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HEART FAILURE

Closing Capacity and Gas Exchange in Chronic Heart Failure*

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Background: **Although it is commonly assumed that pulmonary congestion and edema in patients with chronic heart failure (CHF) promotes peripheral airway closure, closing capacity (CC) has not been measured in CHF patients.**

Purpose: **To measure CC and the presence or absence of airway closure and expiratory flow limitation (FL) during resting breathing in CHF patients.**

Methods: **In 20 CHF patients and 20 control subjects, we assessed CC, FL, spirometry, blood gas levels, control of breathing, breathing pattern, and dyspnea.**

Results: **The patients exhibited a mild restrictive pattern, but the CC was not significantly different from that in control subjects. Nevertheless, airway closure during tidal breathing (*ie*, CC greater than functional residual capacity [FRC]) was present in most patients but was absent in all control subjects. As a result of the maldistribution of ventilation and the concurrent impairment of gas exchange, the mean (± SD) alveolar-arterial oxygen pressure difference increased significantly in CHF patients (4.3 ± 1.2 vs 2.7 ± 0.5 kPa, respectively; $p < 0.001$) and correlated with systolic pulmonary artery pressure ($r = 0.49$; $p < 0.03$). Tidal FL is absent in CHF patients. Mouth occlusion pressure 100 ms after onset of inspiratory effort ($P_{0.1}$) as a percentage of maximal inspiratory pressure (Pimax) together with ventilation were increased in CHF patients ($p < 0.01$ and $p < 0.005$, respectively). The increase in ventilation was due entirely to increased respiratory frequency (*f*R) with a concurrent decrease in $PaCO_2$. Chronic dyspnea (scored with the Medical Research Council [MRC] scale) correlated ($r^2 = 0.61$; $p < 0.001$) with *f*R and $P_{0.1}$/Pimax.**

Conclusions: **In CHF patients at rest, CC is not increased, but, as a result of decreased FRC, airway closure during tidal breathing is present, promoting the maldistribution of ventilation, ventilation-perfusion mismatch, and impaired gas exchange. The ventilation is increased as result of increased *f*R, and Pimax is decreased with a concurrent increase in $P_{0.1}$, implying that there is a proportionately greater inspiratory effort per breath ($P_{0.1}$/Pimax). These, together with the increased *f*R, are the only significant contributors to increases in the MRC dyspnea score.**

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Key words: closing volume; hypocapnia; hypoxemia; maximal inspiratory pressure; peripheral airway closure

Abbreviations: CC = closing capacity; CHF = chronic heart failure; CV = closing volume; DLCO = diffusing capacity of the lung for carbon monoxide; ERS = European Respiratory Society; ERV = expiratory reserve volume; FL = expiratory flow limitation; *f*R = respiratory frequency; FRC = functional residual capacity; MRC = Medical Research Council; ΔN2 = alveolar plateau slope; NEP = negative expiratory pressure; $P(A\text{-}a)O_2$ = alveolar-arterial oxygen pressure difference; Pimax = maximal inspiratory pressure; $P_{0.1}$ = mouth occlusion pressure 100 ms after onset of inspiratory effort; Raw = airway resistance; RV = residual volume; sGaw = specific airway conductance; sPAP = systolic pulmonary artery pressure; TI = inspiratory time; TLC = total lung capacity; TTOT = total respiratory time; VA = alveolar volume; VC = vital capacity; VE = minute ventilation; VT = tidal volume

Collins et al[1] reported that the ratio of closing volume (CV) to vital capacity (VC) was increased in patients with chronic heart failure (CHF), and suggested that pulmonary congestion and edema promote peripheral airway closure. This is in line with the study by Hughes and Rosenzweig,[2] who showed that in isolated perfused dog lungs the volume of trapped gas increased with increased lung water and was greater in the more dependent parts of the lung in which interstitial pulmonary edema

was most prominent on histologic examination. They postulated that enhanced air trapping was caused by premature peripheral airway closure due to the presence of cuffs of edema fluid in the loose connective tissue around the extraalveolar peripheral airways before there was any significant change in alveolar wall thickness. An increase in the CV/VC ratio, however, can be due to an increase in CV and/or a decrease in VC. Clearly, the notion that pulmonary congestion and edema promote peripheral airway closure requires validation by the direct assessment of closing capacity (CC), as follows: CC = residual volume (RV) + CV. Collins et al[1] also reported that in CHF patients CV exceed the expiratory reserve volume (ERV), implying that the opening and closure of the peripheral airway is present during tidal breathing. Furthermore, they suggested that the ensuing maldistribution of ventilation should lead to impaired gas exchange within the lung, but they did not measure blood gas levels.

