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Effect of High-Intensity Inspiratory Muscle Training on Lung Volumes, Diaphragm Thickness, and Exercise Capacity in Subjects Who Are Healthy

Background and Purpose. Previous investigations have demonstrated that a regimen of high-intensity inspiratory muscle training (IMT) resulted in changes in ventilatory function and exercise capacity in patients with chronic lung disease, although the effect of high-intensity IMT in subjects who are healthy is yet to be determined. The purpose of this study, therefore, was to examine whether high-intensity IMT resulted in changes in ventilatory function and exercise capacity in subjects who were healthy. **Subjects.** Twenty subjects were randomly assigned to 2 groups. **Methods.** The training group completed an 8-week program of IMT set at 80% of maximal effort. The control group did not participate in any form of training. Baseline and posttraining measures of body composition, pulmonary function, inspiratory muscle function (including maximal and sustained maximal inspiratory pressures [MIP and SMIP]), relaxed and contracted diaphragm thickness and thickening ratio (Tdi.rel, Tdi.cont, and TR), and exercise capacity were determined. **Results.** The training group demonstrated significant increases in MIP, SMIP, Tdi.cont, TR, VC, total lung capacity, and exercise capacity compared with the control group, which demonstrated no change from baseline measurements at 8 weeks. **Discussion and Conclusion.** The findings of this study suggest that high-intensity IMT results in increased contracted diaphragm thickness and increased lung volumes and exercise capacity in people who are healthy. [Enright SJ, Unnithan VB, Heward C, et al. Effect of high-intensity inspiratory muscle training on lung volumes, diaphragm thickness, and exercise capacity in subjects who are healthy. *Phys Ther.* 2006;86:345–354.]

Key Words: *Healthy subjects, High-intensity inspiratory muscle training.*

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In people who are healthy, the ability to sustain high levels of ventilation has not been thought to play a major role in limiting maximal aerobic capacity.¹ Evidence from previous studies, however, suggests that a regimen of high-intensity inspiratory muscle training (IMT) may reduce dyspnea perception in highly trained people² and increase maximum oxygen consumption ($\dot{V}O_2\text{max}$) in moderately trained people who are healthy.³ In patients with chronic airflow limitation, IMT has been considered a possible therapeutic modality,⁴⁻⁸ although controversy exists in the literature regarding whether IMT improves exercise capacity in these patients.⁹ The conflicting findings are likely to be due to variations in the type of training applied to the inspiratory muscles (strength or endurance training), the mode of training (whether workload is fixed through a full inspiratory volume), and the intensity, duration, and frequency of training. However, the equivocal findings are primarily a result of the failure to maintain an overload on the muscles throughout the training.³

In many published studies, failure to control workload adequately has led to variable findings. For example, simple resistive breathing devices may increase the work of breathing, but a person may reduce the training load by altering inspiratory flow and ventilatory frequency.¹⁰ Generally, training theory suggests that inspiratory muscle strength gains can be achieved at intensities of 80% to 90% of maximal inspiratory pressure (MIP). Strength or endurance gains (maximal effective force that can be maintained) can be achieved at 60% to 80% of MIP, and endurance (the ability to continue a dynamic task for a prolonged period) can be achieved at approximately 60% of MIP, which equates with high-intensity training regimens used in systemic exercise.¹¹ Recent published data¹² have shown that when the physiological strength training principles (with regard to the mode, intensity, duration, and frequency of training) and biofeedback are applied during IMT, increases in lung volumes (vital capacity [VC] and total lung capacity [TLC]), dia-

phragm thickness, and exercise capacity were found in patients with cystic fibrosis. However, the effect specifically of this regimen of controlled high-intensity IMT in people who are healthy is yet to be determined.

The inspiratory muscles, including the diaphragm, are morphologically and functionally skeletal muscles and therefore should respond to training in the same way as would any locomotor muscle if an appropriate physiological load is applied.¹¹ In support of this theory, it has been documented that the diaphragm increases its thickness when resistance is applied during weight training.¹³ Although a previous investigation failed to demonstrate significant increases in twitch diaphragmatic pressure following IMT using a resistive breathing device,¹⁴ the effect specifically of a regimen of high-intensity IMT, in which volume and flow are fixed, on diaphragm thickness in people who are healthy has not been identified.

