

Acute Left Ventricular Dysfunction during Unsuccessful Weaning from Mechanical Ventilation

Francois Lemaire, M.D.,* Jean-Louis Teboul, M.D.,† Luc Cinotti, M.D.,‡ Guillen Giotto, M.D.,§
Fekri Abrouk, M.D.,§ Gabriel Steg, M.D.,§ Isabelle Macquin-Mavier, M.D.,¶ Warren M. Zapol, M.D.**

The authors studied the hemodynamic effects of rapidly weaning from mechanical ventilation (MV) 15 patients with severe chronic obstructive pulmonary disease (COPD) and cardiovascular disease who were recovering from acute cardiopulmonary decompensation. In each patient, 10 min of spontaneous ventilation (SV) with supplemental oxygen resulted in reducing the mean esophageal pressure ($\bar{X} \pm SD$, $+5 \pm 3$ to -2 ± 2.5 mmHg, $P < .01$) and increasing cardiac index (CI) 3.2 ± 0.9 to 4.3 ± 1.3 l/min/M², $P < .001$, systemic blood pressure (BP) 77 ± 12 to 90 ± 11 mmHg, $P < .001$, heart rate (HR) 97 ± 12 to 112 ± 16 beats/min, $P < .001$, and, most importantly, transmural pulmonary artery occlusion pressure markedly increased (PAOP_{tm}) 8 ± 5 to 25 ± 13 mmHg, $P < .001$, mandating a reinstatement of MV. In four patients with left ventricular (LV) catheters, the PAOP correlated with the LV end-diastolic pressure during both MV and SV. Gated blood pool imaging showed SV increased the LV end-diastolic volume index (65 ± 24 to 83 ± 32 /M², $P < .002$) with LV ejection fraction unchanged. Patients were treated for a mean of 10 days with diuretics, resulting in a reduction of blood volume (4.55 ± 0.9 l to 3.56 ± 0.55 l) and body weight (-5 kg, $P < .001$). Subsequently, nine of the 15 patients were weaned successfully from mechanical ventilation with unchanged PAOP. (Key words: Chronic obstructive pulmonary disease. Heart: failure. Lung: respiratory failure. Ventilation, mechanical: weaning.)

This article is accompanied by an editorial. Please see: Permutt S: Circulatory effects of weaning from mechanical ventilation: The importance of transdiaphragmatic pressure. ANESTHESIOLOGY 69:157-160, 1988.

WHEN PATIENTS WITH chronic obstructive pulmonary disease (COPD) and diminished respiratory reserve are recovering from acute exacerbations of respiratory failure, they can become completely dependent on me-

* Professor of Intensive Care Medicine, Hopital Henri Mondor.

† Chief Resident Intensive Care Medicine, Hopital Henri Mondor.

‡ Consultant in Nuclear Medicine, Hopital Henri Mondor.

§ Resident in Intensive Care Medicine, Hopital Henri Mondor.

¶ Consultant in Clinical Pharmacology, Hopital Henri Mondor.

** Professor of Anesthesia, Massachusetts General Hospital.

Received from the Services de Reanimation Medicale, Medecine Nucleaire, et Pharmacologie Clinique, Hopital Henri Mondor, Universite Paris XII, France; and the Department of Anesthesia, Massachusetts General Hospital, Boston, Massachusetts. Accepted for publication January 25, 1988. Supported in part by INSERM and NHLBI Specialized Center of Research in Adult Respiratory Failure #HL23591.

