Inspiratory Muscle Training Improves Lung Function and Exercise Capacity in Adults With Cystic Fibrosis*

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Study objectives: **To investigate the effects of high-intensity inspiratory muscle training (IMT) on inspiratory muscle function (IMF), diaphragm thickness, lung function, physical work capacity (PWC), and psychosocial status in patients with cystic fibrosis (CF).**

Design: **Twenty-nine adult patients with CF were randomly assigned to three groups. Two groups were required to complete an 8-week program of IMT in which the training intensity was set at either 80% of maximal effort (group 1; 9 patients) or 20% of maximal effort (group 2; 10 patients). A third group of patients did not participate in any form of training and acted as a control group (group 3; 10 patients).**

Interventions: **In all patients, baseline and postintervention measures of IMF were determined by maximal inspiratory pressure (PImax), and sustained PImax (SPImax); pulmonary function, body composition, and physical activity status were also determined. In addition, diaphragm thickness was measured at functional residual capacity (FRC) and total lung capacity (TLC) [TDIcont], and the diaphragm thickening ratio (TR) was calculated (TR = thickness during PImax at FRC/mean thickness at FRC). Subjects also completed an incremental cycle ergometer test to exhaustion and two symptom-related questionnaires, prior to and following training.**

Results: **Following training, significant increases in PImax and SPImax ($p < 0.05$), TDIcont ($p < 0.05$), TR ($p < 0.05$), vital capacity ($p < 0.05$), TLC ($p < 0.05$), and PWC ($p < 0.05$) were identified, and decreases in anxiety scores ($p < 0.05$) and depression scores ($p < 0.01$) were noted in group 1 patients compared to group 3 patients. Group 2 patients significantly improved PImax and SPImax (both $p < 0.05$) only with respect to group 3 patients. No significant differences were observed in group 3 patients.**

Conclusion: **An 8-week program of high-intensity IMT resulted in significant benefits for CF patients, which included increased IMF and thickness of the diaphragm (during contraction), improved lung volumes, increased PWC, and improved psychosocial status.**

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Key words: diaphragm thickness; exercise tolerance; lung volumes; respiratory muscle training

Abbreviations: CF = cystic fibrosis; CRDQ = chronic respiratory disease questionnaire; FRC = functional residual capacity; IMF = inspiratory muscle function; IMT = inspiratory muscle training; LBM = lean body mass; METS = metabolic equivalents; PImax = maximal inspiratory pressure; PWC = physical work capacity; RME = respiratory muscle endurance; RMS = respiratory muscle strength; RV = residual volume; SPImax = sustained maximal inspiratory pressure; TDIcont = diaphragm thickness measured by ultrasound at total lung capacity; TDIrel = diaphragm thickness measured by ultrasound at functional residual capacity; TFco = transfer factor using carbon dioxide; TLC = total lung capacity; TR = thickness ratio; VC = vital capacity

In patients with cystic fibrosis (CF), continuous pulmonary infection and inflammation with thickened secretions causes airways obstruction and hyperinflation.[1] This leads to altered pulmonary mechanics and limited exercise tolerance.[2] The loss of fat-free mass causes a reduction in skeletal muscle mass that includes the inspiratory muscles and is associated with impaired inspiratory muscle function (IMF).[3,4] The effects of reduced IMF are added to

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by changes in total lung capacity (TLC) and pulmonary compliance, and by increased residual volume (RV).

The force that a skeletal muscle can generate depends on its effective cross-sectional area and on the geometry with which it applies its tensile force.[5] Therefore, increasing the cross-sectional surface area of the inspiratory muscles by hypertrophy may reverse or delay the complications of impaired IMF. Respiratory muscle training has been considered a therapeutic option for patients with chronic airflow limitation, however, a meta-analysis[6] of 1,085 citations revealed only 17 with sufficient data for analysis, due to inherent methodological flaws. A major flaw in numerous studies was the failure to adjust the workload during training to maintain an overload on the muscles and to produce a training effect. These authors concluded, however,[6] that if workload were controlled and substantial pressures were generated during training, then improvements in respiratory muscle function might be possible. In inspiratory muscle training (IMT) studies[7] in CF patients, in which workload was known and partially fixed, significant improvements were reported in respiratory muscle strength (RMS), respiratory muscle endurance (RME), and vital capacity (VC) following training.