Therefore, the primary objectives of this investigation were: (1) to determine the effects of a high-intensity program of IMT on the strength and endurance of the inspiratory muscles in subjects who are healthy, (2) to assess whether these changes were consistent with an increase in diaphragm thickness and lung volumes, and (3) to determine whether an 8-week program of IMT would increase exercise capacity in subjects who are healthy.

Method

Subjects

Twenty moderately trained adults of both sexes (9 male, 11 female) who were healthy and who were students attending the University of Salford (United Kingdom) volunteered to take part in this investigation. Each subject's level of physical activity was assessed by questionnaire,¹⁵ and each subject was determined to be recreationally active, defined as participating in at least 4 hours of sporting activity per week, which was of suffi-

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Dr Enright was responsible for manuscript preparation, data analysis, and acquisition of research funding. Professor Unnithan supervised the project with Dr Davies and Dr Enright, and Ms Heward and Ms Withnall were responsible for recruitment of subjects and data collection.

The local Research Ethics Committee approved the study.

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Table 1.

Baseline Measures of Anthropometric Data, Pulmonary Function, Diaphragm Thickness, Inspiratory Muscle Function, and Exercise Capacity^a

	Training Group	Control Group	P (Between Groups)
Sex (male/female)	4/6	5/5	
Age (y)	22.0 (3.3)	21.8 (4.8)	NS
Stature (cm)	168.5 (8.0)	171.7 (8.3)	NS
Mass (kg)	59.9 (12.2)	54.9 (14.3)	NS
PAS (MET)	38 (10.2)	44 (8.9)	NS
Body fat (%)	23.0 (6.9)	20.6 (8.2)	NS
BMI (kg/m ²)	22.0 (2.2)	22.6 (2.6)	NS
VC (L)	4.1 (0.5)	4.5 (0.6)	<.05
RV (L)	1.6 (0.4)	1.7 (0.3)	NS
TLC (L)	5.7 (0.6)	5.7 (0.8)	NS
FRC (L)	2.7 (0.7)	2.9 (0.8)	NS
Tdi.rel (mm)	2.2 (0.4)	2.3 (0.7)	NS
Tdi.cont (mm)	4.1 (0.5)	4.0 (0.5)	NS
MIP (cm H ₂ O)	90 (16)	93 (18)	NS
SMIP (PTU)	504 (184)	415 (129)	NS
Borg Scale for Rating of Perceived Exertion scores	8 (2.3)	7 (1.7)	NS
Work capacity (min)	5.0 (1.3)	4.4 (0.9)	NS
Power output (W)	245 (68)	220 (48)	NS
Peak heart rate (bpm)	183 (24)	210 (14)	NS

^aThe training group (n=10) completed an 8-week program of inspiratory muscle training set at 80% of maximal effort. The control group (n=10) did not participate in any form of training. All values are means with standard deviations shown in parentheses. PAS=physical activity status, MET=metabolic equivalent (1 MET=3.5 mL O₂/kg/min), BMI=body mass index, VC=vital capacity, RV=residual volume, TLC=total lung capacity, FRC=functional residual capacity, Tdi.rel=diaphragm thickness at FRC, Tdi.cont=diaphragm thickness at TLC, MIP=maximum inspiratory pressure, SMIP=sustained maximum inspiratory pressure, NS=no significant difference. All statistical analyses were performed using unpaired *t* tests.

cient intensity to elevate the heart rate to within 80% of the age-predicted maximum. The mean age of the subjects was 21.9 years (SD=4.0). All subjects were nonsmokers and had no evidence of pulmonary pathology (eg, asthma) or any known metabolic or endocrine disorder. Subjects were informed of the nature of the study and gave full verbal assent and written consent prior to the study.

Study Design

This was a single-center, controlled study in which the subjects were assigned to 2 groups using a system of random number tables.¹⁶ The training group (n=10) completed an 8-week supervised program of IMT in which the training intensity was set at 80% of each subjects' sustained maximal inspiratory effort. The subjects performed no other forms of exercise training during the study period. The other group of subjects did not participate in any form of training and acted as a control group (n=10). At the initial screening visits, body composition, pulmonary function, and physical activity status were determined.¹⁵ In addition, all subjects had measurements of inspiratory muscle function, diaphragm thickness at functional residual capacity (FRC)

(Tdi.rel) and TLC (Tdi.cont), and exercise capacity taken (Tab. 1). These measurements (excluding body composition) were repeated at the end of the 8-week training period and were obtained by independent laboratory-based data collectors who were blinded to the group allocation.