Address reprint requests to Dr. Lemaire: Service de Reanimation Medicale, Hopital Henri Mondor, 94010 Creteil, France.

chanical ventilatory support, spending weeks or even months receiving ventilatory care. Disconnected from the ventilator, these patients can rapidly develop ineffective low tidal volume respiration, tachypnea, evidence of sympathetic nervous system hyperactivity (tachycardia, systemic hypertension, sweating), and, if spontaneous ventilation (SV) persists for several minutes, hypercapnea and hypoxia.¹ Such ventilatory decompensation can be induced either by discontinuing mechanical ventilation (MV) or by rapidly reducing mechanical ventilator rates during intermittent mandatory ventilation.²

During these episodes of acute ventilatory decompensation, we noted the frequent occurrence of wheezing, suggesting cardiac asthma or bronchospasm. Since many of our patients with COPD had a history of myocardial infarction and angina, as well as electrocardiogram (ECG) evidence of coronary artery disease, we suspected that acute left ventricular dysfunction might be an important impediment to weaning. Referring to studies of the interaction between the ventilatory and circulatory systems that demonstrate that reducing the intrathoracic pressures during SV can increase both left ventricular preload³ and afterload,^{4,5} we hypothesized that, in patients with previously impaired cardiac function, the hemodynamic stress produced by SV could cause acute LV dysfunction. Measurements of PAOP that would document LV failure during SV have not been reported in these patients, perhaps because, usually, they are discharged from the ICU and committed to long-term ventilation in intermediary care units.

To search for evidence of LV failure, we prospectively examined a group of patients who had resolved their acute phase of lung disease and who were difficult to wean from MV. Their inspiratory force, vital capacity, minute ventilation, and tidal volume appeared sufficient to permit sustained spontaneous ventilation^{1,6,7}; however, none of these patients could be weaned from the ventilator. Therefore, radial and pulmonary artery catheters were inserted and gated blood pool scintiscanning was performed to examine their cardiopulmonary performance during MV and SV.

Materials and Methods

Fifteen adult patients were studied in the medical Intensive Care Unit of Henri Mondor Hospital. The pa-

TABLE 1. Clinical Description of COPD Patients with Outcome

Patient	Age	Sex	Prior Cardiocirculatory Disease	Cause of ARF	Duration of MV Before Study (Weeks)	Ventilatory Outcome W/D	Hospital Survival/Death
1	64	F	Systemic hypertension*	Bacterial pneumonia	12	D	Death
2	66	M	Systemic hypertension, myocardial ischemia	Post op vascular surgery	2	D	Death
3	64	F	Cor pulmonale	Acute bronchitis	1	W	Survival
4	75	M	Cardiomyopathy*	Bacterial pneumonia	6	D	Death
5	74	M	Cor pulmonale	Bacterial pneumonia	2	W	Survival
6	71	F	Myocardial infarction*	Post-op vascular surgery	2	D	Death
7	54	M	Cor pulmonale	Bacterial pneumonia	4	W	Survival
8	73	M	Cor pulmonale	Bacterial pneumonia	4	D	Survival
9	64	M	Myocardial infarction, Cor pulmonale	Bacterial pneumonia	8	W	Survival
10	76	M	Systemic hypertension	Acute bronchitis	1	W	Survival
11	42	M	Cardiomyopathy	Acute bronchitis	1	W	Survival
12	64	M	Myocardial infarction, Cor pulmonale	Acute bronchitis	6	W	Survival
13	69	M	Cardiomyopathy Systemic hypertension	Ileus	4	W	Survival
14	72	M	Myocardial infarction	Post-op abdominal surgery	3	D	Death
15	60	F	Cor pulmonale Cardiomyopathy	Acute bronchitis	2	W	Survival

D—remained dependent upon mechanical ventilation; W = weaned from mechanical ventilation; ARF = acute respiratory failure; MV = mechanical ventilation.

* Autopsy demonstrated severe diffuse coronary atherosclerotic occlusions.

tients, their diagnoses, and other clinical information are listed in table 1. All patients had severe COPD and acute ventilatory decompensation requiring MV. Eleven suffered an acute bout of pulmonary inflammation involving increased secretion of purulent sputum, and six of these had radiographic evidence of lung consolidation. Three additional patients had acute ventilatory insufficiency following abdominal surgery and one after an ileus. The criteria for selecting patients for study were: acute exacerbation of lung disease had been resolved for several days to weeks, either the trachea had remained intubated or tracheostomy was present; the patient was receiving mechanical ventilation despite the fact that ventilatory capacities exceeded standard criteria for successful weaning^{6,7}; and the patient did not tolerate weaning from the ventilator for over 30 min on at least two trials.