The fundamental importance of improving exercise capacity in patients with CF is clinically relevant, as greater levels of aerobic fitness have been associated with lower levels of mortality.[8] Moreover, increases in exercise capacity have been associated with improved psychosocial status in patients with chronic pulmonary disease.[9] However, the effect of controlled IMT, with no additional form of aerobic training, on exercise performance and psychosocial status in patients with chronic pulmonary disease is still to be determined.[10]

The aim of this investigation was to evaluate the effect of an 8-week IMT program with a fixed workload applied from RV to TLC, and at high intensity in patients with CF. The hypothesis of this study was that IMT would improve IMF, VC, and TLC, and also would induce morphologic changes within the diaphragm, as revealed by increased thickness with ultrasound measurements, while it would improve physical work capacity (PWC) and psychosocial status in patients with CF.

Materials and Methods

Subjects

The study population consisted of 29 adult CF patients (16 men) who were recruited from outpatients attending an adult CF center (mean [± SD] age, 22.0 ± 4.2 years; mean height, 167.0 ± 9.8 cm; mean weight, 60.2 ± 12.2 kg). The individuals who volunteered for the study were representative of the general population of CF patients who attended the CF clinic based on mean age (22.8 years), gender (55 men and 56 women), and mean Shwachman scores (general CF population, 68.4; study participants, 67.3). The diagnosis of CF had been previously identified on the basis of appropriate clinical criteria,[11] sweat Na^+ and Cl^- levels of > 70 mmol/L, and CF genotype. Patients were studied during a period of stability, which was defined as no change in symptoms or treatment in a month preceding the study, and an FEV_1 within 10% of the best value recorded in the previous 12 months. On reviewing the medical records of the patients, there was evidence that during an acute exacerbation of their respiratory symptoms there had been a reduction in FEV_1 of at least 10% compared to that patient's usual values in the previous 6 months of clinical stability. Patients with cor pulmonale, liver cirrhosis, or diabetes mellitus were excluded from the study, and none of the patients were receiving oral steroids at the time of the study.

Study Design

This was a single-center, controlled study in which patients were randomly allocated to three groups. An adequate sample size in the present study was found to be at least nine subjects per experimental group at $\alpha = 0.05$ and $1\text{-}\beta = 90\%$ (Table 1). Two of the three groups completed an 8-week supervised, domiciliary program with a training intensity of either 80% of maximal inspiratory effort (9 patients) or 20% of maximal inspiratory effort (10 patients). No other exercise training was allowed during the study. A third group did not undertake any form of training and acted as a control group (10 patients). The study had local research ethics committee approval, and all subjects gave written informed consent. Subjects entered the study on a staggered basis over a 6-month period. At the initial visit, pulmonary

Table 1—*Study Group Characteristics

Characteristics	IMT Patients		Control Subjects (n = 10)
	80% (n = 9)	20% (n = 10)	
Gender, No.			
Male	4	6	6
Female	6	4	4
Age, yr	24.8 ± 5.5	20.0 ± 4.7	21.3 ± 2.7
Height, cm	164 ± 9.0	168 ± 12.1	168.0 ± 8.4
Weight, kg	59.9 ± 12.1	54.9 ± 14.3	65.8 ± 10.3
Activity, METS	37.1 ± 10.2	40.1 ± 8.9	36.7 ± 9.7
LBM	39.3 ± 9.4	39.5 ± 11.4	38.8 ± 7.4
Fat, %	22.4 ± 9.9	22.1 ± 10.9	22.8 ± 7.7
FEV_1, % predicted	64.2 ± 29.7	69.0 ± 26.3	63.1 ± 27.8
FVC			
L	2.9 ± 1.2	3.5 ± 0.9	3.0 ± 1.1
% predicted	53.1 ± 27.8	69.0 ± 26.3	66.2 ± 28.7
VC			
L	2.9 ± 1.1	3.5 ± 0.9	3.3 ± 0.9
% predicted	77.1 ± 20.4	84.1 ± 18.2	83.8 ± 12.8
RV			
L	1.8 ± 0.7	1.7 ± 0.5	2.0 ± 0.6
% predicted	133.3 ± 51.1	131.1 ± 55.5	116 ± 32.8
TLC			
L	4.9 ± 1.8	5.2 ± 1.1	5.3 ± 0.8
% predicted	0.7 ± 134	94.3 ± 14.7	91.8 ± 13.0