Measurement Protocols

Pretraining assessments. In all subjects, stature (in centimeters) and weight (in kilograms) were determined using a stadiometer* (accurate to 1.5 mm) and an electronic beam scale (Inscale electroscale, model MRP200P[†]) (accurate to 0.1 kg). Subjects were measured wearing lightweight clothing and no shoes. Percentage of body fat was estimated using calipers* by measurement of 4-site skinfolds: biceps, triceps, subscapular region, and suprailiac crest. Three measurements for each site were taken, with the mean used for body fat determination.¹⁷ Body fat measurements were calculated according to the equations of Grant et al¹⁸ (Appendix).

Lung function measurements. All subjects performed maximal expiratory flow maneuvers as per British Thoracic

Society standards¹⁹ using a dry wedge spirometer (Vitalograph[‡]) in order to determine the forced expiratory volume in 1 second (FEV₁), forced vital capacity (FVC), and FEV₁/FVC ratio. Prior to testing, calibration checks were performed using a 3-L calibration syringe, with ambient air to ensure correct equipment function with regard to volume and time. All subjects were asked to refrain from vigorous exercise for at least 24 hours prior to the tests. During all measurements, subjects were seated and a single experienced technician obtained recordings. All lung function measurements were expressed in liters and as a percentage of the predicted values for age, height, and sex.²⁰

Assessment of physical activity status. The level of physical activity was determined before and after IMT using a recall questionnaire.¹⁵ Activity scores were calculated over a 24-hour period and expressed in metabolic equivalents (1 MET=3.5 mL O₂/kg/min, or the resting

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[†] Inscale Measurement Technology Ltd, 7 Heron Close, St-Leonards-on-Sea, East Sussex TN38 8DX, United Kingdom.

[‡] PK Morgan Ltd, Rainham Kent, KF62 5MD, United Kingdom.

energy expenditure in one person at rest). Following the completion of the recall questionnaire, all subjects were encouraged not to change their physical activity patterns during the study period.

Inspiratory muscle function. The MIP and the sustained maximum inspiratory pressure (SMIP) were determined using an electronic manometer and computer connected by serial interface to a laptop computer, which had been programmed with a specifically designed computer software package (Respiratory Trainer, model 2 [RT₂ device]).[§] The manometer had a fixed leak via a 2-mm-diameter aperture to prevent glottal closure during the inspiratory maneuver²¹ and set a maximum flow during the inspiratory effort proportional to the pressure achieved. Pressure generation over a full inspiratory effort from residual volume to TLC was recorded over time by a computer. The MIP was the maximum pressure (in centimeters of water) developed in the first second of inspiration, and the SMIP was the integrated area under the pressure-time curve, measured in pressure-time units (PTUs).²² All data were stored on the computer database for later retrieval and analysis.

Assessment of diaphragm thickness. In all subjects, diaphragm thickness (in millimeters) was assessed by B-mode ultrasonography with the method described by De Bruin et al.²³ With the subject standing, the eighth and ninth intercostal spaces in the right midaxillary line were identified and marked with a wax pencil as described elsewhere.²³ With the subject then lying horizontally on a plinth in the left lateral decubitus position, using the sector mode, and with the transducer (PLE 705S 7.5-MHz linear probe^{||}) held perpendicular to the chest wall, a 2-dimensional coronal image of the diaphragm at the zone of apposition was identified in either the eighth or ninth intercostal space. The diaphragm was identified by 2 clear parallel echodense lines and was measured from the middle of the pleural to the middle of the peritoneal line. The mean of 3 measurements made at the zone of apposition at Tdi.rel and Tdi.cont was recorded. Prior to these measurements, the FEV₁/FVC ratio was measured to determine consistency in lung volume estimations. In order to standardize for any increase in lung volume as a result of training, and thus obtain measurements with the diaphragm in a more contracted state after training, the diaphragm thickening ratio (TR) was determined using the formula described by Ueki et al²⁴ (Appendix).