In these 15 patients weighing 60 ± 11 kg ($\bar{X} \pm SD$), mean spontaneous tidal volume after 10 min of SV was 311 ± 44 ml, mean vital capacity was 986 ± 216 ml, mean inspiratory force was -30 ± 9 cm H₂O, mean minute ventilation was 7.7 ± 1.7 l/min, and mean ventilatory rate was 25 ± 7 /min. Although there are no uniformly accepted or standard criteria for weaning patients, these values lie within satisfactory ranges for successful weaning. Eight of 15 patients received bronchodilator therapy.

A diagnosis of COPD was reached after clinical investigation revealed a history of chronic bronchitis and/or emphysema, and radiographic and pulmonary function tests showed abnormalities characteristic of severe airway obstruction. Ten of the patients had pulmonary

function tests in the months prior to admission, their average vital capacity was $51 \pm 17\%$ predicted, FEV₁ $28.8 \pm 6.4\%$ predicted, and the PaCO₂ of seven was 39.6 ± 4 mmHg.

Arterial blood pressure was monitored continuously with a radial artery catheter and transducer system. A balloon flotation pulmonary artery catheter was inserted *via* an internal jugular vein to measure pulmonary artery pressure and pulmonary artery occlusion pressure (PAOP) at end expiration. Cardiac output, determined with an Edwards Model 9250A computer, was the mean of three measurements obtained by injecting 10 ml of a 0° C dextrose solution. In four patients (patients 1, 3, 5, and 8), a sterile 7 F pigtail catheter was inserted percutaneously, using the Seldinger technique, *via* a common femoral artery into the left ventricle. In these patients, we compared the PAOP with the simultaneously measured LVEDP. A fluid-filled 4 mm diameter silicone catheter was used to measure esophageal pressure (Peso)⁸ that was planimetered to obtain the mean value. To calculate end-expiratory transmural PAOP, we subtracted the instantaneous end-expiratory values of PAOP and Peso. Patients were supine during all pressure measurement and isotope studies.

ISOTOPES

Blood volume was estimated by injecting and, later, sampling autologous red blood cells labeled with ⁵¹Cr.⁹ Values reported are % predicted. Cardiac scintigraphy was carried out by *in vivo* red cell labelling using stannous pyrophosphate with 555–815 MBq of ⁹⁹Tc. Car-

diac output, measured using the Stewart-Hamilton principle during the first pass of the tracer,¹⁰ was only used to calculate stroke volume index (SVI) (cardiac index/heart rate) and ventricular volumes. All the other values in tables 2 and 3 were determined using thermodilution cardiac outputs. In four patients in whom both measurements were performed, there was no difference between thermal dilution cardiac index and nuclear determinations of cardiac index. Then, ECG-gated radionuclide angiography was performed using an equilibrium blood pool technique with a gamma camera (Model CGR Acticamera®, BAC, France; with a Simis 3 Computer) in the LAO projection optimized for ventricular separation. Right and left ventricular ejection fractions were computed by standard techniques¹¹; end-diastolic volume index (EDVI) was calculated as $EDVI = SVI/EF$.

PROTOCOL

Fifteen patients who repeatedly failed to wean from MV were identified. Informed consent was obtained from the patients and the study was approved by the Ethics Committee of the "Societe de Reanimation de Langue Francaise." Catheters were inserted and all patients underwent controlled MV with a Siemens 900C ventilator with FI_{O_2} 0.3-0.6 at a rate of 12-18 breaths/min, and tidal volume of 6-10 ml/kg without positive end-expiratory pressure (PEEP). When a stable hemodynamic state was obtained, pulmonary and systemic hemodynamic measurements and blood gas tensions were recorded (table 2, MV). Then the patient, still connected to the Siemens 900C, was allowed to spontaneously ventilate without PEEP. After 10 min, pulmonary and systemic hemodynamic values were recorded and arterial and mixed venous blood samples were obtained. If an LV catheter had been inserted, LVEDP was measured before and after 10 min of SV₁. The patient was again mechanically ventilated, and 12 of the patients were transported to the nuclear medicine department, as French government regulations prevent the use of radioisotopes outside nuclear medical facilities. Red blood cells labelled with ⁵¹Cr and ^{99m}Tc were injected. Thus, approximately 30 min after a SV hemodynamic study was completed in the intensive care unit, the heart was imaged for 10 min while the patient was being mechanically ventilated. CI, RVEF and LVEF, and end-diastolic volumes were computed. Then, a period of SV was begun again in the nuclear medicine facility, scintigraphic data collected for 10 min, and the patient returned to MV and transferred to the intensive care unit. Measures of hemodynamic events recorded on strip charts in the intensive care unit and monitored on an oscillograph in the nuclear medicine facility did not differ between these two sequential weaning epi-