*Values given as mean ± SD, unless otherwise indicated.

function tests, gas exchange variables, body composition, and physical activity status, which were estimated over a 24-h period, were determined (Table 2). Subjects also completed two symptom-related questionnaires[12,13] and an incremental cycle exercise test,[14] and underwent assessments of their IMF and diaphragm thickness. Subjects were familiarized with the IMT training protocol by performing IMT three times (45 min each time) over a 1-week period. All measurements were repeated at the end of the 8-week training period and were obtained by independent laboratory-based data collectors who were blind to the intensity of the training intervention.

Training Protocol

Both training groups performed IMT three times weekly under direct supervision at home by designated training supervisors. Both the training subjects and the training supervisors were unaware of the significance of the training intensity. The training equipment consisted of an electronic manometer connected by serial interface to a laptop computer, which had been programmed with a specifically designed computer software package (De Vilbiss Healthcare UK Ltd). The manometer had a fixed leak via a 2-mm diameter aperture to avoid glottal closure during the inspiratory maneuver. This set a maximum flow during the inspiratory effort at 450 m/s and allowed continuous measurement of pressure over a full range of lung volumes until no further pressure could be generated. This measure of force was termed *sustained maximal inspiratory pressure* (SPImax). Three SPImax values were recorded at the commencement of each training session, with the highest sustainable profile selected automatically and redrawn by the computer as a training template equal to either 20% or 80% of the maximum pressure profile. The training intensity was set in the computer software prior to the IMT program. Inspiratory maneuvers were repeated under a regimen of six consecutive levels, at each of which six inspiratory efforts were made. At each level, the duration of the rest period between each inspiratory efforts was progressively reduced from 60 to 45, 30, 15, 10, and 5 s. The procedure was followed until the subject was unable to match at least 90% of the computer-generated template of either 20% or 80% of the maximum pressure profile.

Table 2—*Pretraining and Posttraining Diaphragm Thickness and Inspiratory Muscle Function

Variable	Pretest	Posttest	p Value
TDIrel, mm			
Group 1	3.4 ± 1.3	3.8 ± 0.5	NS
Group 2	3.2 ± 1.3	3.0 ± 0.5	NS
Group 3	3.1 ± 0.8	3.0 ± 0.7	NS
TDIcont, mm			
Group 1	4.1 ± 0.8	4.9 ± 0.7	< 0.05
Group 2	4.4 ± 1.3	4.8 ± 0.9	NS
Group 3	3.7 ± 0.7	3.5 ± 0.6	NS
TR			
Group 1	2.7 ± 0.7	3.1 ± 0.8	< 0.05†
Group 2	2.9 ± 0.5	2.9 ± 0.6	NS
Group 3	2.8 ± 0.7	2.8 ± 0.6	NS
PImax, cm H_2O			
Group 1	134 ± 26	159 ± 23	< 0.05‡
Group 2	114 ± 22	155 ± 35	< 0.05
Group 3	128 ± 27	123 ± 27	NS
SPImax, ptu			
Group 1	782 ± 238	923 ± 305	< 0.05‡
Group 2	654 ± 318	808 ± 349	< 0.05
Group 3	775 ± 195	754 ± 196	NS

*Values given as mean ± SD, unless otherwise indicated. NS = not significant; ptu = pressure time units.

†Group 1 had significantly higher TR values at TDIcont and TR posttraining than groups 2 and 3.

‡Groups 1 and 2 had significantly higher PImax and SPImax values posttraining than group 3.