Assessment of exercise capacity. At the time of scheduling, all subjects were instructed to refrain from eating

and participating in vigorous activity for at least 3 and 5 hours before the test, respectively. They also were advised to avoid caffeine and to dress appropriately on the day of the tests. A progressive, incremental exercise test was performed on an electronically braked cycle ergometer (Excalibur Sport[#]) to measure physical work capacity as described by Godfrey and Mearns.²⁵ Subjects began pedaling with no added resistance and at 1-minute intervals. Resistance was added in 8-W increments until the subjects reached their peak heart rate (80% of their age-predicted maximum) or could no longer pedal due to volitional exhaustion. All subjects, therefore, exercised to a self-determined maximum. Accuracy of the incremental load was achieved by using microprocessors, which checked the actual workload 5 times per second. The system also contained a feedback mechanism, which eliminated the influence of temperature, thereby guaranteeing accuracy of workload up to 1,000 W. The incremental loads for each subject were calculated, and the workload was programmed manually into the system using the Excalibur WorkLoad Programmer[#] according to the manufacturer's instructions. Heart rate and ratings of perceived exertion²⁶ were recorded at each work level.

Sample Size Determination and Reliability of the Main Outcome Measures

In an additional group of 10 subjects who were healthy, the reproducibility of measurements obtained for the principal outcome variables was determined on consecutive days using identical methods and experimental protocol used in the present study. An adequate sample size was found to be at least 9 subjects in the experimental group at $\alpha=.05$ and $1 - \beta=90\%$. Unpublished observations from our laboratory have demonstrated reproducibility coefficients of .90 for MIP, .94 for SMIP, .92 for Tdi.rel, and .90 for Tdi.cont in subjects who were healthy.

Inspiratory Muscle Training Protocol

A pressure manometer (the RT₂ device described previously for the measurement of MIP and SMIP) and specifically designed computer software were used in the training program.[§] Two researchers who were experienced in conducting the IMT training protocol (CH and LW) supervised all subjects in the training group. Training was performed 3 times weekly on nonconsecutive days (with at least 24 hours separating training sessions) over 9 weeks, although inspiratory pressure data were not collected until the second week of training to allow the subjects to become familiar with the training equipment and protocol. Three SMIP measurements were recorded at the commencement of each training session, and the highest sustainable profile was selected automat-

[§] DeVilbiss UK Ltd, Sunrise Business Park High Street, Wollaston, Stourbridge, West Midlands DY8 4PS, United Kingdom.

^{||} Toshiba Medical Systems, Japan, 5 Byfield St, North Ryde, NSW 2113, United Kingdom.

[#] Medical Graphics Corp, 350 Oak Grove Pkwy, St Paul, MN 55127.

ically and redrawn by the computer as a training template equal to 80% of the maximum pressure profile.

Therefore, subsequently at each training session, the subjects were retested to determine their current value for 80% of maximal effort. This 80% training intensity was determined by manipulation of the computer software prior to the IMT. Inspiratory training maneuvers were repeated using a regimen of 6 repetitions performed at 80% of the SMIP, and during each set, the rest time between repetitions was progressively reduced from 60 seconds to 45, 30, 15, 10, and 5 seconds. Thus, the subjects were required to complete a total of 36 repetitions during each training session. The procedure was followed until a subject was unable to match at least 90% of the computer-generated template. Within the training group, only 2 subjects failed to achieve 90% of the template during training on one occasion each (at the training levels of 10 and 15 seconds, respectively). Both subjects were allowed to resume the training regimen at the point at which they had failed (ie, to complete the 6 repetitions at either 10 seconds or 5 seconds apart, therefore completing the required total of 36 repetitions). All training sessions were conducted in a quiet room with no distractions, and the same instructions were given to all subjects, thereby ensuring that they were being motivated in a consistent manner during the training period.

