R_5; panel* **B***), and per cent change in R_5 (panel* **C***)*

recommended by the International Olympic Committee Medical Commission Independent Panel to evaluate EIB in Olympic athletes (14-16). In the present study, we compared postchallenge FEV_1 measurements obtained from maximal expiratory flow volume manoeuvres with measurements of airway impedance obtained from IOS during tidal breathing in AHR+ and AHR– subjects. Our results demonstrated that IOS provides a reliable method of evaluating airway obstruction as defined from spirometry measurements in a college-aged athletic population. We identified useful criteria for measuring AHR using IOS. Nine of the 10 subjects with a 10% or greater fall in FEV_1 demonstrated a greater than 50%

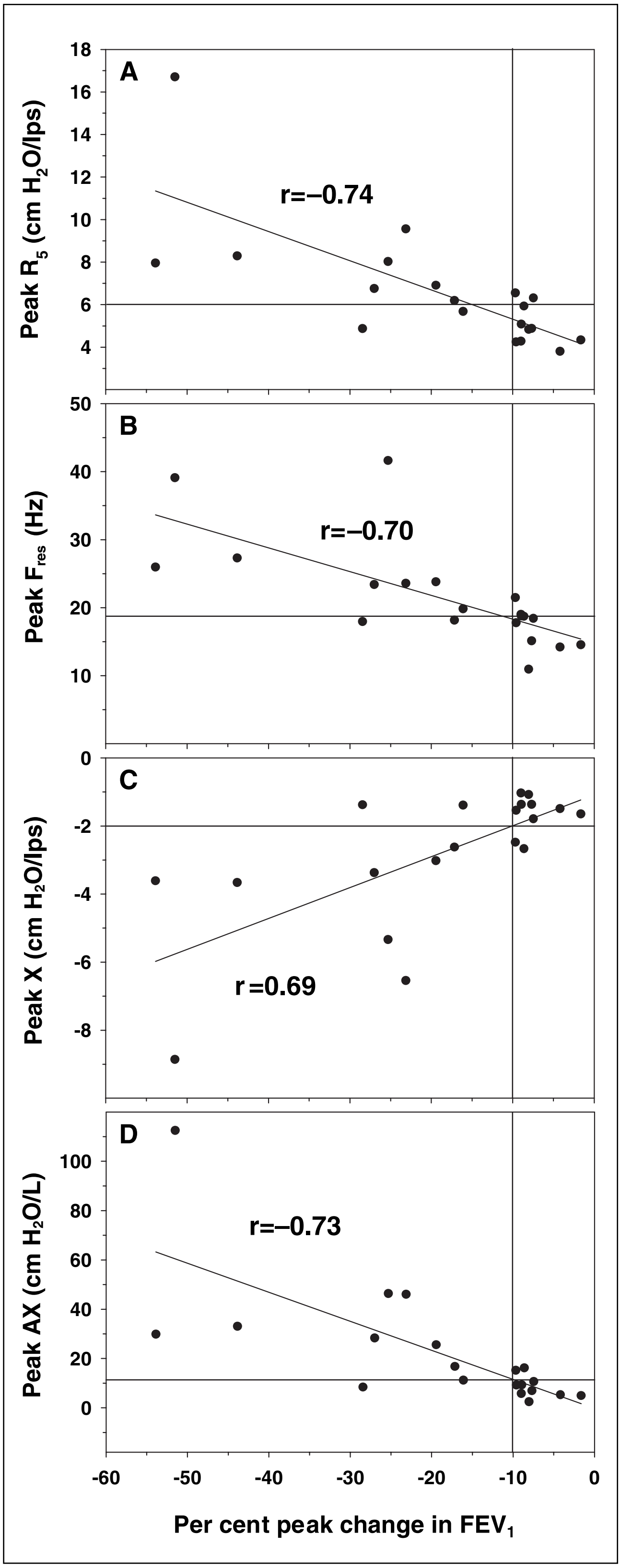

Figure 3) *Peak changes in airway resistance at 5 Hz (R_5) (**A**), resonant frequency (F_{res}) (**B**), reactance (X) at 5 Hz (**C**), and area of reactance integrated from 5 Hz to F_{res} (AX) (**D**) after eucapnic voluntary hyperventilation were significantly correlated to peak per cent change in forced expiratory volume in 1 s (FEV_1) ($P<0.05$). Cutoff reference lines indicate a 10% fall in FEV_1 and 80% specificity for impulse oscillometry indices. Sensitivities were 80% for R_5, F_{res} and X, and 90% for AX*

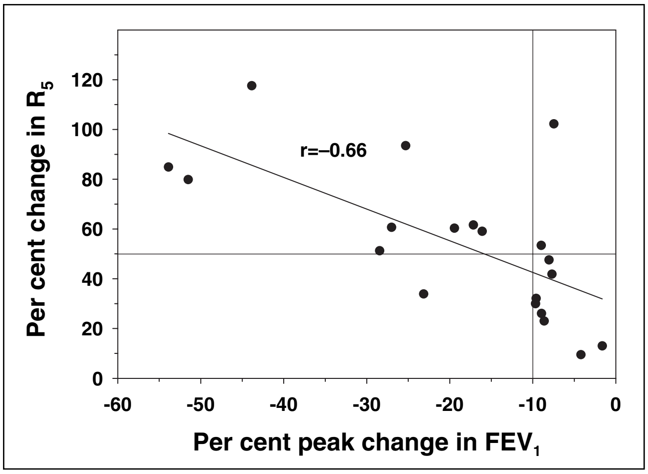

Figure 4) *Peak per cent change in airway resistance at 5 Hz (R_5) was significantly correlated to peak per cent change in forced expiratory volume in 1 s (FEV_1). At 80% specificity, a 50% change in R_5 demonstrated high sensitivity, only missing one subject positive for FEV_1, indicating reasonable agreement with per cent fall in FEV_1*