IMF

Coefficient of reliability values for measurements of maximal inspiratory pressure (PImax) and SPImax were previously established to be 89% and 90%, respectively (unpublished observations from our laboratory). The PImax and SPImax were determined using an electronic manometer and computer software package (RT2; DeVilbiss Healthcare UK Ltd; Wollaston, West Midlands, UK), as previously described[4]. The manometer had a fixed leak via a 2-mm diameter aperture, which prevented glottal closure and set a maximum flow during the inspiratory effort that was proportional to the pressure achieved. Pressure generation over a full inspiratory effort from RV to TLC was recorded over time by a computer. The PImax was the maximum pressure developed in the first second of the inspiration, and SPImax was the integrated area under the pressure-time curve.[4]

Diaphragmatic Ultrasonography

The reproducibility of the principal outcome variables was determined in 10 patients, and 10 age-matched and gender-matched healthy subjects on consecutive days with the identical methods used in the present study. The coefficient of reliability of diaphragm thickness measured by ultrasound at functional residual capacity (FRC) [TDIrel] and of diaphragm thickness measured by ultrasound at TLC (TDIcont) were determined to be 90% and 91%, respectively. Diaphragm thickness was assessed by B-mode ultrasonography.[15] With the subject standing, the eighth and ninth intercostal spaces in the right mid-axillary line were identified and marked with a wax pencil, as previously described.[16] With the subject then lying horizontally on a plinth in the left lateral decubitus position, using the sector mode, and with the transducer (7.5-MHz linear probe, model PLE 705S; Toshiba Medical System; Tokyo, Japan) held perpendicular to the chest wall, a two-dimensional coronal image of the diaphragm at the zone of apposition was identified in either the eighth or the ninth intercostal space. The diaphragm was identified by two clear, parallel echodense lines and was measured from the middle of the pleural line to the middle of the peritoneal line. The mean of three measurements made at the zone of apposition at FRC (*ie*, TDIrel) and TLC (*ie*, TDIcont) were recorded. Prior to these measurements, the FEV_1/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 hence obtaining measurements with the diaphragm in a more contracted state posttraining, the diaphragm thickening ratio (TR) was determined using the formula described by Ueki et al,[16] as follows:

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

Lung Function Measurements

FEV_1, FVC, and FEV_1/FVC ratio were determined by using a dry wedge spirometer (Vitalograph; Buckingham, UK) by the selection of the peak effort of three trials.[17] VC, FRC, TLC, and

RV were obtained using a different spirometer (PK Morgan Ltd; Kent, UK) and were calculated by the helium dilution technique. Gas exchange characteristics were assessed by the measurement of transfer factor using carbon dioxide (TFco) by the single-breath method[17] (model 0906; PK Morgan UK Ltd). All parameters were expressed as percent predicted for age, stature, and gender.[18]

Exercise Testing

A progressive, incremental exercise test was performed on an electronically braked (Siemens-Elema; Solna, Sweden) cycle ergometer to measure PWC.[14] Subjects began pedaling with no added resistance and at 1-min intervals, and resistance was added in 8-W increments until the subjects could no longer pedal due to volitional exhaustion. Heart rate, ratings of perceived exertion,[19] and dyspnea scores[20] were recorded at each work level.

Psychosocial Assessment

All patients completed the hospital anxiety and depression questionnaire[12] and the chronic respiratory disease questionnaire (CRDQ).[13]

Body Composition

Weight, measured to an accuracy of 0.1 kg, and stature barefoot were determined with a beam scale and stadiometer, respectively. Body composition, fat mass, and lean body mass (LBM) were determined by dual-beam radiograph absorptiometry (QRD/2000 (+); Hologic; Waltham, MA).

Physical Activity Status

Physical activity was assessed using a recall questionnaire.[21] Cumulative activity scores over a 24-h period were expressed in metabolic equivalents (METS) [1 MET = 3.5 mL/kg/min]. All subjects were encouraged not to change their pattern of physical activity during the study.

Statistical Analysis

Descriptive statistics (mean ± SD) were used to summarize the data. Prior to all analyses, the normality of the data was assessed by the one-sample Kolmogorov-Smirnov test, accepting an α level of $p < 0.05$. For diaphragm thickness (at TDIrel and TDIcont), TR, inspiratory pressure data (PImax and SPImaxs), exercise capacity, and psychosocial scores, within-group and between-group comparisons were made using a repeated-measures analysis of variance. For all significant data, unplanned pairwise multiple comparisons were made using the Tukey critical difference test. Differences were considered to be significant if $p < 0.05$. Data analyses were performed using a statistical software package (SPSS, version 10.1; SPSS; Chicago, IL).

