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REVIEW

Pathogenesis of hyperinflation in chronic obstructive pulmonary disease

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Abstract: Chronic obstructive pulmonary disease (COPD) is a preventable and treatable lung disease characterized by airflow limitation that is not fully reversible. In a significant proportion of patients with COPD, reduced lung elastic recoil combined with expiratory flow limitation leads to lung hyperinflation during the course of the disease. Development of hyperinflation during the course of COPD is insidious. Dynamic hyperinflation is highly prevalent in the advanced stages of COPD, and new evidence suggests that it also occurs in many patients with mild disease, independently of the presence of resting hyperinflation. Hyperinflation is clinically relevant for patients with COPD mainly because it contributes to dyspnea, exercise intolerance, skeletal muscle limitations, morbidity, and reduced physical activity levels associated with the disease. Various pharmacological and nonpharmacological interventions have been shown to reduce hyperinflation and delay the onset of ventilatory limitation in patients with COPD. The aim of this review is to address the more recent literature regarding the pathogenesis, assessment, and management of both static and dynamic lung hyperinflation in patients with COPD. We also address the influence of biological sex and obesity and new developments in our understanding of hyperinflation in patients with mild COPD and its evolution during progression of the disease.

Keywords: chronic obstructive pulmonary disease, hyperinflation, expiratory flow limitation, operational lung volumes

Introduction

Chronic obstructive pulmonary disease (COPD) is a preventable and treatable lung disease characterized by airflow limitation that is not fully reversible.[1] COPD is a leading cause of mortality and morbidity worldwide, even if it remains largely underdiagnosed.[2,3] Currently, the prevalence of the disease is estimated to be around 10% in the population aged >40 years[4] and could reach around 20%–30%[5,6] when including milder patients (Global initiative for chronic Obstructive Lung Disease [GOLD] stage 1).[1]

In a significant proportion of patients with COPD, reduced lung elastic recoil combined with expiratory flow limitation eventually leads to lung hyperinflation during the course of the disease.[7] In patients with COPD, the lung can be hyperinflated at rest (static hyperinflation) and/or during exercise (dynamic hyperinflation) when ventilatory requirements are increased and expiratory time is shortened. Hyperinflation is clinically relevant for patients with COPD mainly because it contributes to the dyspnea[8] and morbidity associated with the disease.[9] In fact, although measurement of expiratory flows is a prerequisite for the diagnosis and staging of COPD, the effects

of the disease on static and dynamic lung volumes correlate better with patient symptoms and impairment in functional capacity than spirometric indices of the disease.[10] Moreover, dynamic lung hyperinflation is related to reduced daily physical activity in COPD,[11] which is an important component of quality of life.[12]

Despite the difficulties in establishing a cause-effect relationship, exercise intolerance and lung hyperinflation are closely interrelated in COPD.[13,14] While exercise intolerance in patients with COPD is complex and multifactorial,[15–17] dynamic hyperinflation remains a major contributor to exercise limitation that is consistently observed in this disease.[18] During exercise, hyperinflation may impede cardiac[19,20] and respiratory muscle function and increase the work of breathing.[21] Finally, this phenomenon can also occur in patients with mild disease,[22–24] a category of individuals likely representing a great portion of patients diagnosed with COPD.[5]

This review addresses the more recent literature regarding the pathogenesis of both static and dynamic lung

hyperinflation. The pathophysiology and physiological consequences of lung hyperinflation are summarized, as well as management, pharmacological treatment, and the impact of pulmonary rehabilitation on hyperinflation. We also address the influence of biological sex and obesity and new developments in our understanding of hyperinflation in mild COPD patients and its evolution during progression of the disease. The review is based on literature available on the PubMed database, irrespective of the year of publication.