Data Analysis

Between groups, baseline characteristics (age), anthropometric data (mass, stature, fat, and body mass index [BMI]), lung function data (VC, FRC, TLC, and residual volume [RV]), diaphragm thickness (Tdi.rel, Tdi.cont, and TR), inspiratory pressure data (MIP and SMIP), and exercise capacity were compared with unpaired *t* tests. Prior to all analyses, normality of the data was assessed by the one-sample Kolmogorov-Smirnov test. A repeated-measures analysis of variance (ANOVA) was used to identify pretraining and posttraining differences between and within groups for diaphragm thickness (Tdi.rel and Tdi.cont), inspiratory pressure data (MIP and SMIP), and exercise capacity (Borg Scale for Rating of Perceived Exertion scores, exercise duration, power output, and peak heart rate). For all significant data, unplanned, pair-wise multiple comparisons were made using the Tukey critical difference test. Differences were considered to be significant at $P < .05$. All statistical calculations were performed using SPSS, version 12.**

Results

Study Group Characteristics: Baseline Analysis

There was 100% adherence to the training protocols by all subjects, and all subjects had complete data sets of baseline and posttraining measurements of lung function, diaphragm thickness (Tdi.rel and Tdi.cont) TR, and inspiratory pressure, including MIP and SMIP. In addition, Borg Scale for Rating of Perceived Exertion scores and measurements of exercise capacity, exercise duration, power output, and peak heart rate were obtained in both training and control groups. There were no differences in age, mass, stature, body composition (BMI and fat) between the groups at baseline. In addition, there were no differences in the dependent variables of diaphragm thickness (Tdi.rel and Tdi.cont), TLC, or exercise capacity. However, at baseline, VC was found to be higher ($P < .05$) in the control group ($\bar{X} = 4.1$ L, 95% confidence interval [CI] = 3.9–4.4) than in the training group ($\bar{X} = 4.5$ L, 95% CI = 4.3–4.7) (Tab. 1).

Effects of Inspiratory Muscle Training on Maximum Inspiratory Pressure and Sustained Maximum Inspiratory Pressure

Following 8 weeks of IMT, an increase in MIP ($P < .01$) was observed in training group at 80% of their SMIP, from a mean of 90 cm H₂O (95% CI = 80–99) to a mean of 127 cm H₂O (95% CI = 121–133). This represented an increase of 41% in MIP from baseline. No increase was observed in the control group, resulting in a difference between the groups following training ($P < .01$). The SMIP values also improved in the training group ($P < .01$), from a mean of 504 PTUs (95% CI = 390–619) to a mean of 688 PTUs (95% CI = 521–855), representing a 36% increase from baseline values. There was no change in the control group over time, resulting in a different group effect following training ($P < .01$) (Tab. 2).

Effects of Inspiratory Muscle Training on Lung Function

There were no changes in FEV₁, FVC, RV, or FRC in either the training group or the control group, although VC increased ($P < .05$) in the training group, from a mean of 4.1 L (95% CI = 3.8–4.2) to 4.4 L (95% CI = 4.2–4.8). In addition, TLC increased in the training group ($\bar{X} = 5.7$ L, 95% CI = 5.4–5.8, to 6.1 L, 95% CI = 5.9–6.3), representing a 7% increase in these variables from pretraining levels. There were no changes in any lung volumes or capacities in the control group over time, resulting in a difference in both groups following training (Tab. 2).

** SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

Table 2.Group Comparisons Before and After Training for Lung Volumes and Inspiratory Muscle Function^a

	Before Training	After Training	P (Main Effect of Time)	P (Main Effect of Group)	P (Main Effect of Time and Group)
VC (L)					
Training group	4.1 (0.5)	4.4 (0.7)	<.05	<.05	<.05
Control group	4.5 (0.6)	4.5 (0.6)	NS		
TLC (L)					
Training group	5.7 (0.6)	6.1 (0.5)	<.05	<.05	<.05
Control group	5.7 (0.8)	5.7 (0.9)	NS		
FRC (L)					
Training group	2.7 (0.7)	2.8 (0.8)	NS	NS	NS
Control group	2.9 (0.9)	2.9 (0.8)	NS		
RV (L)					
Training group	1.6 (0.4)	1.5 (0.4)	NS	NS	NS
Control group	1.7 (0.3)	1.6 (0.3)	NS		
MIP (cm H ₂ O)					
Training group	90 (16)	127 (10)	<.01	<.01	<.01
Control group	93 (18)	91 (16)	NS		
SMIP (PTU)					
Training group	504 (184)	688 (269)	<.01	<.01	<.01
Control group	415 (129)	404 (102)	NS		

^aThe training group (n=10) completed an 8-week program of inspiratory muscle training set at 80% of maximal effort. The control group (n=10) did not participate in any form of training. All values are means with standard deviations shown in parentheses. VC=vital capacity, TLC=total lung capacity, FRC=functional residual capacity, RV=residual volume, MIP=maximum inspiratory pressure, SMIP=sustained maximum inspiratory pressure, PTU=pressure-time unit, NS=no significant difference. All statistical analyses were performed using unpaired analysis of variance and Tukey critical difference test. The training group had significantly higher values of VC, TLC, MIP, and SMIP following training compared with the control group.