Results

Study Group Characteristics

Patients in the two training groups and control subjects had similar ages, heights, weights, FEV_1 values, LBM, percentages of fat of ideal body weight, and levels of activity when measured at baseline (Table 1).

IMF, Lung Volumes, and Diaphragm Thickness

Training at 80% or 20% intensity increased both PImax and SPImax compared to the control subjects ($p < 0.05$) but with no differences between the two training groups. Eight weeks of either 80% or 20% IMT had no effect on TDIrel, and no change also was observed in the control group. The 80% IMT group increased their TDIcont ($p < 0.05$) and TR ($p < 0.05$) compared to no changes in the 20% training group and the control group (Table 2). FEV_1, FVC, and TFco were unaffected by the training intervention. Increases in VC and TLC occurred only in the 80% IMT group ($p < 0.05$ for both) compared to the 20% IMT group or the control group, who demonstrated no change. There was no change in RV after training in any of the training groups or the control subjects (Table 3).

PWC and Psychosocial Scores

PWC and maximal exercise duration increased only in the 80% IMT group. No changes occurred in the group who trained at 20% or in the control group with respect to PWC or maximal exercise duration. Anxiety and depression scores decreased in the 80%

Table 3—*Pretraining and Posttraining Lung Volumes and Transfer Factors

Variable	Pretest	Posttest	p Value
VC			
Group 1	2.9 ± 1.1	3.6 ± 1.0	< 0.05†
Group 2	3.5 ± 0.9	3.6 ± 1.0	NS
Group 3	3.3 ± 0.9	3.1 ± 0.8	NS
TLC			
Group 1	4.9 ± 1.4	5.5 ± 1.4	< 0.05†
Group 2	5.2 ± 1.1	5.4 ± 1.1	NS
Group 3	5.3 ± 0.8	5.2 ± 1.0	NS
RV, L			
Group 1	1.8 ± 0.7	1.9 ± 0.7	NS
Group 2	1.7 ± 0.5	1.7 ± 0.6	NS
Group 3	2.0 ± 0.6	2.0 ± 0.6	NS
FEV_1, L			
Group 1	2.1 ± 1.1	2.0 ± 1.0	NS
Group 2	2.5 ± 1.0	2.8 ± 1.1	NS
Group 3	2.0 ± 1.1	2.0 ± 1.0	NS
FVC, L			
Group 1	2.9 ± 1.2	3.0 ± 1.2	NS
Group 2	3.5 ± 1.1	3.8 ± 1.0	NS
Group 3	3.0 ± 1.1	2.9 ± 1.0	NS
TFco			
Group 1	21.9 ± 7.6	23.7 ± 6.9	NS
Group 2	25.0 ± 5.5	25.4 ± 5.7	NS
Group 3	27.1 ± 4.7	27.0 ± 4.8	NS

*Values given as mean ± SD, unless otherwise indicated. See Table 2 for abbreviations not used in the text.

†Group 1 had significantly higher VC and TLC values than group 2 and 3 posttraining, although there were no significant differences between Groups 2 and 3.

IMT group. No changes occurred in the group that trained at 20% or in the control group with respect to anxiety and depression. There were no changes in the CRDQ scores in any of the training groups or in the control group (Table 4).

Discussion

This study demonstrated that an 8-week program of IMT improves IMF in adult CF patients. This was associated with increases in lung volumes, diaphragm thicknesses, and TRs, and in improvements in PWC and psychosocial status.

Other studies of IMT in preadolescent children with CF have indicated variable results. Four weeks of normocapnic-hyperpnea and resistive breathing improved RME and RMS, but had no greater effect than that obtained by general aerobic exercise training.[22,23] Threshold IMT for 10 weeks in children with CF improved RMS and RME, and also increased VC,[7] while in adolescents low-intensity inspiratory threshold loading at 40% of maximal inspiratory pressure over a 6-week period improved RME but had no effect on pulmonary function.[24] As in other respiratory disorders, the respiratory training response may be confounded by study design limitations, by comparisons between dissimilar training methods, or by the failure to train at levels known to elicit a training response. The patients in the present study increased both their PImax and SPImax values after training at both 80% and 20% intensity IMT. However, only the group that trained at 80% improved VC and TLC, which suggests that training intensities of $> 20\%$ are required to significantly improve pulmonary function. An analysis of the SPImax data indicated a learning response in the first few weeks of training despite a 1-week habituation period. However, the patients in the 80% training group increased their VC, which may indicate an improvement in their thoracic geometry, particularly at volumes close to TLC and may result from a greater contribution of the upper thorax and neck muscles to the inspired volume after training.[25]

