CHEST

Original Research

COPD

The Effect of Pulmonary Rehabilitation on Critical Walk Speed in Patients With COPD

A Comparison With Self-Paced Walks

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Background: **Walking is frequently used in the exercise rehabilitation of patients with COPD. Walking ability can be characterized by the two-parameter hyperbolic relationship between endurance and speed. One parameter, critical walk speed (*s*_critical), represents the maximum speed that can be endured indefinitely. The purpose of this study was to: (1) determine the effect of pulmonary rehabilitation on the critical speed and (2) compare the critical speed with the speed chosen during self-paced walking.**

Methods: **We estimated critical speed in patients with COPD before and after rehabilitation. Patients completed four high-intensity constant-speed walk tests to intolerance on a 30-m course. The parameters of the hyperbolic relationship were determined using nonlinear regression of endurance on speed. Participants also completed self-paced walks: (1) for as long as they could, (2) at their "usual" and "fast" speeds, and (3) as a 6-min walk test.**

Results: **Twelve participants (FEV_1 [SD], 41 [16] % predicted; FEV_1/FVC, 41 [12]) completed the study. At baseline, the critical speed (65 [12] m/min) was not significantly different from the self-paced, usual, or 6-min walk speeds (65 [12], 67 [14], and 63 [15] m/min, respectively). There was a significant increase in critical speed (6 [1-10] m/min) and 6-min speed (16 [10-21] m/min) after rehabilitation, without changes in the self-paced, usual, or fast speeds.**

Conclusions: **Patients with COPD increase their critical walk speed after pulmonary rehabilitation. The pace chosen during common walk tasks is closely related to critical speed; this relationship is altered after rehabilitation.**

Trial registry: **ClinicalTrials.gov; No.: NCT00781183; URL: www.clinicaltrials.gov**

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Abbreviations: 6MWT = 6-min walk test; *D*′ = curvature constant reserve distance; *s* = speed; *s*_6MWT = 6-min walk test speed; *s*_critical = critical walk speed; *s*_fast = fast walk speed; SPW = self-paced endurance walk; *s*_SPW = self-paced endurance walk speed; *s*_usual = usual walk speed; *t*_limit = limit of endurance time

There is a growing interest in evaluating different features of walking,[1] an important measure that requires further investigation in patients with COPD. Walking speed is a good indicator of the decline in physical performance with age[2] or with chronic conditions.[3] Walk tests are used to assess the effects of interventions, such as pulmonary rehabilitation, as well as for determining the efficacy of an exercise prescription.[4,5] Knowing how patients with COPD choose to walk in relation to their capacity to walk is important for guiding and evaluating treatment. The cornerstone of rehabilitation is exercise training, in which walking is frequently used as the principle endurance component.

People can run or walk at a comfortable speed and maintain it for a long time (hours), but if they go any faster they will slow down or stop after a short time (minutes). The speed defines the power demands of the activity, and the greatest sustainable speed reflects the "critical" power; any speed greater than the critical power has a predictable exhaustion time that is dependent on using the entire anaerobic reserve capacity: the curvature constant walking reserve distance (*D*′). Anaerobic reserve capacity reflects the total energy available to the muscles in the absence of oxygen delivery by the ventilatory and cardiovascular systems. Walking ability may be comprehensively characterized by the two-parameter hyperbolic relationship between speed (*s*) and the limit of endurance time (*t*_limit). The two parameters, the curve's asymptote or critical walk speed (*s*_critical) and the *D′*, represent endurance and the reserve distance, respectively.

The parameters, *s*_critical and *D′*, are determined by plotting the measured endurance time achieved at different power demands, then curvilinear regression is used to estimate the parameters of the curve. Because at least three points are needed to estimate the two parameters, an individual would have to complete at least three constant-power exercise tests to establish his or her curve. The more points observed, the better the precision of the estimates. The *s*_critical signifies the maximum walking speed that can be endured indefinitely without diminishing the reserve, *D′*. Knowing the *s*_critical can help guide pacing strategies as well as the intensity of training exercise.

Because it is impractical to routinely assess walking capability from multiple endurance tests, a single walk test is commonly used as an outcome measure in rehabilitation.[5,6] The simplest tests are those in which the patients set their own speed.