Effects of Inspiratory Muscle Training on Diaphragm Thickness

Following 8 weeks of IMT, there was no increase in Tdi.rel, although Tdi.cont and TR increased in the training group ($P<.05$), from a baseline mean of 4.1 mm (95% CI=3.9–4.3) to 4.6 mm (95% CI=4.2–5.0) for Tdi.cont and 3.8 (95% CI=3.7–3.9) to 4.1 (95% CI=3.9–4.3) for TR. This represented an increase of 12% in Tdi.cont and an increase of 8% in TR in the training group from baseline values. No increase in Tdi.rel, Tdi.cont, or TR was observed in the control group over time, resulting in a different group effect for Tdi.cont and TR ($P<.05$ and $P<.05$, respectively) (Tab. 3).

Effects of Inspiratory Muscle Training on Exercise Capacity

There were no significant changes in either Borg Scale for Rating of Perceived Exertion scores or peak heart rate at each incremental load following IMT in either the training group or the control group, although there was a significant improvement in exercise capacity in the training group. This represented a 23% improvement in these variables in terms of both the duration of exercise (from a mean of 5.0 min, 95% CI=4.2–5.8, to a mean of 6.2 min, 95% CI=5.0–7.4) and power output (from a mean of 245 W, 95% CI=203–286, to a mean of 305 W,

95% CI=242–307) from pretraining levels ($P<.05$ and $P<.05$). No significant change in either the duration of exercise performance or power output was observed in the control group over time, resulting in a significant difference between the groups in both power output ($P<.05$) and the duration of training following IMT ($P<.05$) (Tab. 3).

Discussion

This study demonstrated that IMT set at a level consistent with the recommended load for peripheral muscle strength and endurance training programs improved inspiratory muscle strength (MIP) and endurance (SMIP) in subjects who were healthy. These improvements also were associated with increases in lung volumes, diaphragm thickness, and TR and with improvements in exercise capacity. These data are in agreement with previous research, where lung volumes, diaphragm thickness, and exercise capacity were shown to increase following IMT in age-matched subjects with cystic fibrosis.¹² The results of the present study support the contention that IMT may result in appreciable improvements in ventilatory muscle strength and endurance if the breathing pattern is controlled and substantial pressures are generated during inspiration.²⁷

Table 3.Group Comparisons Before and After Training for Diaphragm Thickness and Exercise Capacity^a

	Before Training	After Training	P (Main Effect of Time)	P (Main Effect of Group)	P (Main Effect of Time and Group)
Tdi.rel (mm)					
Training group	2.2 (0.4)	2.4 (0.4)	NS	NS	NS
Control group	2.3 (0.7)	2.4 (0.7)	NS		
Tdi.cont (mm)					
Training group	4.1 (0.5)	4.6 (0.7)	<.05	<.05	<.05
Control group	4.0 (0.5)	3.9 (0.5)	NS		
TR					
Training group	3.8 (0.1)	4.1 (0.4)	<.05	<.05	<.05
Control group	3.7 (0.2)	3.8 (0.3)	NS		
Borg Scale for Rating of Perceived Exertion scores					
Training group	8.2 (2.3)	7.4 (1.6)	NS	NS	NS
Control group	7.6 (1.7)	7.5 (1.1)	NS		
Work capacity (min)					
Training group	5.0 (1.3)	6.2 (1.9)	<.05	<.05	<.05
Control group	4.4 (0.9)	4.2 (1.1)	NS		
Power output (W)					
Training group	245 (68)	305 (101)	<.05	<.05	<.05
Control group	220 (48)	210 (56)	NS		
Peak heart rate (bpm)					
Training group	183 (24)	189 (27)	NS	NS	NS
Control group	210 (14)	205 (18)	NS		

^aThe training group (n=10) completed an 8-week program of inspiratory muscle training set at 80% of maximal effort. The control group (n=10) did not participate in any form of training. All values are means with standard deviations shown in parentheses. Tdi.rel=diaphragm thickness at functional residual capacity, Tdi.cont=diaphragm thickness at total lung capacity, TR=thickening ratio, NS=no significant difference. All statistical analyses were performed using unpaired analysis of variance and Tukey critical difference test. The training group had significantly higher values of Tdi.cont, TR, work capacity, and power output compared with the control group.