TABLE 2. Hemodynamic Scintigraphic and Gas Exchange Values during Continuous Mechanical Ventilation (MV) and after 10 Min of Spontaneous Ventilation (SV₁)

	Peso	CI	HR	SVI	PAOP _{tm}	PAP _{tm}	RAP _{tm}	BP	LVEDVI	LVEF	RVEDVI	RVEF	P _{aO₂}	P _{aCO₂}	VO ₂
MV	+5 ± 3	3.2 ± 0.9	97 ± 12	34 ± 11	7.5 ± 5	24 ± 6	3 ± 5	77 ± 12	65 ± 24	54 ± 15	83 ± 33	30 ± 8	103 ± 28	42 ± 6	165 ± 41
SV	-2 ± 2.5	4.3 ± 1.3	112 ± 16	40 ± 14	24.5 ± 13	40 ± 14	15 ± 5.5	90 ± 11	83 ± 32	49 ± 13	103 ± 39	27 ± 8	74 ± 25	58 ± 10	182 ± 55
n	15	15	15	15	15	15	15	15	12	12	10	10	15	15	15
t	7.94 *	5.83 *	5.02 *	3.12 *	6.03 *	5.69 *	7.70 *	5.01 *	4.03 *	3.04 NS	5.36 *	1.65	6.50 *	8.02 *	3.21 *

Peso = esophageal pressure (mmHg); CI = cardiac index (l/min/m²); HR = heart rate (b/min); SVI = stroke volume index (ml/m²); PAOP = end-expiratory transmural pulmonary artery occluded pressure (mmHg); PAP = mean pulmonary artery pressure (mmHg); BP = blood pressure (mmHg); RAP = transmural right atrial pressure (mmHg); LVEDVI = left ventricular end diastolic volume index (ml/m²); LVEF = left ventricular ejection fraction (%); RVEDVI = right ventricular end diastolic volume index (ml/m²); RVEF = right ventricular ejection fraction (%); P_{aO₂} = arterial oxygen tension (mmHg); P_{aCO₂} = arterial carbon dioxide tension (mmHg); VO₂ = oxygen uptake (ml O₂/min/m²). * Significant at the 0.05 level.

TABLE 3. A Comparison of Hemodynamics, Gas Tensions, and Other Measurements in Patients Studied at Both SV₁ and SV₂

	Weight	Blood Volume		Peso	CI	PAOP (mm)	PAP (mm)	BP	LVEDVI	RVEDVI	PaO ₂	Paco ₂
		kg	% Predicted									
SV ₁	60 ± 11	4.55 ± 0.9	123 ± 22	-1.9 ± 2.6	4.3 ± 1.0	25 ± 15	40 ± 13	87 ± 10	89 ± 28	122 ± 37	77 ± 25	57 ± 10
SV ₂	55 ± 10	3.56 ± 0.55	102 ± 19	-3.8 ± 1.4	3.77 ± 0.7	9 ± 3	27 ± 8	88 ± 15	65 ± 20	103 ± 41	83 ± 26	50 ± 6
n	12	8	8	8	8	8	8	8	8	5	12	8
t	6.49	2.87	2.33	NS	1.24	3.67	2.55	0.21	2.47	1.16	0.012	2.23
P	*		NS	NS	NS	*	NS	NS	NS	NS	NS	NS

Peso = esophageal pressure (mmHg); CI = cardiac index (l/min/m²); PAOP = transmural end-expiratory pulmonary artery excluded pressure (mmHg); PAP = mean transmural pulmonary artery pressure (mmHg); BP = blood pressure (mmHg); LVEDVI = left ventricular end-diastolic volume index (ml/m²); RVEDVI = right ventricular end-diastolic

volume index (ml/m²); PaO₂ = arterial oxygen tension (mmHg); Paco₂ = arterial carbon dioxide tension (mmHg); NS = not significant.