Pathophysiology of hyperinflation

Lung volumes can be divided into several compartments defined by the normal cycle of tidal breathing and the maximum capacity to inhale and exhale (Figure 1A). In health, during relaxed tidal breathing, the lungs tend to return to a basal level of inflation, which is termed functional residual capacity (FRC) or end-expiratory lung volume (EELV). During the hyperpnea of exercise, both tidal volume (V_T) and respiratory rate increase to meet the increased ventila-
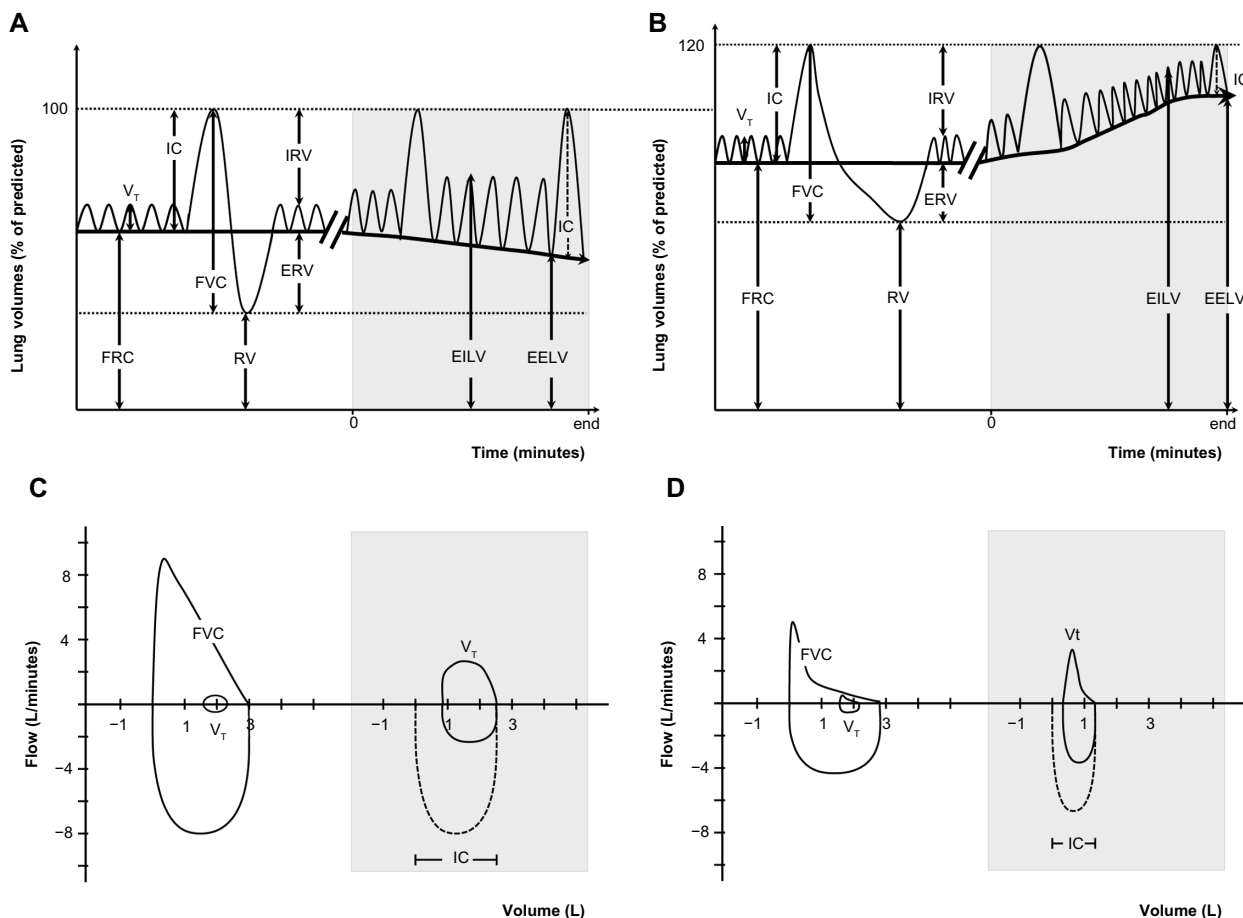
Figure 1 Lung volumes and capacities at rest and during exercise.
Notes: Lung volumes and capacities in a healthy elderly control (**A** and **C**) and in an aged-matched COPD patient (**B** and **D**). Gray parts represents lung volumes during exercise.
Abbreviations: COPD, chronic obstructive pulmonary disease; EELV, end-expiratory lung volume; EILV, end-inspiratory lung volume; ERV, expiratory reserve volume; FRC, functional residual capacity; FVC, forced vital capacity; IC, inspiratory capacity; IRV, inspiratory reserve volume; RV, residual volume; V_T, tidal volume.

tory requirements. Therefore, maintenance of stable lung volumes requires that expiratory muscles must be recruited to elevate pleural and alveolar pressure, increase expiratory flow, and force the increased V_T to be completely exhaled before the next inhalation.[25]

Hyperinflation, defined as an increased volume of air remaining in the lung at the end of spontaneous expirations, is present when resting FRC or EELV is increased above normal.[26] Two types of hyperinflation can be distinguished, ie, static and dynamic hyperinflation. A significant proportion of patients with COPD have some degree of lung hyperinflation, which often remains undetected in the absence of detailed physiological analysis (see section on assessment). Both static and dynamic effects of breathing contribute differently to lung hyperinflation in COPD.