In accordance with the work of Belman and Shadmehr,⁶ the present study used a pressure- or flow-based training program that is designed to increase both pressure generation and inspiratory flow throughout the training maneuver and as an outcome of training. However, as MIP increased during inspiration, this program of training also leads to an increase in the area under the pressure-time curve. This type of training approach is intended to not only produce an increase in MIP as measured from RV but also create a longer duration of inspiratory muscle contraction with greater pressure generation at higher lung volumes. This method of IMT effectively trains the inspiratory muscles from RV where the inspiratory muscles are in a lengthened position to TLC where they are maximally shortened. In comparison with the quasi-static MIP maneuver, SMIP incorporates a flow component, which allows training throughout an individual's full inspiratory volume. Analysis of the MIP and SMIP data indicated a learning response in the first few weeks of training despite a 1-week habituation period (in the group at 80% of their SMIP, there were 32% and 24% increases in MIP and SMIP, respectively, in the first 3 weeks of training). This learned

response could be attributable to an improved neuromuscular recruitment pattern, which is a well-described mechanism for the early improvements of strength training and may partially explain the large magnitude of change in MIP and SMIP over the 8-week training period.²⁸ However, the subjects in the training group increased their VC and TLC, which indicates an increased ability of the inspiratory muscles to expand the thorax following training. The increase in these lung volumes also may result from a greater contribution of the upper thorax and neck muscles to the inspired volume after training.²⁹

These increases in VC and TLC are in agreement with the findings of an early study by Leith and Bradley.³⁰ Their subjects trained for a 5-week period for gains in either endurance (4 subjects performed voluntary normocarbic hyperpnea to exhaustion) or strength (4 subjects performed repeated static maximum inspiratory and expiratory maneuvers against obstructed airways). Although this study³⁰ was designed to demonstrate how ventilatory muscle strength or endurance can be specifically increased by appropriate ventilatory muscle train-

ing programs, increases in VC and TLC of 4% were observed only in the subjects who trained for strength at an appropriate intensity. The finding of no increase in lung volumes in the subjects who trained for endurance only (at an intensity of approximately 20% of MIP) is in agreement with the findings of a recent study¹² where a similar training intensity failed to elicit changes in lung volumes in patients with cystic fibrosis.

In people who are healthy, the dimensions of the diaphragm can be increased by weight training.¹³ The effect of IMT on diaphragm thickness has not been previously reported in people who are healthy. The results of the present investigation show that the effect of loading the inspiratory muscles during IMT increases diaphragm thickness, although this was evident for Tdi.cont in the training group at 80% of their SMIP. The protocol used for the assessment of diaphragm thickness in the present study was in accordance with that used in a previous investigation,²³ and the reproducibility of this assessment of diaphragm thickness was found to be satisfactory prior to this study. The coefficients of reliability for these measured variables were above 90% and 91%, respectively (unpublished data). However, as the training group demonstrated an increase of 7% in VC and TLC after training, the diaphragm may have been measured at a different lung volume after training, which has been shown to influence the measurement of diaphragm size.¹³ This methodological problem was overcome by also assessing diaphragm thickness as the TR.²⁴ When corrected for lung volume, the training group still demonstrated increases in diaphragm thickness. This increase in diaphragm thickness may result in increased inspiratory muscle efficiency or improved pulmonary mechanics, or both. The training intervention in this study was successful in achieving a sustained training intensity, which is consistent with the overload principle.³¹