* Significant at the simultaneous 0.05 level.

sodes; values from the strip-chart recordings are reported in this manuscript.

Patients were then treated with controlled mechanical ventilation supplemented by intravenous furosemide (80 mg/day). They received feedings of 2000 kcal per day, orally or *via* a naso-gastric tube. Nine patients eventually weaned from MV to SV and were discharged; about 1 week after the first study, eight of these underwent repeat radial and pulmonary artery catheterization and scintigraphic and blood volume studies after weaning (SV₂). One patient (patient 8) was discharged from the hospital requiring mechanical ventilation and died 5 months later. Five patients died from heart failure, pneumonia, and infection while still in the hospital; autopsies were performed on three, and each demonstrated extensive coronary atherosclerosis (table 1).

CATECHOLAMINES

Blood samples were obtained from eight patients for analysis of the levels of epinephrine and norepinephrine before and 10 min after weaning (SV₁). Catecholamines were measured by the enzymatic methods of Brown and Jenner.¹² In our laboratory, the coefficients of variation of the measurements were 3.1% for norepinephrine and 3.3% for epinephrine. Sensitivity was 1.5 pg/ml for both norepinephrine and epinephrine.

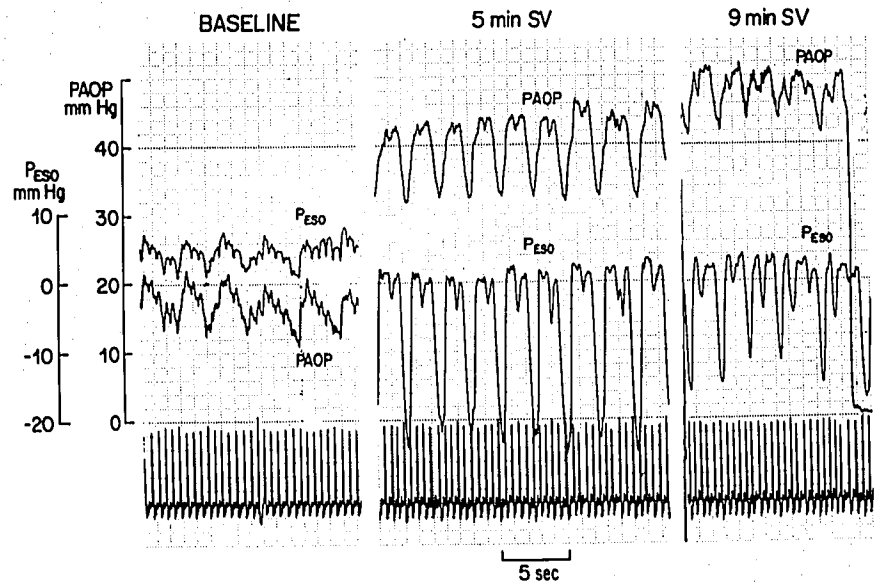
STATISTICAL ANALYSIS

Multiple paired *t* tests were used to compare data during MV and SV. Significance was judged according to Bonferroni's inequality, using a (simultaneous) significance level of 0.05; *i.e.*, 0.05 was divided by the number of comparisons to obtain the significance level that an individual *P* value must satisfy to achieve significance.¹³

Results

The most important finding of our study was that after 10 minutes of SV₁, transmural end-expiratory PAOP had increased from 8 to 25 mmHg (*P* < .001; table 2; fig. 1). In every patient, there was a progressive increase of PAOP, with seven patients showing a marked increase above 20 mmHg (four of seven are included in figure 2). SV was usually accompanied by wheezing and always associated with dyspnea, tachypnea, and progressive ventilatory failure with CO₂ retention, requiring re-institution of mechanical ventilation. In the four patients in whom the LVEDP was measured and compared with end-expiratory PAOP during MV and SV, both pressures were within a few mmHg (fig. 3).