Static and dynamic hyperinflation
Static hyperinflation

Under normal physiological conditions, for a given change in pleural pressure generated by the respiratory muscles, the attainable end-inspiratory lung volume (EILV) and EELV are determined by the passive pressure–volume relationship of the respiratory system (Figure 2).[26,27] In healthy subjects, elastic recoil pressure of the respiratory system decreases progressively during exhalation, reaching zero at FRC or EELV and the elastic work of breathing is minimized by maintaining V_T within 20%–80% of the vital capacity range. With advancing age, damage to the connective tissue of the lung occurs, resulting in a reduction of the lung elastic recoil pressure.[28] The equilibrium point (FRC or EELV) therefore occurs at a higher lung volume than in younger subjects, with a consequence of an increased volume of air
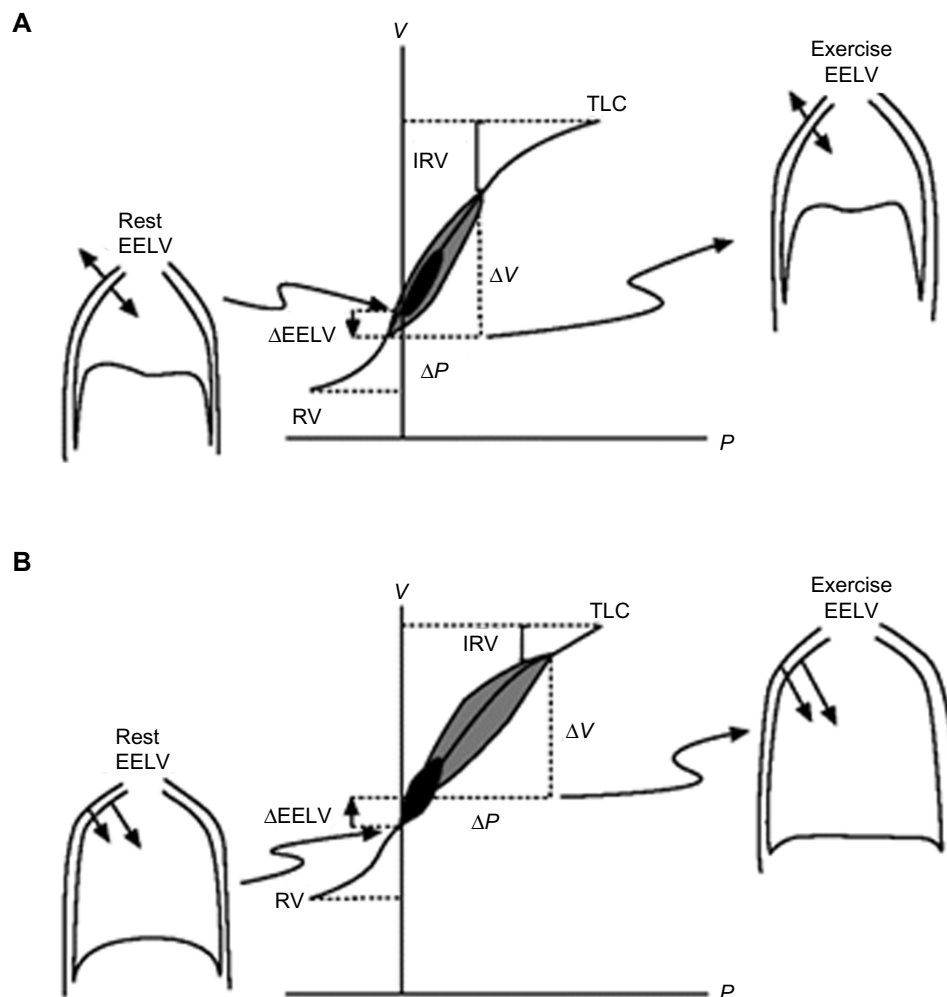
Figure 2 Pressure–volume relationships of the total respiratory system.
Notes: Pressure–volume relationships of the total respiratory system in healthy subjects (**A**) and in COPD (**B**). Tidal pressure–volume curves during rest (black) and exercise (gray) are shown. In COPD, the ability to further expand tidal volume is reduced. In contrast with health, the combined recoil pressure of the lungs and chest wall in hyperinflated patients with COPD is inwardly directed during both rest and exercise. Reproduced with permission of the European Respiratory Society. *Eur Respir Rev December 2006 15:61–67; doi:10.1183/09059180.00010002.*[26] Copyright © remains with European Respiratory Society.
Abbreviations: COPD, chronic obstructive pulmonary disease; EELV, end-expiratory lung volume; IRV, inspiratory reserve volume; P, pressure; RV, residual volume; TLC, total lung capacity; V, volume.

remaining in the lung at the end of spontaneous expirations. This is referred to as static hyperinflation, which exists at rest.[28] In COPD with emphysema, the lung recoil pressure is further reduced by a reduced elastic load related to smoking or α1-antitrypsin deficiency.[29] Therefore, the elastic recoil pressure of the respiratory system falls to zero at a larger FRC or EELV, resulting in more static hyperinflation.

Dynamic hyperinflation

Dynamic lung hyperinflation refers to the temporary increase in EELV above the resting value during periods of increased ventilatory needs (eg, exercise). It is dependent on operational lung volumes and expiratory time, and is thus a key mechanistic consequence of expiratory flow limitation.[14]

During exercise, respiratory rate increases and V_T expands to accommodate increased respiratory demands. The hyperpnea induces phasic activity of expiratory muscles in both healthy individuals and in those with COPD.[30,31] In healthy individuals, the increased expiratory effort progressively decreases EELV and expiratory airflows are sufficient to allow complete exhalation of the inhaled V_T before the next inhalation, even when breathing approaches maximal ventilation. In contrast, the combined effects of decreased lung elastic recoil pressure and increased airways resistance in patients with COPD results in an increased mechanical time constant for lung emptying in many alveolar units. Thus, as the respiratory rate and expiratory flow increases, the expiratory time available for exhalation can become insufficient and complete exhalation of V_T to the relaxation volume becomes increasingly compromised, and EELV usually increases with hyperpnea.[32] In addition, similar to healthy subjects, patients with COPD recruit expiratory muscles to increase their pleural and alveolar pressures, in an effort to increase expiratory flow. However, in these patients, the airways typically collapse when the pleural pressure becomes positive, thereby preventing increased expiratory flow.[33] As a result, exhalation may not be completed prior to the onset of the next breath, causing an increase in operational lung volumes and progressive air retention called "air trapping".[13,26,34] This is referred to as dynamic hyperinflation, which can occur independently of static hyperinflation. Usually observed during exercise, the onset of dynamic hyperinflation will also occur at lower minute ventilations as disease severity limiting exhalation worsens, and may even occur during quiet breathing in severe patients or during an acute exacerbation.[14,35]

Natural history of hyperinflation

Development of hyperinflation during the course of COPD is insidious. In early COPD, the forced expiratory volume in one second (FEV$_1$) may not be the optimal indicator of small airways obstruction.[36] In fact, considering the extent of small airway inflammation reported in patients with mild COPD,[37] it is conceivable that substantial structural damages could have taken place before marked expiratory flow limitation is objectively measured via FEV$_1$.[38] Early changes observed in pulmonary function of heavy smokers without COPD likely imply increased total lung capacity (TLC) and residual volume because of the loss of elastic recoil.[39] These early changes reflecting lung hyperinflation are observed without any apparent reduction in FEV$_1$.[39] In mild COPD, measures of TLC, FRC, and residual volume were found to be significantly above predicted values while vital capacity and inspiratory capacity (IC) were preserved.[40] Throughout the continuum of hyperinflation from mild to more severe COPD, vital capacity and IC decrease linearly with the progression of airflow obstruction (FEV$_1$ decline). On the other hand, the progressive increase in TLC, FRC, and residual volume appears to be exponential with the worsening airflow limitation during the course of COPD.[40]