Accordingly, in seated CHF patients and control subjects we assessed the following: (1) the magnitude of CC; and (2) the presence or absence of flow limitation (FL) and airway closure during tidal breathing. Measurements include spirometry, body plethysmography, blood gases, and control of breathing.

Materials and Methods

Patients

The study was carried out in 20 stable ambulatory patients (18 men) with congestive heart failure due to cardiomyopathy (6 after ischemia) without pleural effusions. None had been hospitalized within 20 days preceding the study. None were current smokers, but nine patients were ex-smokers. All patients received therapy with diuretics (carvedilol, 15 patients; digitalis, 9 patients; oral anticoagulant therapy [dicumarol], 7 patients; and dobutamine IV, 1 patient). Within 1 month prior to entering our study, Weber class was determined by cardiopulmonary exercise testing[3]: Weber class B, 7 patients; Weber class C, 10 patients; and Weber class D, 3 patients. Heart failure was defined as symptomatic left ventricular dysfunction, with a left ejection fraction of < 0.45 documented by bidimensional echocardiography. Patients were excluded if they had primary pulmonary, neurologic, or myopathic disease. The echocardiographic ejection fraction and systolic pulmonary artery pressure (sPAP) were measured within the 2 weeks preceding entry into our study. The mean ejection fraction was 23% (range, 9 to 34%) [Table 1]. Twenty healthy subjects (control subjects) who were matched for sex and age were also studied with the same protocol as for the CHF patients. All control subjects were nonsmokers, but nine patients were ex-smokers (Table 1). The study was approved by the local ethics committee, and informed consent was obtained from each subject.

Experimental Protocol

Chronic dyspnea was scored using the modified Medical Research Council (MRC) scale based on six increasing grades (0 to 5).[4] Dyspnea at rest was measured by a modified Borg scale, ranking magnitude from 0 (none) to 10 (maximal).[5]

Each patient underwent a spirometric, plethysmographic, and pulmonary diffusion (*ie*, diffusing capacity of the lung for carbon monoxide [DLCO]) study in the sitting position. Using a plethysmograph (Autobox 2800; SensorMedics; Yorba Linda, CA), airway resistance (Raw) was measured at a panting frequency of < 1 Hz. Spirometric and plethysmographic volumes were assessed according to European Respiratory Society (ERS).[6] DLCO was measured with a water-sealed spirometer (Biomedin; Padua, Italy) using helium for the measurement of alveolar volume

Table 1—*Anthropometric Characteristics and Baseline Respiratory Data in a Seated Position in CHF Patients and Control Group

Variables	CHF Patients (n = 20)	Control Subjects (n = 20)	p Value
Sex, No.			
Male	18	18	
Female	2	2	
Age, yr	59 ± 11	59 ± 11	NS
BMI, kg/m^2	26 ± 3	23 ± 8	NS
Smoking status			
Nonsmokers	11	11	
Ex-smokers	9	9	
Ejection fraction, %	23 ± 8		
sPAP, mm Hg	46 ± 18		
FVC, % predicted	82 ± 18	103 ± 11	< 0.001
VC, % predicted	80 ± 17	103 ± 12	< 0.001
FEV_1, % predicted	82 ± 19	105 ± 11	< 0.001
FEV_1/FVC ratio, % predicted	102 ± 7	105 ± 7	NS
FEF_{75}, % predicted	51 ± 24	78 ± 23	< 0.001
TLC, % predicted	81 ± 15	97 ± 7	< 0.001
FRC, % predicted	78 ± 12	93 ± 13	< 0.001
IC, % predicted	84 ± 20	103 ± 13	< 0.001
ERV, % predicted	56 ± 23	103 ± 13	< 0.001
RV, % predicted	88 ± 17	93 ± 11	NS
RV/TLC ratio, % predicted	109 ± 17	96 ± 12	NS
DLCO, % predicted	69 ± 21	94 ± 11	< 0.001
DLCO/VA ratio, % predicted	90 ± 23	103 ± 18	NS
Raw, % predicted	116 ± 46	105 ± 36	NS
sGaw, % predicted	100 ± 37	96 ± 23	NS
MRC score	2.2 ± 1	0	
Borg score	0.5 ± 0.7	0	