increase from baseline in R_5 (or had a postchallenge value of 5.5 cm H_2O/lps). Moreover, an additional three subjects who were borderline AHR– by FEV_1 demonstrated elevated R_5 values consistent with airway obstruction, suggesting that the forced expiratory manoeuvre may mask changes in airway tone.

We used postchallenge falls from baseline in FEV_1 as the 'gold standard' indirect measure of changes in airway calibre after EVH because it is the most widely used index of AHR (22,23). $FEF_{25–75}$ was also used as an indication of airway obstruction; however, postchallenge $FEF_{25–75}$ is only valid when vital capacity is unaltered (16,37). In the present study, vital capacity remained relatively unchanged; therefore, comparisons of $FEF_{25–75}$ with IOS indices were made. Peak falls in $FEF_{25–75}$ were highly correlated to peak falls in FEV_1. A significant response to EVH was obtained; mean postchallenge per cent peak falls for respective AHR+ and AHR– subjects were 30.6±14.0% and 7.5±2.6% for FEV_1, and 50.7±17.8% and 22.4±7.7% for $FEF_{25–75}$. The falls for the AHR– group were substantially greater than expected. Rundell et al (16) obtained a fall of 4.7±3.2% after EVH in 21 AHR– subjects, suggesting that underlying hyperreactivity could have been present in our control population; only two subjects in the AHR– group had peak falls in FEV_1 of less than 7.5%. Interestingly, those two subjects were the only subjects that demonstrated post-EVH increases in R_5 of less than 20% (9.5% and 13.0%; Figure 4). The cutoff value to define reversible airway obstruction is usually based on the mean plus two standard deviations of the response in healthy subjects. Although we used the widely accepted cutoff of a 10% fall in FEV_1, values of 7.5% and 6.5% have been suggested to define AHR in elite cold weather athletes (11) and elite Finnish runners (21), respectively.