During exercise, some studies report that dynamic hyperinflation is already present in patients with mild disease (GOLD stage 1), even when resting hyperinflation is slightly present[22,23] or absent.[24,41–43] Even if patients with mild COPD usually have preserved resting IC, they still exhibit dynamic hyperinflation and abnormal ventilatory mechanics during exercise when compared with healthy controls.[22,44] At peak exercise, notwithstanding the severity of the disease, patients seem to show a consistent fall of approximately 20% of their resting IC at peak exercise.[22–24,45–48]

In patients with moderate-to-severe COPD, the level of dynamic hyperinflation is poorly related to FEV$_1$.[49] However, when comparing two patients with similar FEV$_1$, the one presenting with a reduced diffusion capacity, more severe small airway obstruction, and a higher ventilatory response to exercise will tend to develop more dynamic hyperinflation early during exercise.[13] Moderate levels of dynamic hyperinflation can even be observed in healthy elderly individuals aged >70 years without any pulmonary disease following normal aging of the lung parenchyma.[50–52] Likewise, the ventilatory response during exercise of a healthy elderly subject could be similar to that of a patient with GOLD stage 1 COPD.[53]

Physiological and sensory consequence of lung hyperinflation
Dyspnea

The interrelation between hyperinflation and dyspnea has been evaluated indirectly using regression analysis.

O'Donnell and Webb[54] evaluated 23 patients with severe COPD and found that the change in EILV from baseline was the strongest predictor of the change in Borg dyspnea ratings (r=0.63, P<0.001). In this study, EELV and V_T (both components of EILV) combined with breathing frequency accounted for 61% of the variance in dyspnea intensity. A subsequent study in a larger cohort of COPD patients (n=105) demonstrated that the V_T/IC ratio, an index of EILV and V_T constraint, was the strongest predictor of exertional dyspnea based on multiple linear regression analysis.[13] Moreover, interventions that deflate the lungs (ie, reduce EILV and EELV) and delay the onset of critical V_T constraints consistently reduce dyspnea intensity in patients with COPD during exercise.[45,46,55,56]

Although dynamic hyperinflation is a cardinal feature of COPD with important physiological consequences, a small proportion of patients (~15%–20%) do not dynamically hyperinflate during exercise even though they still experience intolerable dyspnea.[13,42,57] Guenette et al[42] recently evaluated the effects of dynamic hyperinflation on dyspnea by comparing a group of well characterized COPD patients who did not acutely increase their EELV during exercise (nonhyperinflators, n=65) with those that did increase their EELV (hyperinflators, n=65). Despite being well matched for age, sex, body mass index, and baseline airflow obstruction, the authors were not able to show that the hyperinflators experienced more dyspnea than the nonhyperinflators. The authors concluded that perhaps the regulation of EILV provides a better index of critical constraints to ventilation (and therefore dyspnea) during exercise than the behavior of dynamic EELV per se. This finding does not necessarily diminish the physiological and sensory significance of dynamic hyperinflation, but rather shows that some individuals with airflow obstruction can still experience similar critical V_T constraints (and thus similar dyspnea ratings), regardless of how they regulate EELV.

Respiratory and limb muscle function
Respiratory muscles
Static lung hyperinflation alters the geometry of the thorax and shortens the diaphragm,[58] thereby placing the diaphragm in a suboptimal contractile position to generate pressure. This mechanical disadvantage reduces the force-generating capacity of the inspiratory muscles and is likely to become further exaggerated in patients who dynamically hyperinflate.[59] Indeed, the ability of the respiratory muscles to generate pressure decreases at high lung volumes in humans.[58,60] These functionally weakened respiratory muscles coupled with the increased elastic and threshold loading of the inspiratory

muscles[61] results in a substantial increase in the work and oxygen cost of breathing.[21,62]

Despite the known deleterious effects of static and dynamic hyperinflation on respiratory muscle function, some have postulated that respiratory muscle strength and function may actually be preserved in some patients with COPD.[58,63,64] Chronic exposure to lung hyperinflation may result in physiological adaptations to preserve inspiratory muscle strength and perhaps obviate the development of diaphragmatic fatigue.[65] Some of the documented adaptations include: an increase in the relative fraction of fatigue-resistant slow-twitch (type I) muscle fibers[66] that can occur even in mild-to-moderate COPD;[67] a reduction in sarcomere length which permits an increase in pressure production at higher lung volumes;[68] increased mitochondrial density;[68] and/or an improvement in mitochondrial respiratory chain capacity.[69]

Limb muscles
A direct link between dynamic hyperinflation and peripheral muscle function has not been fully established. Studies in healthy subjects suggest that high levels of respiratory muscle work may result in a sympathetically mediated metaboreflex which causes redistribution of blood flow from the locomotor muscles to the respiratory muscles.[70–72] A reduction in locomotor muscle blood flow could result in an accelerated rate of development of limb muscle fatigue during exercise. This contention is supported by studies that show reduced limb muscle fatigue and corresponding improvements in perceived leg discomfort when the work of breathing is mechanically unloaded during exercise in healthy humans[73] and in patients with COPD.[74] In theory, dynamic hyperinflation and the associated increase in work and oxygen cost of breathing may compromise blood flow to the periphery, leading to compromised oxygen delivery and therefore causing increased leg fatigue. Indeed, studies that have unloaded the respiratory muscles of hyperinflated patients with bronchodilators or heliox resulted in an improvement in indices of limb muscle fractional oxygen extraction.[75,76] For example, Louvaris et al[77] recently demonstrated that improving operating lung volumes in hyperinflated COPD patients with heliox enhanced oxygen delivery to the quadriceps muscles during exercise by increasing arterial oxygen content and blood flow to the quadriceps muscles. The authors speculated that this was likely due to blood flow redistribution from the respiratory muscles since cardiac output was similar between heliox and room air.