The 6-min walk test (6MWT), in which patients walk as far as possible in 6 min, is commonly used to characterize the exercise capacity of a patient with COPD.[4] Casas et al[7] suggested that the 6MWT speed (*s*_6MWT) may represent the maximal "sustainable" (ie, critical) speed; this helps explain how some patients increase their distance on successive tests,[8,9] suggesting that they had a reserve to continue walking at the same speed for > 6 min.

The self-paced endurance walk (SPW) has been used to characterize walking ability before and after rehabilitation.[10-12] Patients walk unaccompanied at their own pace. We recently described the properties of self-paced walking in patients with COPD and its responsiveness to rehabilitation.[12] Although it is likely that the SPW speed (*s*_SPW) is near to the *s*_critical, to our knowledge this has yet to be shown.

The usual walk speed (*s*_usual) is determined by a test in which the person is instructed to walk, without encouragement, at his or her usual speed. It is a brief, valid, sensitive measure that is often included in clinical research studies.[13] The *s*_usual has been associated with survival in older adults,[1] but has not been reported in patients with COPD. During this test, subjects also demonstrate their "fast" speed (*s*_fast),[2,14,15] which reflects their potential to respond to increased demands.

The primary purpose of this study was to determine the effect of pulmonary rehabilitation on walking endurance at different speeds (power) and its effect on the estimated *s*_critical and *D′* of the speed to endurance relationship. We hypothesized that *s*_critical would increase after rehabilitation without a change in *D′*.

The secondary purposes of this study were: (1) to compare the *s*_SPW, *s*_usual, *s*_fast, and *s*_6MWT with the *s*_critical and (2) to determine the effect of rehabilitation on these relationships. We hypothesized that: (1) the *s*_usual and *s*_SPW would be less than the *s*_critical and the *s*_fast and *s*_6MWT would be greater than *s*_critical, and (2) the relationship between the speed during walk tasks and *s*_critical would be similar before and after rehabilitation. Some of the results of these studies have been previously reported in the form of abstracts.[16,17]

MATERIALS AND METHODS

We recently reported the results of a prospective study to examine the measurement properties of the SPW.[12] In doing so, we also asked participants if they would partake in a more rigorous comprehensive evaluation of their walking ability to determine their *s*_critical. This report includes data on all participants who agreed to the more comprehensive evaluation.

Study Design

Upon admission, each participant completed two sessions on successive days, each comprising two constant-speed endurance walks, with 20-min rests between tests, for a total of four tests. Before each test session, participants were asked to demonstrate their *s*_usual and *s*_fast over 15 m. The sessions were repeated during the last 7 days of the 6-week program.

Participants completed SPWs before and after rehabilitation. Other recorded measures included: (1) 6MWT distance[4] with calculation of average *s*_6MWT, (2) Medical Research Council dyspnea scale ratings[18,19], (3) spirometry results[20] (Elite DL, Medical Graphics), and (4) age, sex, height, and weight data.

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Participants

The study was approved by the Joint West Park-Bridgepoint-Toronto Central CCAC Research Ethics Board (FB 091008A), and written informed consent was obtained before participation. The inclusion criterion was clinical stability in patients with moderate to severe COPD. Exclusion criteria comprised unstable cardiovascular, respiratory, orthopedic, or neurologic conditions. The use of supplemental oxygen or a wheeled ambulatory aid were standardized before and after rehabilitation.

Measurements

Critical Walk Speed: The characteristics of the walk tests are summarized in Table 1. The participants completed four high-intensity walks, at different constant speeds (s) to intolerance (t_limit), on a 30-m course. During each test, the participant followed a test administrator in a level, enclosed, temperature-controlled corridor. The test administrator, guided by an earphone audio signal and marked intervals, walked at a preselected speed. The patient received standardized instructions (e-Appendix 1) and encouragement to walk for as long as possible. The endurance time for each speed occurred when the patient stopped despite encouragement to maintain the speed.

The walk speeds were selected to attain a t_limit between 2 and 15 min.[21] Speeds, presented in random order, were based on the patient's performance during his or her 6MWT and SPW (e-Appendix 1). Tests of >24 min[21] were discarded. Recognizing s as the independent variable and t_limit as the dependent variable, the parameters, s_critical and D', were determined from nonlinear regression such that: $t\_\text{limit} = D'/(s - s\_\text{critical})$.

Usual and Fast Walk Speeds: The participant demonstrated his or her s_usual and s_fast while unaccompanied on the 30 m course. Speed was calculated over the middle 15 m, allowing the participant a dynamic (rolling) start. Instructions (e-Appendix 1) were standardized.