FIG. 1. Weaning of patient 6 from mechanical ventilation (baseline) to spontaneous ventilation (SV₁). There is a progressive increase of pulmonary artery occlusion pressure (PAOP) from 14 mmHg (baseline) to 50 mmHg (9 min SV). The esophageal pressure is reduced during SV with marked negative inspiratory excursions.

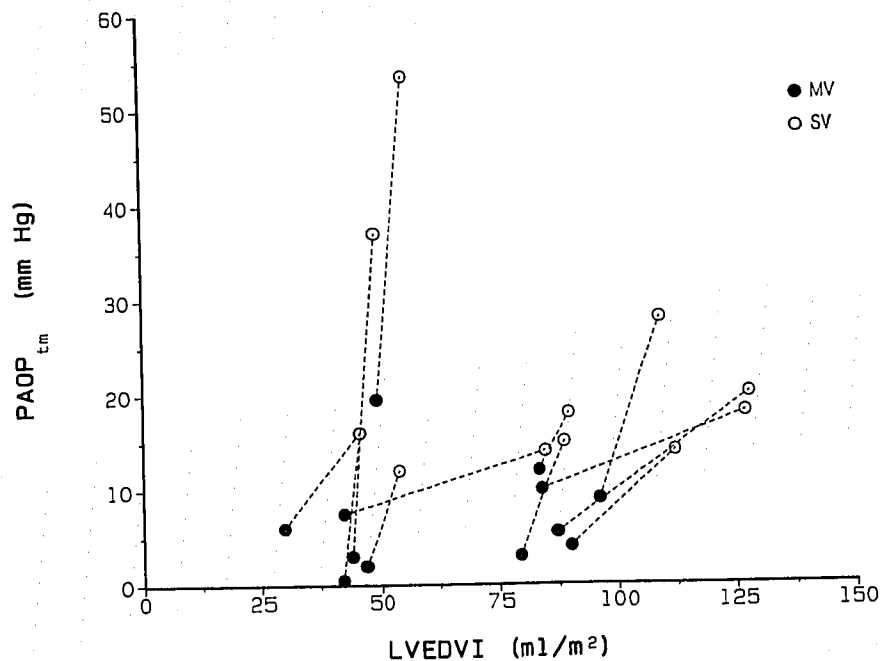


After 10 min of SV₁, esophageal pressure was reduced while cardiac index, heart rate, and central venous, pulmonary, and systemic arterial blood pressures were increased. Although the heart rate increased, the lead II ECG was unchanged. Scintigraphic studies showed the LVEDVI and RVEDVI were increased ($P < .002$), while LVEF and RVEF were unchanged. During SV₁, eight of the 12 patients (patients 1, 3, 5, 6, 8, 10, 11, and 12) had a marked increase of PAOP_{tm} with only a small increase of LVEDVI (fig. 2). Three patients (patients 1, 3, and 9) had scintigraphic

evidence of abnormal LV wall motion during MV which became more severe during SV₁ (for an example, see figure 4A).

There was evidence of acute ventilatory failure during the 10 min of SV₁ (table 2). The PaCO₂ rose from 42 to 58 mmHg ($P < .001$) and the pH decreased from 7.44 ± 0.04 to $7.32 \pm .06$. Since the FI_{O₂} during SV₁ was 0.3–0.6, only one patient (patient 6) had a PaO₂ below 50 mmHg during weaning. However, the mean measured arterial oxygen saturation (SaO₂) decreased from $97 \pm 2\%$ to $84 \pm 15\%$ during SV₁. These mea-

FIG. 2. Changes of transmural pulmonary artery occlusion pressure (PAOP_{tm}) and left ventricular end diastolic volume (LVEDVI) during the transfer from mechanical ventilation (MV) to spontaneous ventilation (SV₁) in 12 patients.