Cardiac function
Lung hyperinflation has been shown to adversely affect cardiovascular function in patients with COPD. Lung

hyperinflation reduces right ventricular preload and venous return at rest and during exercise.[78–81] Left ventricular afterload may also increase due to the high intrathoracic pressure swings needed to overcome the high elastic and resistive loads encountered by patients with COPD during exercise.[80] In addition, right ventricular afterload increases during exercise because there is an increase in pulmonary vascular resistance resulting from patients breathing at a high EILV.[82,83] There is also indirect evidence to suggest that lung hyperinflation is associated with pulmonary hypertension. A number of mechanisms have been proposed to explain this association as recently described,[84] including increased intrathoracic pressures, cardiovascular effects, increased lung volume, altered gas exchange, pulmonary vascular remodeling, and endothelial dysfunction. Collectively, these cardiovascular consequences of lung hyperinflation likely contribute, in highly variable combinations, to the reduced cardiac performance observed in some COPD patients during exercise.[20,85] However, it should be acknowledged that not all studies have been able to demonstrate a direct link between dynamic hyperinflation and cardiac performance during exercise. For example, Stark-Leyva et al[86] found that voluntary hyperinflation in healthy subjects did not adversely affect cardiac output during exercise. It remains to be determined if these findings in a healthy model can be extrapolated to patients with both static and dynamic hyperinflation, such as those with COPD.

Exercise tolerance

The mechanisms of exercise intolerance in COPD are complex and multifactorial and have been the subject of rigorous scientific debate.[16–18] Potential mechanisms include abnormal ventilatory mechanics, limb muscle dysfunction, and impaired cardiac function, among other factors.[87] All of these mechanisms are related, at least in part, to lung hyperinflation as previously described. Thus, it is difficult to directly demonstrate a cause–effect relationship between hyperinflation and exercise performance because interventions that reduce hyperinflation may also improve any one or a combination of these contributory factors to varying degrees. Nevertheless, correlative evidence indicates that there is a link between exercise performance and indices of lung hyperinflation. For example, peak V_T relative to predicted vital capacity was found to be the best predictor of peak aerobic capacity ($r=0.68$, $P<0.0005$) in 105 patients with COPD.[13] Work from other groups supports these results by showing a significant correlation between resting IC and peak work rate and peak oxygen uptake, particularly

in patients with demonstrable expiratory flow limitation at rest.[88] The notion that lung hyperinflation is inversely related to exercise tolerance is also supported, albeit indirectly, by studies showing statistically significant correlations between improvements in resting and exercise IC and improvements in peak oxygen uptake and cycle endurance time following different interventions.[46,56,89,90]

Influence of comorbidities and sex on hyperinflation
Obesity

Obesity is an abnormal or excessive fat accumulation that may impair health.[91] Added weight on the thorax and abdomen (and also the neck), can significantly affect static and dynamic lung volumes along with respiratory mechanics,[92–112] usually in a dose-response fashion. While several studies have addressed this issue, significant variability has been observed when evaluating the effects of obesity on lung volumes. These discrepancies may arise from heterogeneity in the severity of obesity and/or fat distribution, the precision of its measurement, or other confounding factors, such as underlying lung disease or sex differences. These uncertainties may well be exaggerated when the respiratory effects of obesity are studied alongside another heterogeneous disease such as COPD. As such, caution is recommended in drawing conclusions.

Total respiratory system compliance is usually reduced in obese patients. Obesity alone appears to have a "deflationary" effect. Obese patients consistently have a reduced expiratory reserve volume (or FRC) proportional to the magnitude of obesity.[99,108,110,113–120] Total lung capacity is usually not affected (ie, it remains within the lower limits of normal values), although some studies report decreases in cases of very severe obesity (body mass index >45 kg/m^2).[110,112,121] Obesity is associated with a small decrease in FEV$_1$ and forced vital capacity (although they remain within normal values)[108,122,123] and the FEV$_1$/forced vital capacity ratio is preserved.[124] The physiological consequences of a combination of obesity and COPD are not well known and could theoretically provide advantages and disadvantages. On the one hand, both of these pathologies may have opposing effects in terms of lung volumes, COPD being primarily hyperinflating and obesity being deflating. This could provide an advantage to patients with COPD who are obese by reducing the deleterious effects of dynamic hyperinflation. On the other hand, this combination could increase mechanical loading and airway closure,[125] and thus worsen trapping of air in the lung.

While very few studies have addressed the impact of the combination of obesity and COPD on lung volumes, available

results suggest that compared with normal weight patients, obese patients with COPD have reduced TLC and FRC[126–129] and that lower lung volumes are maintained throughout exercise.[126,128,129] Obese patients with COPD still hyperinflate to a similar degree (Δ IC from rest to peak exercise capacity) than their normal weight counterparts.[126,128,129] Obesity in COPD appears to have a deflating effect at rest, and as a consequence, even if patients hyperinflate at a similar rate, they remain at lower volumes during exercise. Therefore, these studies all report that obese patients with COPD have either preserved or increased exercise capacity,[126–129] except when walking is the testing modality.[127] Mechanistic data[126] showed that the elastic properties of the lung were better preserved and that diaphragmatic function appeared not to be better in obese patients with COPD. Also, the increased metabolic load induced by obesity appeared to be compensated by an increased ventilatory efficiency (ie, lower ventilatory equivalent for CO_2) in these patients. The precise mechanisms by which obesity and COPD interact to affect lung volumes are presently not well known. They are likely influenced by several factors, such as COPD phenotype[42] and fat distribution.[96]