Self-Paced Endurance Walk: The participants walked for as long as possible in a level, enclosed, temperature-controlled 250-m corridor, at a self-selected pace[12] (e-Appendix 1). The time until the participant first felt that he or she needed to stop was recorded, and the speed was calculated.

Pulmonary Rehabilitation

Six weeks of rehabilitation included supervised daily exercise training (cycle and treadmill), daily walks, interval training, and peripheral muscle strengthening as well as self-management education. Training progressed based on symptom limitation, with the goal of increasing exercise intensity and time.

Analyses

All analyses were performed using SAS (version 8.0) and SigmaPlot (version 9.02) statistical software. Mean values were expressed as mean [SD] and mean [95% CI]. We conducted a one-way analysis of variance to identify any effect of test order on t_limit before and after rehabilitation. To determine if there was an effect of rehabilitation and the type of walk on speed, we conducted a two-way repeated measures analysis of variance examining the effects of walk type and rehabilitation, and the interaction between the two, on the dependent variable, speed. Age, sex, and height, which predicted s_usual,[14] were calculated for each participant.

RESULTS

Twelve participants completed the study (Fig 1). Their baseline characteristics are shown in Table 2.

Table 1—*Characteristics of Walk Tests*

Test	Goal	Test Outcome	Speed	Duration	Distance	Study Outcome
6WMT	Walk as far as possible in 6 min	Distance	Self-paced	6 min; stops allowed but encouraged to continue	Speed dependent	Average speed
Self-paced walk test	Walk for as long as possible	Time	Self-paced	Continuous to intolerance	Endurance-time and chosen-speed dependent	Average speed
Usual walk	Walk at usual speed	Speed	Self-paced	Continuous; speed dependent	15 min	Average speed
Fast walk	Walk at fast speed	Speed	Self-paced	Continuous; speed dependent	15 min	Average speed
Constant-speed walk test, speed #1	Walk for as long as possible	Time	Constant; set by administrator walking at one of four participant-specific predetermined speeds to intolerance; intended to last between 2 and 15 min (ie, 2, 6, 10, and 14 min)	Continuous to intolerance	Endurance-time dependent	Estimate s_critical
Constant-speed walk test, speed #2						
Constant-speed walk test, speed #3						
Constant-speed walk test, speed #4						

6MWT = 6-min walk test; s_critical = critical walk speed.

There was no significant effect of the order of the constant-speed walk on *t*_limit before or after rehabilitation ($P = .49$). The predominant reason for stopping was "breathing" (72% of constant-speed tests) across the entire range of speeds. The second and third most common reasons for stopping were "general fatigue" (10%) and "leg fatigue" (7%), respectively. The averaged *s* to *t*_limit function established at baseline is shown in Figure 2, along with the *s*_6MWT, *s*_SPW, *s*_usual, and *s*_fast. Upon entering pulmonary rehabilitation, *s*_critical and D' were 65 (12) m/min and 95 (47) m, respectively. There was no significant difference in speed among the various types of walks (*s*_6MWT, 63 [15]; *s*_SPW, 65 [12]; and *s*_usual, 67 [14] m/min), except that *s*_fast, at 88 [13] m/min, was significantly greater than *s*_critical ($P < .001$). *s*_critical was 82 (15) % predicted of the *s*_usual.

The *s* to *t*_limit function after rehabilitation is shown in Figure 3. There was a significant increase in *s*_critical (change, 6 [1-10] m/min) and no significant change in D' (change, −9 [−52 to 34] m). After rehabilitation, *s*_critical was 89% of predicted *s*_usual. Speeds for the different walks are shown in Figure 4. There was a significant interaction on speed between walk type and rehabilitation ($F_{3,32}$, 5.7; $P = .03$). After rehabilitation, the *s*_6MWT was significantly greater than the *s*_critical (difference, 8 [3-14] m/min). There was no significant change in the *s*_fast ($P = .30$). There were no significant changes in *s*_SPW ($P = .18$) and *s*_usual ($P = .55$), and they were not significantly different from *s*_critical after rehabilitation.