*Values are given as mean ± SD, unless otherwise indicated. BMI = body mass index; FEF_{75} = forced expiratory flow when 75% of FVC has been exhaled; IC = inspiratory capacity; NS = not significant.

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(VA).[6] Predicted values of Raw were from Peslin,[7] and those for DLCO were from the ERS.[6] With the patient in the sitting position, arterial P_{O_2} and P_{CO_2} were measured (ABL 735; Radiometer; Copenhagen, Denmark).

Breathing pattern and mouth occlusion pressure 100 ms after onset of inspiratory effort ($P_{0.1}$),[8] maximal inspiratory pressure (PImax),[9] CV, CC, and alveolar plateau slope (ΔN_2)[10] were measured (VMAX 229; SensorMedics), as previously described. The PImax was measured at RV according to American Thoracic Society/ERS criteria[9] with predicted values obtained from Black and Hyatt.[11]

The CV and ΔN_2 were measured in triplicate by a single-breath N_2 test[11] with the mean taken as the final value. The CV was expressed in liters or as the percentage of VC measured during the single-breath exhalation. By adding RV to CV, the CC (in liters) was obtained and was also expressed as the percentage of total lung capacity (TLC) [*ie*, CC/TLC ratio]. Predicted CV/VC and CC/TLC ratios were obtained from Buist and Ross.[12] From these predicted ratios, the predicted values of CV and CC (in liters) were computed using predicted values of VC and TLC,[6] respectively.

Tidal FL was assessed with the negative expiratory pressure (NEP) technique.[13] A NEP of −5 cm H_2O was applied (Direc/NEP System 200A; Raytech Instruments; Vancouver, BC, Canada) 0.2 s after the onset of expiration. Flow-volume curves obtained without and with NEP were superimposed; patients in whom the expiratory flow with NEP was the same as the reference flow during part of the whole expiration were considered to have FL.[13]

The alveolar oxygen tension used to compute the alveolar-arterial oxygen pressure difference ($P[A\text{-}a]O_2$) was estimated using the following equation: alveolar oxygen tension = $([PB - 47) \times F_{IO_2}]) - P_{aCO_2}/R$, where PB is barometric pressure, F_{IO_2} is the fractional O_2 concentration of inspired air, and R is the respiratory quotient, which was assumed to be 0.8.

Statistical Analysis

The data are presented as mean ± SD. Correlation coefficients were obtained with the Spearman (ρ) nonparametric test for MRC score and the Pearson test (*r*) for all other parameters. In a stepwise multivariate analysis, we also used the Pearson multiple correlation for determining the MRC score because the Poisson fit was almost identical to that obtained with the Pearson correlation. Where appropriate, paired and unpaired Student *t* tests were used. Statistical analysis was performed using a statistical software package (SPSS Statistical Package; SPSS; Chicago, IL).

RESULTS

Table 1 provides the anthropometric characteristics and baseline respiratory data for control subjects and CHF patients. In the control subjects, all baseline respiratory data were within normal limits; the MRC and Borg scores were zero, while the CHF patients exhibited slightly higher levels of MRC and Borg dyspnea scores.