Sex

Respiratory volumes and flows are significantly different between the sexes, as shown by the reference equations for lung function.[130,131] These differences (mainly smaller lungs and maximal flow rates in women) may also affect dynamic volumes because fit women may suffer from expiratory flow limitation that induces an increase in EELV.[132–134] It is therefore possible that COPD affects women differently than men. Women with COPD appear to be more susceptible to resting hyperinflation, despite lower tobacco use and younger age.[135] When restricted to emphysema, women also present a different pattern of disease compared with men, ie, smaller airway lumen and thicker airway walls.[136,137] During constant work rate cycle exercise testing at the same relative intensity, women with COPD hyperinflated at a rate similar to that in men (Δ IC).[138] However, considering their smaller lung volumes, they reached a critical inspiratory reserve volume sooner than men and thus stopped exercise earlier than men. Similar results were obtained in another sample of COPD patients.[139] It would appear that women may be more susceptible to the deleterious effects of COPD because of their smaller respiratory systems compared with men.

Assessment of hyperinflation
Static assessments

In order to calculate lung hyperinflation at baseline, two subdivisions of the vital capacity must be measured. These are the IC and the expiratory reserve volume (Figure 1B).[140] Methods used for assessment of these parameters in COPD are body plethysmography, nitrogen washout, and helium dilution techniques.[141] Body plethysmography is considered the gold standard. This test is performed in a body plethysmograph allowing measurement of intrathoracic gas while airflow is occluded. Based on Boyle's law,[142] changes in thoracic volumes caused by a compression or decompression of the gas in the lungs during respiratory maneuvers can be computed. FRC is thus obtained and constitutes the key measurement of static hyperinflation. A minimum of three values must be obtained, and the difference between the lowest and the highest FRC must be within 5% to be considered reliable. The mean value is then reported. In elderly healthy subjects, residual volume and FRC represent 30% and 55% of TLC, respectively.[130] In COPD, these values can be increased to 70% and 85% of the TLC for residual volume and FRC, respectively.[143] Usually, lung volumes/capacities exceeding 120%–130% of the predicted value are considered to be clinically relevant in COPD, but this remains arbitrary given that no consensus about the definition or severity of lung hyperinflation is available.[131,141] It seems that the FRC calculated by body plethysmography is overestimated because it includes both ventilated and nonventilated lung compartments.[130,142] In contrast, nitrogen washout and helium dilution techniques underestimate FRC in the presence of severe airflow obstruction or emphysema.[32,140] Complete details about these three techniques are available in the latest American Thoracic Society/European Respiratory Society task force document.[141] Finally, because of a lack of standardization, radiographic techniques[144–147] are not commonly used clinically to measure static hyperinflation in COPD.[32] In fact, lung volumes calculated from radiographic techniques are based on the volume of gas within the outline of the thoracic cage and thus include the volume of tissue as well as the lung gas volume.[140] This method is usually reserved for patients with a limited ability to correctly perform the other techniques. Nevertheless, high-resolution computed tomography might constitute a useful upcoming technique to assess hyperinflation in COPD.[32]

Dynamic assessments

Dynamic hyperinflation is determined from assessment of EELV (Figure 1B). This volume can be used interchangeably with FRC, although it is usually more appropriate to use it during exercise because this value is temporarily increased. EELV is commonly measured during exercise or any condition increasing minute ventilation by assessment of serial

IC measurements as recently described by Guenette et al.[41] As for the resting EELV, a minimum of three IC maneuvers must be performed at rest. Values within 10% or 150 mL of the largest acceptable IC are usually considered reproducible. During exercise, patients are asked to take a deep inspiration after a normal expiration at specific intervals ranging from 1 to 3 minutes as well as at symptom limitation and during recovery. Because TLC remains stable during exercise,[148,149] a temporary decrease in IC reflects a temporary increase in EELV (Figure 1B and D). More than 80% of patients with moderate-to-severe COPD showed significant increases in EELV during exercise.[11,13,46,150] This volume has been shown to be reliably measurable and is responsive to treatment in COPD.[57,89] Moreover, inspiratory-to-total lung capacity ratio <25% has also been used as a prognostic tool in COPD.[151] A recent study showed that reduction of the inspiratory reserve volume (IC − V_T, Figure 1A and B) reflecting "room to breathe" was even more related to exercise dyspnea than EELV[42] (Figure 1B). Finally, other methods such as optoelectronic plethysmography[152] and respiratory inductance plethysmography[153] are available for the assessment of dynamic hyperinflation, but they are still mainly used for research purposes in COPD.