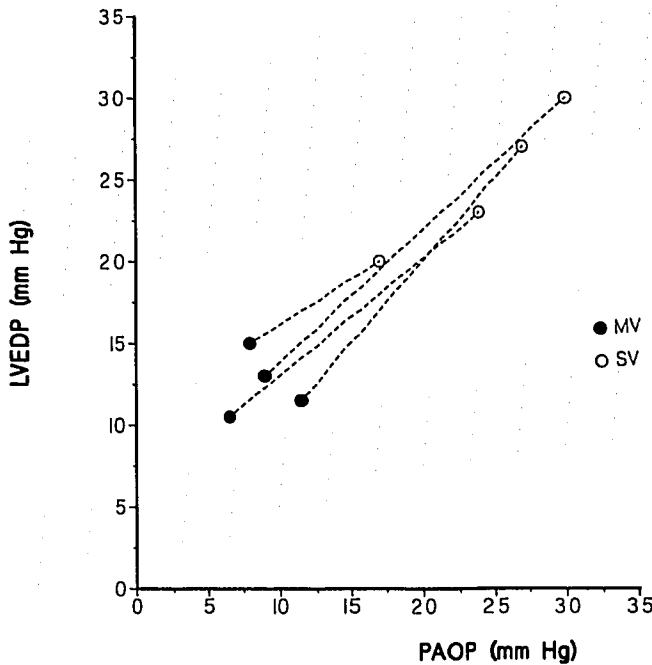


FIG. 3. Correlation between left ventricular end diastolic pressure (LVEDP) and pulmonary artery occluded pressure (PAOP) in four patients during mechanical ventilation (MV) and spontaneous breathing (SV).

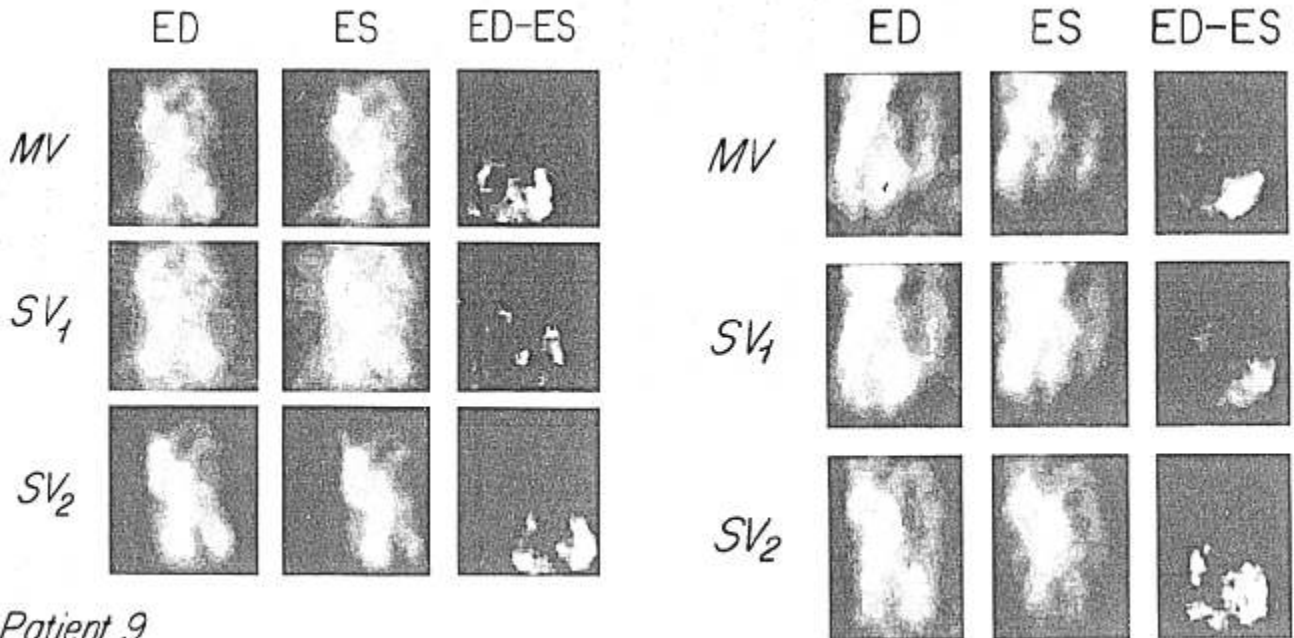
measurements returned rapidly to the prior control values when the patients were returned to mechanical ventilation.