In healthy subjects, the dimensions of the diaphragm and thorax are related to height,[26] and diaphragm thickness increases when resistance is applied during weight training.[27] The specific effect of IMT on diaphragm thickness has not been previously reported. The results of the present investigation show that the effect of loading the inspiratory muscles during IMT increases diaphragm size, although this was evident only in the 80% training group at TDIcont using the same method of assessment and protocol as in other studies.[15] In the present investigation, TDIcont was determined using a published method,[15,16,26–28] and the reproducibility of this assessment of diaphragm thickness was found to be satisfactory prior to this study, where the coefficients of reliability for these measured variables were $> 90\%$ and 91%, respectively (unpublished data). However, as the CF patients demonstrated an increase in VC in the 80% IMT group after training, the diaphragm may have been measured at a different lung volume posttraining, which has been shown to influence the measurement of diaphragm size.[27] This methodological problem was overcome by also assessing diaphragm thickness as the TR.[16] When corrected for lung volume, the data in the present study still demonstrated increases in diaphragm size. This may have an impact on increasing inspiratory muscle efficiency, improving pulmonary mechanics, or both.

Unlike selective skeletal muscle-training regimes, the impact of IMT on exercise capacity in CF

Table 4—*Pretraining and Posttraining PWC and Psychosocial Status Scores

Variable	Pretest	Posttest	p Value
PWC, kg/min			
Group 1	328 ± 140	496 ± 159	< 0.05†
Group 2	389 ± 153	371 ± 159	NS
Group 3	343 ± 154	330 ± 165	NS
PWC, min			
Group 1	7.2 ± 2.7	10.3 ± 1.8	< 0.05†
Group 2	7.4 ± 3.0	7.1 ± 3.0	NS
Group 3	6.5 ± 2.7	6.4 ± 2.9	NS
Anxiety			
Group 1	6.0 ± 4.3	3.1 ± 2.7	< 0.05†
Group 2	4.6 ± 3.6	3.7 ± 3.6	NS
Group 3	4.1 ± 3.6	3.7 ± 3.4	NS
Depression			
Group 1	2.8 ± 1.8	0.8 ± 0.7	< 0.01†
Group 2	2.3 ± 1.4	2.0 ± 1.7	NS
Group 3	3.0 ± 2.9	3.3 ± 2.1	NS
CRDQ			
Dyspnea			
Group 1	16.6 ± 4.4	16.2 ± 4.2	NS
Group 2	17.7 ± 4.5	18.4 ± 2.8	NS
Group 3	19.0 ± 2.6	19.6 ± 2.5	NS
Mastery			
Group 1	23.1 ± 1.9	22.1 ± 3.1	NS
Group 2	22.8 ± 4.2	22.5 ± 3.9	NS
Group 3	23.4 ± 3.3	25.1 ± 2.8	NS
Fatigue			
Group 1	15.0 ± 2.3	16.0 ± 3.2	NS
Group 2	20.0 ± 3.4	21.5 ± 2.3	NS
Group 3	20.4 ± 4.4	22.1 ± 2.3	NS
Emotion			
Group 1	32.8 ± 5.0	32.4 ± 8.2	NS
Group 2	37.6 ± 10.5	35.7 ± 9.2	NS
Group 3	36.2 ± 5.9	37.4 ± 5.2	NS

*Values given as mean ± SD, unless otherwise indicated. See Table 2 for abbreviation not used in text.