In CHF patients, the FEV_1/FVC ratio was within normal limits, while TLC and its subdivisions were reduced. This is also shown in Figure 1, where, for comparative purposes, volumes are expressed as the percentage of the predicted TLC.[14]

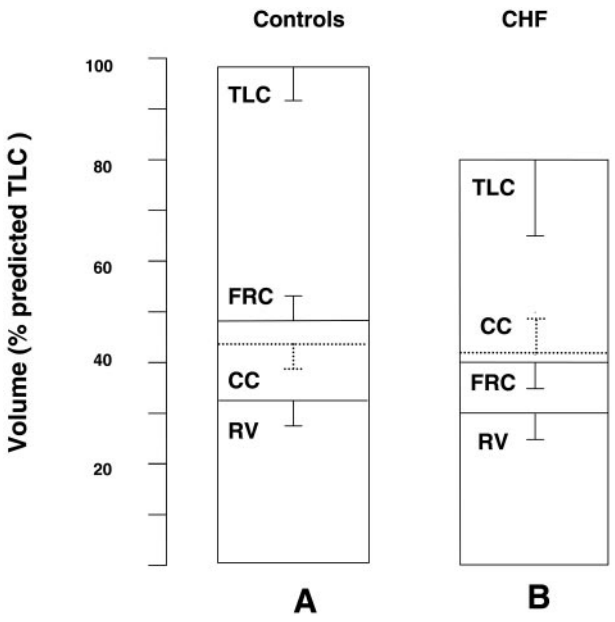

FIGURE 1. Lung volumes expressed as a percentage of the predicted TLC. *Left*, *A*: control subjects. *Right*, *B*: observed values in CHF patients. Values are given as mean ± SD (bars).

There were no significant differences in lung function between nonsmokers and ex-smokers in both CHF patients and control subjects, except for RV (percent predicted), which in control subjects was significantly ($p < 0.05$) lower in nonsmokers than in ex-smokers (Table 2).

The increased Raw and decreased DLCO levels in CHF patients were probably due mainly to the reduced functional residual capacity (FRC) because the specific airway conductance (sGaw) and DLCO/VA ratio values were in the normal range. None of the CHF patients or control subjects exhibited tidal FL.

The ΔN_2 and CV/VC ratio were increased in CHF patients relative to control subjects (Table 3). The increase in the CV/VC ratio was due entirely to decreased VC because there was no significant difference in CV between CHF patients and control subjects.

Also, no significant difference was found in CC, expressed both in liters and percent predicted. In fact, the CC was, on average, actually lower in CHF patients than in control subjects, although not significantly. This is also seen in Figure 1, which also shows that in CHF patients the CC was, on average, higher than FRC (CC was greater than FRC in 13 of the 20 CHF patients). In contrast, in all 20 control subjects CC was lower than FRC. In both CHF patients and control subjects, the CC percent predicted did not differ significantly between nonsmokers and ex-smokers (Table 2).

Table 2—*Respiratory Data of All CHF Patients and Control Subjects, Stratified in Nonsmokers and Ex-smokers

Variables	CHF Patients		Control Subjects	
	Ex-Smokers (n = 9)	Nonsmokers (n = 11)	Ex-Smokers (n = 9)	Nonsmokers (n = 11)
TLC, % predicted	83 ± 16	80 ± 15	94 ± 5	100 ± 8
FRC, % predicted	80 ± 13	75 ± 12	94 ± 10	92 ± 15
RV, % predicted	89 ± 17	86 ± 18	98 ± 8	87 ± 11†
FEV_1, % predicted	84 ± 20	80 ± 20	98 ± 9	111 ± 9
FEV_1/FVC, % predicted	102 ± 7	101 ± 7	107 ± 7	102 ± 8
FEF_{75}, % predicted	47 ± 18	53 ± 30	76 ± 26	80 ± 21
CC, % predicted	95 ± 16	94 ± 23	102 ± 8	98 ± 12
$P(A\text{-}a)O_2$, kPa	4.1 ± 1.5	4.5 ± 1.0	2.9 ± 0.6	2.6 ± 0.5

*Values are given as mean ± SD. See Table 1 for abbreviation not used in the text.
†$p < 0.05$ ex-smokers vs nonsmokers.