Management and treatment of hyperinflation
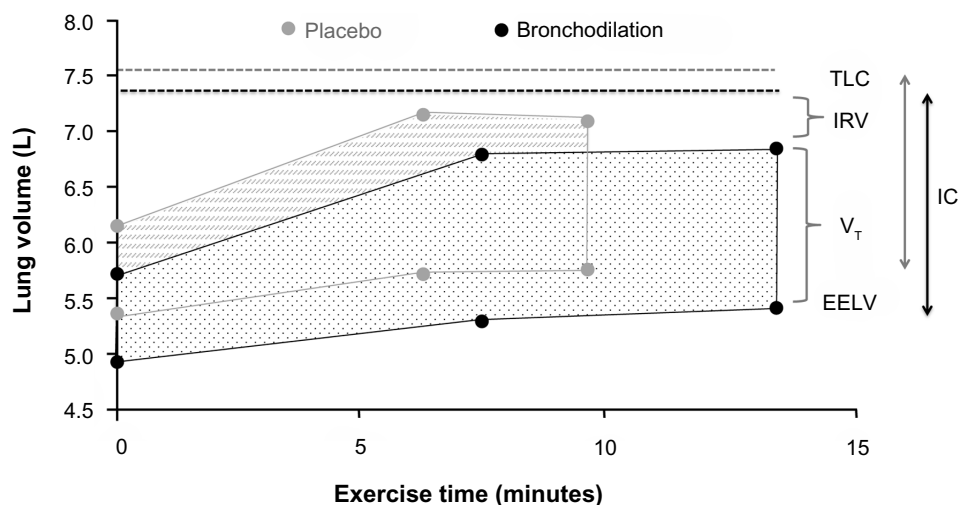### Bronchodilator therapy
Pharmacological interventions that reduce operating lung volumes and delay the onset of ventilatory limitation consistently reduce the intensity of dyspnea during exercise in patients with COPD.[46,55,56] It should be noted, however, that the rates of increase in EELV (dynamic hyperinflation) and dyspnea symptoms during exercise are not modified after administration of bronchodilators. Rather, pharmacotherapy delays the development of restrictive ventilatory mechanics during exercise by deflating the lungs and decreasing EELV at rest. The resulting increase in resting IC causes a parallel downward shift in operating lung volumes during exercise in comparison with exercise performed without bronchodilation (Figure 3).[41,150] Thus, for any given exercise intensity or ventilation, patients breathe on the more linear portion of the respiratory system pressure–volume curve, with attendant improvements in neuromechanical coupling and, by extension, dyspnea. However, the absolute magnitude of dynamic hyperinflation does not change, and may even increase during peak exercise, reflecting the higher levels of ventilation that can be achieved following pharmacotherapy.[10,45,90]

Nonpharmacological interventions
Ventilatory support
The use of noninvasive ventilatory support consistently increases endurance time and reduces perception of dyspnea during constant load cycling tasks in patients with COPD.[154,155] However, assisting ventilation by continuous positive airway pressure or pressure support will not affect EELV at rest or the increase in EELV during exercise.[156] The use of ventilatory support techniques will therefore not directly impact either static or dynamic lung hyperinflation.

Figure 3 Acute effects of bronchodilation therapy on operational volume during constant work rate cycle ergometry in patients with COPD.
Notes: Example of operating lung volumes during constant work rate cycle ergometry performed at 75% maximal workload after dosing of placebo (gray symbols) or bronchodilation therapy (black symbols). Adapted with permission from the American College of Chest Physicians. Maltais F, Hamilton A, Marciniuk D, et al. Improvements in symptom-limited exercise performance over 8 h with once-daily tiotropium in patients with COPD. *Chest*. 2005;128(3):1168–1178.[150]
Abbreviations: COPD, chronic obstructive pulmonary disease; EELV, end-expiratory lung volume; IC, inspiratory capacity; IRV, inspiratory reserve volume; TLC, total lung capacity; V_T, tidal volume.

The effects of these interventions on dyspnea are probably mostly related to unloading of the inspiratory muscles during exercise.[155,157–160] Respiratory muscle function is often impaired in patients with COPD.[161] As previously described, these muscles have to overcome higher elastic and threshold loads during exercise which increases the work and oxygen cost of breathing in comparison with healthy subjects.[26,162] Optimal continuous positive airway pressure reduces the elastic work of breathing throughout inspiration, counterbalances intrinsic positive end expiratory pressure, and takes away the threshold load on the inspiratory muscles while pressure support provides variable resistive and elastic unloading of the ventilatory muscles.[156,163]

Unloading respiratory muscles by proportional assisted ventilation improved leg blood flow and exercise performance during sustained high intensity exercise in healthy trained cyclists, indicating a competition for blood flow between respiratory and limb muscles.[164,165] One study has so far investigated these mechanisms in patients with moderate-to-severe COPD.[166] These authors found positive effects of respiratory muscle unloading by proportional assisted ventilation during a relatively short (average of 4–5 minutes) constant load cycling task on endurance time, leg muscle oxygenation, and dyspnea and leg fatigue symptoms.[166]

Oxygen/heliox administration

Supplemental oxygen during exercise consistently improves endurance and maximal exercise capacity and reduces ventilation and dyspnea at isotime during endurance exercise testing in COPD patients with and without resting hypoxemia.[167] Oxygen supplementation during exercise delays the attainment of ventilatory limitation and accompanying intolerable symptoms of dyspnea during exercise by reducing ventilatory demand.[168,169] Oxygen supplementation will however not affect EELV and IC at rest and will also not change EELV for a given level of ventilation during exercise.[168,170] The improvements observed at a given level of exertion are therefore not caused by a direct effect on static or dynamic hyperinflation. Both improved oxygen delivery to the peripheral muscles (resulting in less reliance on anaerobic metabolism), and attenuated peripheral chemoreceptor stimulation have been proposed as possible explanations for the reduction in ventilatory demand for a given level of exertion.[168,169]

Heliox is a low density gas mixture (79% helium, 21% oxygen) that has been used in patients with COPD to reduce airflow resistance with increasing ventilatory requirements during exercise.[171] Heliox supplementation has been shown to improve exercise intensity and endurance in patients with COPD in comparison with room air breathing.[172] Effects on dyspnea are likely but less clearly documented in the current literature.[172] Two papers evaluating dyspnea at isotime during an endurance cycling task however consistently showed significant reductions in perception of dyspnea.[171,173] Heliox breathing increases the size of the maximal resting flow–volume envelope and seems to actually slow down the increase in EELV during exercise by decreasing airflow resistance, thereby directly altering dynamic hyperinflation.[170,171] The response with regard to exercise capacity seems to be correlated with the magnitude of change in EELV during exercise.[171] In three studies, the responses to hyperoxic helium (60%–70% helium, 30%–40% oxygen) and oxygen supplementation alone were compared during a constant load cycling task in patients with moderate (nonhypoxemic),[173] severe,[174] and very severe (on long-term oxygen therapy) symptoms.[175] These studies all found significant differences in endurance time in favor of the hyperoxic helium group.[173–175] They further demonstrated reductions in the resistive work of breathing,[173] and reductions in exercise-induced dynamic hyperinflation (increases in EELV)[174,175] in comparison with hyperoxia alone.