†Group 1 had significantly higher PWC values and lower anxiety and depression scores than group 2 and 3 posttraining, although there were no significant differences between groups 2 and 3.

patients who are undertaking no other additional form of aerobic endurance training has not been studied. The fundamental importance of exercise capacity was underlined in 1992 by Nixon et al,[8] who found that CF patients with higher levels of aerobic fitness had significantly lower levels of mortality. In addition to this, increases in exercise capacity have been associated with improved psychosocial status in patients with chronic pulmonary disease.[9] According to a recent meta-analysis of controlled IMT, improved exercise capacity following IMT (alone and as an adjunct to exercise reconditioning) and its impact on quality of life is still to be determined.[10] The present study has identified positive benefits of IMT on PWC in CF patients in which both maximal exercise duration and PWC increased when assessed by cycle ergometry.[14] These improvements also were associated with improved psychosocial status in the group who trained at 80%. Accepting the limitations of cycle ergometry to measure functional improvements following IMT, the impact of this regime of IMT on the improved exercise endurance of these patients suggests that IMT may improve functional capacity and may enhance psychosocial status in patients with CF.

The inability to adequately fix the workload, volume, or intensity at which training occurred confounded earlier IMT studies[6,10] in patients with chronic pulmonary disease. The IMT methodology used in this study fixed the workload and reset it before each training session according to the PImax generated. The biofeedback with an on-screen template ensured that patients consistently performed IMT at either 80% or 20% of their maximal inspiratory effort. The failure to control for changes in lung volume allows subjects to change their breathing strategy to tolerate a resistive load by altering the lung volume at which training takes place and thereby to reduce the workload to sub-training threshold levels.[29] This was controlled for in the CF patients who were required to sustain a SPImax through a full inspiratory volume, from RV to TLC, a maneuver that is more closely correlated with IMF in CF patients than PImax, which is relatively well-preserved compared with SPImax.[2,4] PImax has been shown to be well-preserved in CF patients, which according to Lands et al[2] may be due to a selective "training stimulus" from chronic lung disease. However, loads of $> 60\%$ of peak force are not sustainable,[30] and the preservation of PImax in situations in which the inspiratory muscles are loaded to such levels will produce fatigue rather than a training response unless the breathing strategy is altered to avoid fatigue. Therefore, the relative preservation of PImax may be an adaptive response to loading[31] rather than a training response.

Variations in the severity of respiratory disease also can confound the evaluation of IMT due to the loss of homogeneity of the study population. This study attempted to control for this by determining the FEV_1, physical activity, and the LBM prior to randomization to ensure a similar degree of disease severity within each group. Consequently, the design of the study allowed for identification of differences between the groups as a result of training, which were independent of height, severity of disease, or inherent within-subject variability.

In conclusion, this study has shown that a regimen of high-intensity IMT produces an increase in IMF, induces diaphragmatic thickening, and increases lung volumes in patients with CF. These benefits also were associated with an increase in PWC and with improved psychosocial status. These findings, coupled with the relationship previously established in a retrospective study[4] that found that patients who died had more severe IMF, suggest that increasing IMF by fixed load and full inspiratory volume range IMT, as described in this study, may have significant long-term health implications for patients with respiratory disability.

References

1 Davis PB, Drumm M, Konstan MW. Cystic fibrosis (state of the art). Am J Respir Crit Care Med 1996; 154:1229–1256

2 Lands LC, Heigenhauser GJ, Jones NL. Respiratory and peripheral muscle function in cystic fibrosis. Am Rev Respir Dis 1993; 147:865–869

3 Arora NS, Rochester DF. Respiratory muscle strength and maximum voluntary ventilation in undernourished patients. Am Rev Respir Dis 1982; 126:5–8

4 Ionescu AA, Chatham K, Davies CA, et al. Inspiratory muscle function and nutritional status in cystic fibrosis. Am J Respir Crit Care Med 1998; 158:1271–1276

5 Rochester DF. Tests of respiratory muscle function. Clin Chest Med 1988; 9:249–261

6 Smith K, Cook D, Guyatt GH, et al. Respiratory muscle training in chronic airflow limitation: a meta-analysis. Am Rev Respir Dis 1992; 145:533–539

7 Sawyer EH, Clanton TL. Improved pulmonary function and exercise tolerance with inspiratory muscle conditioning in children with cystic fibrosis. Chest 1993; 104:1490–1497