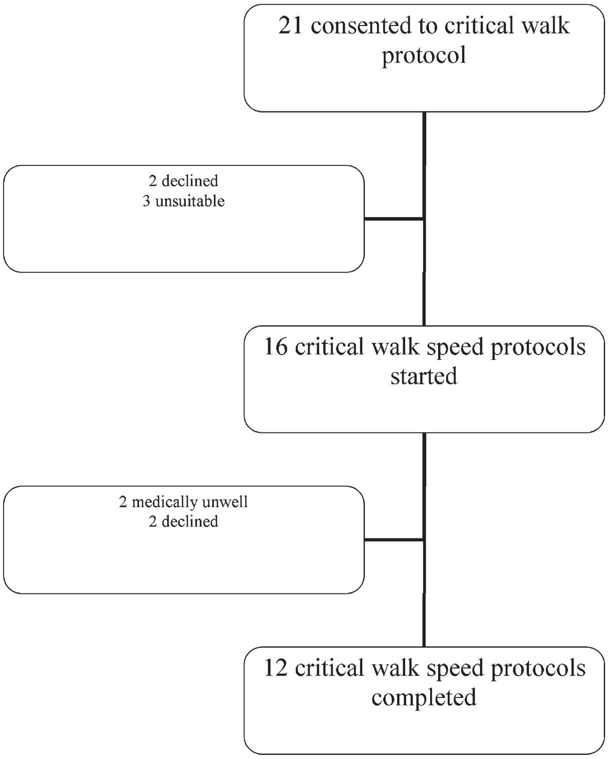

Figure 1. Flow diagram of study participants.

Table 2—*Baseline Characteristics*

Characteristic	Data
No.	12
Sex, M (F)	5 (7)
Age, y	67 (7)
BMI, kg/m^2	26.2 (5.9)
FEV_1, L	1.1 (0.6)
FEV_1, % predicted	41 (16)
FEV_1/FVC, %	42 (12)
MRC dyspnea scale[a]	3 (3-4)
6-min walk distance, m	379 (89)
Rollator prescription	3
Supplemental oxygen prescription	1

Data shown as mean (SD) unless otherwise stated. F = female; M = male; MRC = Medical Research Council.

[a]Data shown as median (interquartile range).

DISCUSSION

We examined how pulmonary rehabilitation affected the capacity to walk in participants with COPD and how they chose to walk in relation to their capacity. We determined: (1) the effect of rehabilitation on *s*_critical, (2) the relationship between *s*_critical and three self-paced walking tasks, and (3) the change in *s*_critical after rehabilitation compared with the change in speed for the self-paced walking tasks. After rehabilitation, participants increased their tolerance to walking at relatively high speeds, increasing the estimated *s*_critical without affecting the curvature constant (D'). At baseline, the *s*_SPW, *s*_usual, and *s*_6MWT were similar to the *s*_critical. After rehabilitation, only the *s*_6MWT was greater than the *s*_critical, with no change in *s*_usual or *s*_SPW.

The most common response to endurance training on the endurance curve is an increase in the asymptote without a change in the curvature constant.[22,23] In patients with COPD, the impact of exercise training on critical power has been reported for cycling,[24] but not walking. We observed a significant increase in the *s*_critical without a change in the curvature constant. The reason for the increase was likely multifactorial, but could reflect improved cardiopulmonary capacity and improved ventilatory efficiency,[25] as well as increased tolerance to dyspnea and fatigue associated with exercise. The most common reason given for stopping, before and after rehabilitation, was "breathing."

Because endurance is influenced by the intensity of exercise, the hyperbolic nature of the *s* to *t*_limit relationship could explain the disparity among studies in which single tests of endurance are used to assess

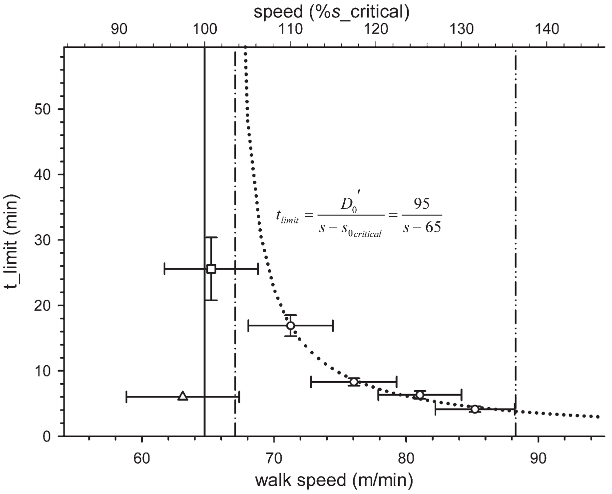

FIGURE 2. Endurance time as a function of *s* (dotted line) derived from the *t*_limit at four different speeds (○). Also plotted are the self-paced endurance walk speed (*s*_SPW) (□) and the 6-min walk test speed (*s*_6MWT) (△). Vertical reference lines indicate the *s*_critical (solid), usual walk speed (*s*_usual) (broken with one dot), and fast walk speed (*s*_fast) (broken with two dots). Data are shown as mean ± SE. *D′* = curvature constant reserve distance; *s* = speed; *s*_critical = critical walk speed; *t*_limit = limit of endurance time.