Resting ventilation and $P_{0.1}$ were higher in CHF patients than in control subjects (Table 4), with the increase of minute ventilation ($\dot{V}E$) resulting from increased respiratory frequency (fR). While the tidal volume (VT)/inspiratory time (TI) ratio was significantly higher in CHF patients (reflecting the higher $P_{0.1}$), TI/total breathing cycle time (TTOT) ratio was the same in CHF patients and control subjects. The $P_{0.1}$/PImax ratio (percentage) was, on average, more than twice as large in CHF patients as in control subjects, reflecting in part the increased $P_{0.1}$ and in part the decreased PImax.

As a result of the increased $\dot{V}E$, the $PaCO_2$ was lower in CHF patients than in control subjects.[15,16] The PaO_2 was also significantly lower in CHF patients than in control subjects, while the $P(A\text{-}a)O_2$ was increased, reflecting the fact that in most of our CHF patients (13 of 20) the CC was higher than the FRC. This implies opening and closing of peripheral airway closure during tidal breathing with maldistribution of ventilation and impaired gas exchange, as reflected by the increased $P(A\text{-}a)O_2$. In control subjects, $P(A\text{-}a)O_2$ correlated best with age ($r = 0.65$; $p < 0.002$), while in CHF patients it did not correlate with age but with sPAP ($r = 0.49$; $p < 0.03$).

Significant correlations were found for MRC score with PImax, $P_{0.1}$/PImax ratio, fR, and $PaCO_2$. However, according to stepwise multivariate regression analysis, the only significant independent predictors of MRC score were fR (in breaths/min) and $P_{0.1}$/PImax ratio (percentage):

$$MRC = 0.08 + 0.08\,fR + 0.14\,P_{0.1}/PImax$$

where $r = 0.78$, $r^2 = 0.61$, and $p < 0.001$.

Table 3—*ΔN_2, CV, and CC in CHF Patients and Control Subjects

Variables	CHF Patients (n = 20)	Control Subjects (n = 20)	p Value
ΔN_2			
$\%N_2$/L	3.8 + 2.7	1.8 + 1.3	< 0.005
%predicted	270 ± 151	121 ± 48	< 0.001
CV			
L	0.71 ± 0.25	0.72 ± 0.16	NS
% predicted	83 ± 24	89 ± 22	NS
CV/VC ratio			
%	24 ± 5	19 ± 5	< 0.002
% predicted	115 ± 28	89 ± 29	< 0.002
CC			
L	2.70 ± 0.71	2.83 ± 0.39	NS
% predicted	94 ± 20	100 ± 10	NS

*Values are given as the mean ± SD. See Table 1 for abbreviation not used in the text.

Discussion

The new findings of this study are that in CHF patients at rest (mostly in Weber class B and C), the

Table 4—*Control of Breathing Data and Blood Gases in CHF Patients and Control Subjects

Variables	CHF Patients	Control Subjects	p Value
$\dot{V}E$, L/min	12.9 ± 5.0	10.2 ± 2.7	< 0.005
VT, L	0.72 ± 0.23	0.72 ± 0.18	NS
f_R, min	17.9 ± 5.1	14.2 ± 4.0	< 0.02
VT/TI ratio, L/s	0.55 ± 0.17	0.40 ± 0.13	< 0.003
TI/TTOT ratio	0.41 ± 0.04	0.41 ± 0.04	NS
PImax			
cm H_2O	69 ± 30	87 ± 23	< 0.05
% predicted	65 ± 28	80 ± 17	< 0.05
$P_{0.1}$, cm H_2O	2.8 ± 1.1	2.0 ± 0.4	< 0.005
$P_{0.1}$/PImax ratio, %	5.3 ± 4.2	2.5 ± 0.9	< 0.01
PaO_2, kPa	10.7 ± 1.4	12.0 ± 0.4	< 0.001
$PaCO_2$, kPa	4.9 ± 0.4	5.2 ± 0.3	< 0.03
$P(A\text{-}a)O_2$, kPa	4.3 ± 1.2	2.7 ± 0.5	< 0.001
pH	7.44 ± 0.03	7.40 ± 0.03	< 0.001
Borg score	0.5 ± 0.7	0	
FL/NFL ratio	0/20	0/20	
CC > FRC	13/20	0/20	