8 Nixon PA, Orenstein DM, Kelsey SF, et al. The prognostic value of exercise testing in patients with cystic fibrosis. N Engl J Med 1992; 327:1785–1788

9 Lacasse Y, Brosseau L, Milne S, et al. Pulmonary rehabilitation for chronic obstructive pulmonary disease. Cochrane Database Syst Rev 2002; 3:CD003793

10 Lotters F, van Tol B, Kwakkel G, et al. Effects of controlled inspiratory muscle training in patients with COPD: a meta-analysis. Eur Respir J 2002; 20:570–576

11 Høiby N, Kotch C. Cystic fibrosis: 1. *Pseudomonas aeruginosa* infection in cystic fibrosis and its management. Thorax 1990; 45:881–884

12 Zigmond AS, Snaith RD. The hospital anxiety and depression scale. Acta Psychiatr Scand 1983; 67:361–370

13 Guyatt GH, Berman LB, Townsend M, et al. A measure of quality of life for clinical trials in chronic lung disease. Thorax 1987; 42:773–778
14 Godfrey S, Mearns M. Pulmonary function and response to exercise in cystic fibrosis. Arch Dis Child 1997; 46:144–151
15 De Bruin PF, Ueki J, Bush A, et al. Diaphragm thickness and inspiratory strength in patients with Duchenne muscular dystrophy. Thorax 1997; 52:472–475
16 De Jong W, van Aalderen WM, Kraan J, et al. Inspiratory muscle training in patients with cystic fibrosis. Respir Med 2001; 95:31–36
17 Ueki J, De Bruin PF, Pride NB. *In vivo* assessment of diaphragm contraction by ultrasound in normal subjects. Thorax 1995; 50:1157–1161
18 British Thoracic Society and the Association of Respiratory Technicians and Physiologists. Guidelines for the measurement of respiratory function: recommendations of the British Thoracic Society and the Association of Respiratory Technicians and Physiologists. Respir Med 1994; 88:165–194
19 Cotes JE. Lung function: assessment and applications in medicine. 5th ed. Cambridge, MA: Blackwell Scientific Publications, 1993; 445–514
20 Borg GA. Psychophysical basis of perceived exertion. Med Sci Sports Exerc 1982; 14:377–381
21 American College of Sports Medicine: Guidelines for exercise testing and prescription. 5th ed. Philadelphia PA: Lea & Febiger, 1995
22 Wilson PW, Paffenbarger RS Jr, Morris JN, et al. Assessment methods for physical activity and physical fitness in population studies: report of NHLBI workshop. Am Heart J 1986; 111:1177–1192
23 Keens TG, Krastins IR, Wannamaker EM, et al. Ventilatory muscle endurance training in normal subjects and patients with cystic fibrosis. Am Rev Respir Dis 1977; 116:853–860
24 Asher MI, Pardy RL, Coates AL, et al. The effects of inspiratory muscle training in patients with cystic fibrosis. Am Rev Respir Dis 1982; 126:855–859
25 Rochester DF, Farkas GA, Lee YY. Contractility of the *in situ* diaphragm: assessment based on dimensional analysis. In: Roussos C, Macklem PT, eds. Respiratory muscles and their neuromuscular control. New York, NY: Marcel Dekker, 1987; 327–336
26 McCool FD, Conomos P, Benditt JO, et al. Maximal inspiratory pressures and dimensions of the diaphragm. Am J Respir Crit Care Med 1997; 155:1329–1334
27 McCool FD, Benditt JO, Conomos P, et al. Variability of diaphragm structure among healthy individuals. Am J Respir Crit Care Med 1997; 155:1323–1328
28 Wait JL, Nahormeck PA, Yost WT, et al. Diaphragmatic thickness-lung volume relationships in vivo. J Appl Physiol 1989; 67:1560–1568
29 Goldstein RS. Pulmonary rehabilitation in chronic respiratory insufficiency: 3. Ventilatory muscle training. Thorax 1993; 48:1025–1033
30 Bellemaire F, Grassino A. Effect of pressure and timing of contraction on human diaphragm fatigue. J Appl Physiol 1982; 53:1190–1195
31 Roussos C, Macklem PT. The respiratory muscles. N Engl J Med 1982; 307:786–797