In conjunction with the improvements in specific indexes of inspiratory muscle function, there was also an increase in exercise capacity. The nonsignificant change in Borg Scale for Rating of Perceived Exertion scores may reflect the subjects' ability to sustain a higher workload without an increase in breathlessness. These data support the findings of earlier studies where increases in respiratory muscle strength and endurance (MIP and SMIP) were associated with decreased breathlessness, improved sports performance, and $\dot{V}O_2\text{max}$ in subjects who were healthy.³ Although impaired ventilatory muscle function is considered the principal factor in limiting exercise tolerance and capacity in patients with chronic respiratory disease,³² the ability to sustain high levels of ventilation has not been thought to play a major role in limiting exercise capacity in people who are healthy.¹ However, it has been shown in subjects who are

healthy that diaphragm fatigue occurs during exercise at an intensity of at least 85% of $\dot{V}O_2\text{max}$.³³ Respiratory muscle fatigue has been demonstrated after endurance competition³⁴ and has been shown to impair exercise performance.³⁵ This respiratory muscle fatigue has been attributed to possible limb muscle vasoconstriction and reduction in limb blood flow elicited by a metaboreflex originating in the diaphragm and causing systemic vasoconstriction during periods of inspiratory muscle fatigue.³⁶⁻³⁸ These findings further add strength to the rationale for IMT particularly in patients with inspiratory muscle weakness or fatigue.

Studies of IMT have remained controversial due to the inadequacy of some study designs. For example, some studies^{39,40} have omitted control groups, therefore preventing the efficacy of IMT from being fully identified. The criteria for methodological quality established by Smith et al in 1992,²⁷ namely, the use of random sampling, comparable groups, comparable cointerventions, and standardization of testing techniques were all observed in the present study. Consequently, the true efficacy of IMT could be judged. However, unlike a previous investigation,¹² which utilized this training method in patients with cystic fibrosis, this study failed to compare the effects of IMT between a group of subjects who received a suboptimal training intensity in addition to an intervention and a control group. This may be considered to be a limitation of this study, because improvement in some of the measured outcomes in the training group may be attributable to the active participation of the subjects when compared with the controls (ie, the Hawthorn effect). However, although this limitation may have had an effect on some of the volitional tests such as exercise capacity, MIP, and SMIP, it could not account for the increase in diaphragm thickness or lung volumes, which would be unaffected by this phenomenon.

A further methodological flaw, which has hindered previous IMT studies, is the lack of control of workload²⁷ and the lung volume at which training is applied.¹⁴ The training program in our study used a technique of incremental loading of the inspiratory muscles where the workload was fixed and reassessed at each training session. This was achieved by selecting the best of 3 maximum sustained inspiratory efforts at the commencement of each training session in each subject to maintain overload. The program also required the subjects to work through their full inspiratory volume from RV to TLC, thereby maintaining consistency with the volume at which the training was applied. In addition to this, the use of computer software to run the training program maintained consistency of effort and loading, with the additional advantage of accurate recordings of training levels, which were independent of observer

input, allowing checks on adherence to the training process.

Conclusion

This study has shown that this regimen of high-intensity IMT produces an increase in inspiratory muscle function, induces morphological changes in the diaphragm, and increases lung volumes in people who are healthy. These findings also were associated with an increase in physical work capacity. These findings suggest that increasing inspiratory muscle function by fixed load and full inspiratory volume IMT, as described in this article, may have a significant impact in improving exercise capacity in people who are healthy.

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Appendix.

Calculations Used in the Estimation of Body Composition and Diaphragm Thickening Ratio in Subjects Who Are Healthy^a

Formula for the calculation of BMI:

$$\text{kg/m}^2$$

Formulae for the assessment of percentage of body fat:

$$\text{For men: } \frac{[35.055 \log (\text{sum of 4-site skinfold thickness [mm]})] - 32.175 \times 10}{[1.1715 - (0.0779 \log [\text{sum of 4-site skinfold thickness (mm)}])]}$$

$$\text{For women: } \frac{[29.025 \log (\text{sum of 4-site skinfold thickness [mm]})] - 15.255 \times 100}{[1.1339 - (0.0645 \log [\text{sum of 4-site skinfold thickness (mm)}])]}$$

Formula for the calculation of the diaphragm thickening ratio (TR):

$$\text{TR} = \frac{\text{Diaphragm thickness during MIP maneuver at FRC}}{\text{Mean thickness while relaxing at FRC}}$$

^aBMI=body mass index, MIP=maximum inspiratory pressure, FRC=functional residual capacity.

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