*Values are given as the mean ± SD, unless otherwise indicated. NFL = patients without tidal expiratory FL. See Table 1 for abbreviation not used in the text.

following conditions prevail: (1) CC is not increased; (2) as a result of decreased FRC, however, airway closure with compromised pulmonary gas exchange is present during tidal breathing; (3) tidal FL is absent; (4) ventilation is increased as a result of increased *f*R with a concurrent decrease in $PaCO_2$; and (5) PImax is decreased. Together with the concurrent increase in $P_{0.1}$, this implies a proportionately greater inspiratory effort per breath ($P_{0.1}$/PImax ratio). These, together with the increased *f*R, are the only significant contributors to the MRC dyspnea score.

Lung Volumes

In line with the results of most previous reports,[1,14,17] our patients exhibited a reduction in TLC and FRC but normal FEV_1/FVC ratio. In contrast, Yap et al[14] found a significant reduction in TLC but not in FRC. Their patients, however, were studied just after a period of acute decompensation, which may be associated with the presence of FL and dynamic hyperinflation with the patient in the sitting position.[18] Hart et al[19] found no reduction of either TLC or FRC in 10 CHF patients; half of their patients, however, had CHF due to coronary artery disease. In the present study, only 30% of the patients (6 of 20) had a history of coronary artery disease. The reduction of FRC (gas), which in our patients averaged 11% of the predicted TLC (Fig 1), was probably mainly due to space competition of gas with solids and/or liquids (*eg*, cardiomegaly, congestion, or interstitial edema). Assuming an equal elastance of the lung and chest wall at FRC, the chest wall volume should have also increased by 11% of the predicted TLC (*ie*, an amount equal to the reduction of FRC [gas]).[20] However, TLC was reduced more than FRC, namely, 19% of the predicted TLC. This probably reflects the PImax decrease due to (1) chest wall expansion by an increased volume of the heart and blood, (2) an intrinsic weakness of the inspiratory muscles, and (3) increased elastic lung recoil pressure due to pulmonary congestion[21,22] and/or fibrosis.[23] A decrease in the force of skeletal muscles (including inspiratory muscles) has been documented in CHF patients by many authors.[17,24–26] Other functional abnormalities, such as the increased Raw shown in Table 1, probably mainly reflect the reduced thoracic gas volume in CHF patients. Indeed, while the Raw was abnormal, sGaw was within normal limits.

CC and Gas Exchange

In CHF patients, Collins et al[1] found an increased CV/VC ratio relative to normal control subjects and, in line with the results of previous studies,[21,23] suggested that pulmonary congestion and edema promote the premature closure of peripheral airways. In our CHF patients, the CV/VC ratio was also significantly increased, but the CV was not abnormal. This implies that the increase in CV/VC ratio was due entirely to decreased VC. There also was no significant difference in CC between CHF patients and control subjects, indicating that in our CHF patients there was "no premature airway closure." In fact, in CHF patients the CC was actually smaller than that in control subjects, although not significantly. This may reflect the fact that pulmonary fibrosis[23] and/or vascular engorgement[21,22] may render the peripheral airways more resistant to collapse. In line with the findings of Collins et al,[1] however, in most of our patients (13 of 20) the CC exceeded the FRC (*ie*, during tidal breathing there was cyclic opening and closing of peripheral airways with a concurrent maldistribution of ventilation and a risk of mechanical injury to the peripheral airways).[27] As a result of this maldistribution of ventilation, PaO_2 decreased and $P(A\text{-}a)O_2$ increased (Table 4).

The ΔN_2 was increased in CHF patients, providing further evidence for the presence of pulmonary mixing inhomogeneity. It is not clear whether the increased ΔN_2 resulted from the enhancement of the gravity-dependent inhomogeneity within the lung or was an expression of the local differences in elastic properties of the alveolar walls.[11] In CHF patients with chronic pulmonary hypertension and edema, the pulmonary capillary and tissue membranes undergo remodeling, which may result in changes in elastic properties.[22] The remodeling at the level of alveolar-capillary membranes could also contribute to decreased DLCO (Table 1). In fact, in CHF patients there is a reduced alveolar-capillary diffusion transfer, which is inversely related to pulmonary vascular resistance.[28] This may explain the fact that in our CHF patients the values of DLCO normalized for VA (and DLCO/VA ratio) remained significantly lower than those in the control subjects.