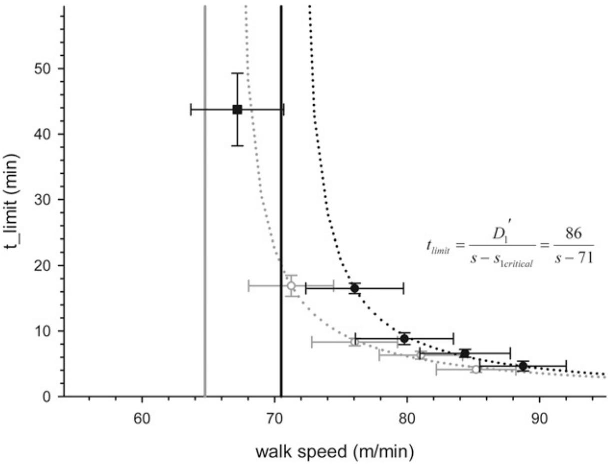

FIGURE 3. Gray lines and symbols on the graph indicate data at the baseline; black lines and symbols indicate data after rehabilitation. Endurance time is plotted as a function of *s* (dotted lines) derived from the *t*_limit at four different speeds (circles) for both baseline and after rehabilitation. Vertical reference lines indicate the average *s*_critical for both baseline and after rehabilitation. Also plotted is the *s*_SPW (square). Data are shown as mean ± SE. See Figure 2 legend for expansion of abbreviations.

treatment response. Small effects on *s*_critical can yield wide differences in endurance time, depending on the endurance test's intensity relative to *s*_critical. In the participants, a 10% change in *s*_critical with no change in *D′* would change the *t*_limit of a constant-speed walk of 8 min (a walk at 120% *s*_critical) to 18 min, an increase of 225%. If the same 10% increase in *s*_critical were applied to a constant-speed walk of 4 min (135% of *s*_critical), the *t*_limit would only increase to 5.5 min, an increase of 37.5%. This hyperbolic relationship is also important when considering the repeatability of endurance tests and their minimal clinically important difference,[26] and when calculating sample sizes. Casaburi[27] has suggested that the desirable intensity for a single endurance test targets a *t*_limit of 4 to 7 min. We note that a target of 8 min would maximize the sensitivity to change without a postintervention duration so long (> 20 min) as to be affected by motivational factors. As a practical example, the effect of supplemental oxygen could be assessed compared with a normoxic endurance test at a speed that results in the normoxic *t*_limit close to 8 min (ie, walking speeds equivalent to 120% of *s*_critical). Upon implementation, if individuals rarely walk beyond their usual speed, they are unlikely to notice the acute performance benefits of oxygen, but if they walk at a faster speed (ie, 105%-130% of *s*_critical), they would notice performance enhancement as their speed to endurance curve is improved with oxygen. Furthermore, they are unlikely to notice the benefits of oxygen during very fast walking (> 135% of *s*_critical).

The *s*_6MWT was less than expected based on observations when the pace was set externally. This suggests that an exercise prescription does not necessarily need to start lower than the *s*_6MWT.[28] Using the speed to endurance curve (Fig 2), the group should have been able to tolerate a speed of 81 m/min for 6 min, and their maximal distance should have been higher than observed for their 6MWT. They reduced this disparity after rehabilitation but continued to underestimate the optimum speed for the 6MWT.

Because most of the patients with COPD selected an *s*_SPW similar to the estimated *s*_critical, instructions to slow down would be counterproductive. Whereas leisure walking is relatively comfortable for those who walk at or below *s*_critical, those who walked above s_critical may require coaching on pacing if their goal is to walk for a long time without unendurable dyspnea.