Respiratory impedance was evaluated using IOS and compared with FEV_1 and $FEF_{25–75}$ values obtained from spirometry. The IOS manoeuvre involves tidal breathing for 20 s to 30 s while respiratory flow is overlaid with pulses emitted from a loudspeaker. Based on the airflow response, impedance estimated as the spectral ratio between pressure and flow through 5 Hz to 35 Hz is resolved into resistance and X. Debate exists concerning which is more discriminating when detecting airway obstruction; however, it is widely accepted that IOS measurements are frequency-dependent with the pronounced changes occurring at lower frequencies (24,25,38,39). Some studies have shown that resistance at 5 Hz significantly correlates with baseline FEV$_1$ (26,28), postmethacholine challenge FEV$_1$ (25,27,32) or postbronchodilator FEV$_1$ values (24,33,38). Others have suggested that X at 5 Hz is most sensitive to changes in airway calibre. Buhr et al (35) found that X determined by oscillometry significantly correlated with airway resistance determined using body plethysmography (r=0.86), and Ortiz and Menendez (30) suggested that a 30% change in X following a bronchodilator challenge is approximately equal to a 12% increase in FEV$_1$. Goldman et al (36) proposed that the integrated X over a range of low frequencies (5 Hz to F$_{res}$) provides meaningful evidence of airflow obstruction beyond the sensitivity of spirometry. Still others have shown that F$_{res}$ correlates best with baseline FEV$_1$ (r=–0.55) (28). Schmekel and Smith (31) found that the change in F$_{res}$ following EVH correctly diagnosed asthma with 89% sensitivity and 100% specificity. Our study showed that the changes from baseline in R$_5$, F$_{res}$, X and AX following EVH were significantly greater for AHR+ subjects than for AHR– subjects. Moreover, all were significantly correlated with post-EVH change in FEV$_1$, with highest sensitivities (90% at predetermined specificities of 80%) for per cent change in R$_5$ and absolute postchallenge AX (cm H$_2$O/L).

AHR in asthmatics is often associated with abnormalities in baseline lung function. In the present group of athletic subjects, baseline FEV$_1$ was within a normal range; only two subjects demonstrated values that were 80% or less than that predicted, and FEF$_{25–75}$ values were at or below 70% of the predicted values for five AHR+ subjects and two AHR– subjects. Baseline values in FEF$_{25–75}$ were strongly correlated to baseline values in FEV$_1$ and, similar to the results of others (24,28,29,38,40), we observed significant correlations between baseline spirometric parameters and baseline IOS measurements. No baseline lung functions determined using spirometry correlated with postexercise falls in FEV$_1$; however, significant correlations with peak post-EVH falls in FEV$_1$ were observed for baseline R$_5$ and AX values.

Currently, there is no consensus on IOS criteria for the diagnosis and grading of airway obstruction (24). In the present study, we provided cutoff criteria, sensitivity and predictive values for 80% specificity to the gold standard of 10% change in FEV$_1$ after EVH. We identified significant correlations of peak falls in FEV$_1$ to post-EVH increases in R$_5$, F$_{res}$, X and AX. Our study supports R$_5$ per cent change and change in AX (cm H$_2$O/L) as the most sensitive indices of airway obstruction; a 50% increase in R$_5$ and a postchallenge AX value of greater than 12 cm H$_2$O/L provided 90% sensitivity to peak fall in FEV$_1$. This is in agreement with Goldman et al (36), who demonstrated that inspiratory R$_5$ and AX are most sensitive to daily changes in respiratory status.

In summary, substantial and significant changes in R$_5$, F$_{res}$, X and AX were noted after EVH, and all were significantly correlated with post-EVH falls in FEV$_1$. We defined acceptable cutoff criteria for determining postchallenge airway obstruction for per cent change in R$_5$ and increases in AX. The sensitivities of these measures to post-EVH falls in FEV$_1$ support the use of IOS as an acceptable method for diagnosis of airway obstruction and AHR; these measures can be used with patients where accurate and reliable spirometry measures may be difficult to obtain.

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