Ventilation and Breathing Pattern

In line with previous reports,[15–17] $\dot{V}E$ was increased in CHF patients with a concurrent decrease in $PaCO_2$. The increase in $\dot{V}E$ was due entirely to increased *f*R since the VT was the same in CHF patients and control subjects.

In line with the findings of Ambrosino et al[17] the TI/TTOT ratio was the same in CHF patients as in control subjects, whereas the inspiratory drive, as reflected by $P_{0.1}$ and the VT/TI ratio, was significantly higher in CHF patients. The mechanisms for the increased inspiratory drive in CHF patients are poorly understood. It is of interest, however, to note

that, despite the increased $P_{0.1}$ and VT/TI ratio and the decreased PImax, the CHF patients exhibited a normal VT at rest. In CHF patients, lung compliance is decreased due to congestion or fibrosis,[21–23] and, under these conditions, the respiratory muscles usually try to conserve energy by decreasing VT and increasing *f*R. A possible explanation for the finding of increased central drive without a decrease in the VT would be the difference in operational length compensation of the diaphragm.[29] Patients with CHF have smaller lungs and longer resting length of their diaphragms, which results in greater force generation for the same output during quiet breathing.[29] This implies greater inspiratory effort with weaker inspiratory muscles, leading to an increased Borg dyspnea score at rest.

Dyspnea

The resting values of $P_{0.1}$/PImax ratio and *f*R were also the only significant predictors of the level of MRC dyspnea. In fact, the $P_{0.1}$/PImax ratio (percentage) and the *f*R explained 61% of the variance in MRC score. This suggests that the increased inspiratory load and effort, as implied by higher than normal values for the $P_{0.1}$/PImax ratio and *f*R, is a cause of dyspnea in CHF patients.

Several studies in CHF patients[30–32] have failed to demonstrate a direct relationship between dyspnea and cardiac function data such as pulmonary capillary wedge pressure. In the present study, neither MRC dyspnea score nor Borg dyspnea score at rest correlate with sPAP and ejection fraction. On the other hand, some previous studies[19,32,33] have suggested increased inspiratory muscle load relative to inspiratory muscle capacity as a cause of dyspnea and exercise intolerance. Furthermore, McParland et al[25] reported that in CHF patients PImax as well as maximal expiratory pressure were reduced, both being significantly correlated with dyspnea during daily activities. The present results support the notion that inspiratory force and loading play a significant role in eliciting dyspnea, as shown by the significant relationship of the level of MRC score and the resting values of $P_{0.1}$/PImax ratio (percentage) and *f*R (equation 1). However, the relationship of these resting measurements to the mechanisms of dyspnea during exercise remains to be elucidated in CHF patients.

The absence of FL with the patient in the seated position is not surprising in CHF patients. FL was found in a small percentage of seated patients with acute heart failure.[18,34] In contrast, FL is frequently observed in patients in the supine position, which is correlated to orthopnea and can be reversed by therapy.[34] The ERV reduction secondary to FRC reduction (because of cardiomegaly and vascular engorgement) can decrease ERV predisposing the patient to FL. In CHF patients, cardiac diameters and vascular engorgement would be smaller than in patients with acute heart failure, and this factor could explain why none of our CHF patients had FL in a sitting position.

In conclusion, the present results show that in CHF patients, relative to control subjects, the CC does not change while FRC decreases. Due to the decrease of FRC, most patients exhibit airway closure during tidal breathing with maldistribution of ventilation and impaired gas exchange within the lung (decreased $PaCO_2$ and increased $P[A\text{-}a]O_2$). The impaired gas exchange is partly compensated by increased pulmonary ventilation, which is associated with increased inspiratory effort due to *f*R. Since PImax is reduced, the association of increased inspiratory effort in the face of decreased potential force may explain the fact that CHF patients complain of dyspnea at rest (Borg score) and also exhibit chronic dyspnea (MRC score).

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