It is important for the physician to know that a patient's chosen tolerable walk speed (SPW) relates to his or her capacity to walk[5] because the chosen speed is a good indicator of a decline in physical performance[2] and a natural improvement in walk speed is associated with a reduction in mortality.[29] For exercise training, intensity rather than duration of walking is linked to all cause mortality[30] as well as cardiorespiratory fitness.[31]

A minimum of three walks at different speeds is required to fit a curve of a two-parameter model as used here. It may not be practical to use three demanding constant-speed walk tests to intolerance to estimate *s*_critical in routine clinical practice. In

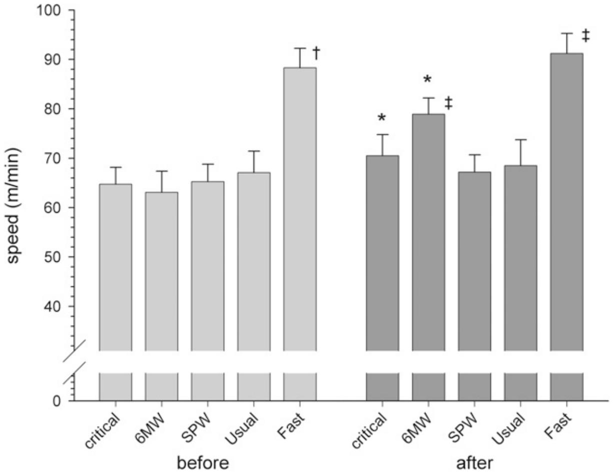

FIGURE 4. Chart shows the comparison of walk speeds before (light gray) and after (dark gray) pulmonary rehabilitation. Data are shown as mean ± SE. *Significant change from baseline ($P < .05$); †significant difference from *s*_critical before pulmonary rehabilitation ($P < .01$); ‡significant difference from *s*_critical after pulmonary rehabilitation ($P < .05$). 6MW = 6-min walk; SPW = self-paced endurance walk. See Figure 1 legend for expansion of other abbreviation.

contrast to the alinear model, a mathematically equivalent linear relationship, with D' as the slope and *s*_critical as the intercept, is established using the inverse of time t_limit (1/t_limit) as the independent variable and *s* as the dependent variable. Linear regression requires only two data points (ie, walks). This is a more practical approach to estimating *s*_critical. However, linear regression assumes that the independent variable, time in this case, is observed without error, which it is not; moreover, the intercept, *s*_critical in this case, is very sensitive to error in the independent variable. The precision of this linear transformation method and using only two walks, given the large variability of endurance time, remains questionable.

The effectiveness of pulmonary rehabilitation is well established,[6] and the small increase in *s*_SPW following rehabilitation among the subjects was likely attributable to the modest sample size and heterogeneity in walk strategy, because we have previously reported significant increases in SPW after pulmonary rehabilitation among a substantially larger sample of patients with COPD.[12] Given the size of the sample, the reported mean and the variance of the *s*_critical are not precise estimates of the COPD population parameters. Notwithstanding the modest sample size, our observations provide an important perspective on how patients walk during different tasks compared with their capacity to walk to intolerance. These observations also illustrate how the speed:endurance relationship changes in response to pulmonary rehabilitation.

In conclusion, pulmonary rehabilitation increased *s*_critical in patients with moderate and severe COPD without changing the curvature constant. Before rehabilitation, the mean *s*_SPW, *s*_6MWT, and *s*_usual were not different from the *s*_critical estimated from four high-intensity endurance walks. An understanding of how patients with COPD choose to walk in relation to their capacity to walk, established from their speed to endurance relationship, provides an understanding when choosing target times for endurance tests and evaluating the effects of an intervention, such as pulmonary rehabilitation.

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Mr Dolmage: contributed to the conception and design of the study, conducting the study, the analysis and interpretation of data, and drafting the article.

Dr Evans: contributed to conducting the study, the analysis and interpretation of data, and revising the article critically for important intellectual content.

Dr Hill: contributed to the design of the study, the interpretation of data, and revising the article critically for important intellectual content.

Ms Blouin: contributed to conducting the study, the interpretation of data, and revising the article critically for important intellectual content.

Dr Brooks: contributed to the design of the study, the interpretation of data, and revising the article critically for important intellectual content.

Dr Goldstein: contributed to the design of the study, the interpretation of data, and revising the article critically for important intellectual content.

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Additional information: The e-Appendix can be found in the Online Supplement at http://chestjournal.chestpubs.org/content/141/2/413/suppl/DC1.

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