Lung volume reduction surgery

In selected patients, lung volume reduction surgery decreases static and dynamic hyperinflation, and improves neuromechanical coupling, respiratory muscle function, exertional dyspnea, and exercise performance.[176–179] Lung volume reduction surgery increases maximal ventilatory capacity as evidenced by increases in both maximal voluntary ventilation and maximal minute ventilation at peak exercise.[176–178,180–182] The positive effects of this intervention on airflow obstruction have been ascribed to increases in lung elastic recoil or to reductions in TLC and residual volume leading to an increased vital capacity and improvements in respiratory muscle function.[183,184] However, the understanding of the exact mechanisms of improvement in lung function remains incomplete and needs to be improved to select the optimal patients for this procedure.[183,184] Besides the effects on static hyperinflation, it seems that the intervention also exerts a direct effect on dynamic hyperinflation during exercise.[176–178] While minute ventilation has been reported to be stable at comparable work rates after lung volume reduction surgery, decreases in EELV have been observed, with reductions in breathing frequency and increases in V_T.[183] Thus, lung volume reduction surgery improves airway conductance and lung emptying both at

rest (comparable with bronchodilators) and during exercise (comparable with heliox breathing).

Exercise

The improvements in dyspnea and exercise capacity during constant load cycling tasks after properly conducted exercise training programs are larger than those observed with any of the previously described interventions.[185,186] Several physiological and psychological factors, including a reduction in dynamic hyperinflation, have been proposed to explain these improvements.[187–189] It is generally accepted that exercise training, unlike bronchodilators, does not have an impact on resting pulmonary mechanics.[190] From the available data, it also appears that, unlike heliox breathing or lung volume reduction surgery, exercise training does not have a direct effect on the rate of increase in EELV (dynamic hyperinflation) during exercise.[170] Similar to the acute effects of oxygen supplementation, exercise training reduces ventilatory needs for a given level of exertion.[170,190,191] This decrease in ventilatory needs is probably related to improvements in limb muscle function after training with an accompanying reduced reliance on anaerobic metabolism during exercise.[187,189] Less ventilation will allow patients to reduce their respiratory rate, increase V_T, and reduce EELV for a given workload and will eventually result in reduced symptoms of dyspnea and improved exercise endurance.[187,189] For a given level of ventilation, EELV seems, however, not to be altered after exercise training.[187–189]

Breathing techniques

Pursed lip breathing is used spontaneously by some patients with severe dyspnea, airflow obstruction, and lung hyperinflation.[192] Therapeutically, it has been applied to reduce breathing frequency and increasing V_T during exercise in several small studies, with mixed results in terms of dyspnea reduction and improvements in exercise capacity.[192–194] Spahija et al[192] observed that during constant work bicycle exercise, a reduction in dyspnea during application of pursed lip breathing was related to changes in EELV and pressure generation of the inspiratory muscles. Even though the evidence base is limited, pursed lip breathing might be used on a trial-and-error basis in individual patients. A recent study by Collins et al[195] used a computerized ventilation feedback intervention aimed at slowing respiratory rate in combination with an exercise training program and showed reductions in respiratory rate, ventilation, and dynamic hyperinflation at isotime during a constant load cycling task. Feasibility of this approach on a larger scale needs to be addressed.

Inspiratory muscle training

Strengthening inspiratory muscles by specific training programs has been applied frequently in patients with COPD with the aim to alleviate dyspnea and improve exercise capacity. Reduced contractile muscle effort has been proposed as an important dyspnea relieving mechanism in studies that used ventilatory support to unload these muscles during exercise.[157–160] Inspiratory muscle training aims to increase the capacity of these muscles to allow them to function at a lower fraction of their maximal capacity during exercise. Strong evidence supports effects of inspiratory muscle training to improve inspiratory muscle function (strength and endurance) and to reduce dyspnea and improve exercise capacity when applied as a standalone intervention.[196] Positive effects of inspiratory muscle training on operational lung volumes and breathing patterns during exercise have so far only been demonstrated in a single study.[197] More research into the mechanisms linking inspiratory muscle training to reduction of dyspnea during daily activities is warranted.

Summary

Although measurement of FEV_1 is mandatory to establish a diagnosis of COPD, research in recent years has clearly demonstrated that hyperinflation, at rest and/or during exercise, is more closely associated with important clinical outcomes such as dyspnea and exercise intolerance than with expiratory flow indices. Hyperinflation has become an important endpoint in several clinical trials evaluating the efficacy of pharmacological and nonpharmacological therapeutic approaches to COPD. These trials have shown that measuring hyperinflation at rest and/or during exercise in the context of a multicenter randomized trial is feasible and valid. These trials have also confirmed that reducing hyperinflation in patients with COPD is a realistic therapeutic objective and is associated with relevant clinical benefits.

Disclosure

The authors report no conflicts of interest in this work.

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