The mean plasma norepinephrine levels increased from 1.13 ± 0.55 ng/ml (MV) to 1.85 ± 0.96 ng/ml (SV₁) ($P < .02$) and epinephrine increased from 0.10 ± 0.05 ng/ml (MV) to 0.20 ± 0.13 ng/ml (SV₁) ($P < 0.04$).

One week later, eight of the patients underwent repeat hemodynamic study (SV₂) after successful therapy and weaning from mechanical ventilation. At SV₂, measurements of tidal volume, respiratory rate, minute ventilation, and inspiratory force were not different than the values measured at the commencement of SV₁. The SV₂ data listed in table 3 shows mean body weight reduced by 5 kg ($P < .001$) and blood volume decreased from $123 \pm 22\%$ (SV₁) to $102 \pm 19\%$ (SV₂) of the predicted value. At the time of restudy (SV₂), the PAOP_{tm} was maintained at 9 ± 3 mmHg and did not increase.

Discussion

Our study shows that left ventricular filling pressure can increase markedly when weaning from mechanical ventilation is attempted in COPD patients with pre-ex-



A Patient 9

B Patient 2

FIG. 4. Cardiac scintiscans during mechanical ventilation (MV) and 30 min later during a period of spontaneous ventilation (SV₁), and a follow-up study after 10 days of therapy during spontaneous ventilation (SV₂). Images are presented at end diastole (ED) and end systole (ES), with the subtraction image (ED-ES) to provide an estimate of wall motion.

A. Patient 9: Compared with MV during SV₁, there is increased end-diastolic and end-systolic biventricular activity with markedly reduced left ventricular (LV) wall motion. After therapy, the SV₂ cardiac image is similar to MV, the ventricles are not enlarged, and there is good LV wall motion. B. Patient 2: In comparison to MV during SV₁, there is increased end-diastolic and end-systolic biventricular activity with evidence of maintained left ventricular wall motion. After therapy, the SV₂ cardiac image is similar to MV, the ventricles are not enlarged, and there is good LV wall motion.

isting heart disease. After 10 min of SV₁, the mean transmural pulmonary artery occlusion pressure increased from 7.5 mmHg to 24.5 mmHg. The PAOP_{tm} increase was progressive and, in seven patients, rose above 20 mmHg. Often, by 5 min of SV₁, the PAOP had increased (fig. 1), but we did not study this systematically. Simultaneously acute respiratory failure occurred, with the mean PaCO₂ increasing 16 mmHg. Our studies cannot dissociate cause from effect, since, by 10 min of SV₁, both acute cardiac and respiratory dysfunction co-existed.

The key event in changing from MV to SV is the shift from a positive intrathoracic pressure to a negative pleural pressure generated by the respiratory muscles. During MV, the mean esophageal pressure, at 5 mmHg (table 2), was probably elevated by the retarded expiratory flow of these COPD patients.^{14,15} During SV₁, the mean esophageal pressure was reduced to -2 mmHg and there were large negative inspiratory excursions (e.g., -20 mmHg; fig. 1). These large negative esophageal pressures may be caused by bronchoconstriction during weaning¹⁶ and augmented by the inspiratory airflow resistance of tracheal tubes and the demand valves of mechanical ventilators. Large negative inspiratory pressures could also be due to reductions of static lung compliance, but this is unlikely in COPD patients without alveolar edema or bacterial pneumonia. To minimize demand valve resistance, we selected the Servo 900 C, a ventilator adding minimal inspiratory resistance.¹⁷ In several of these COPD patients, when briefly breathing through a T piece, we measured similar values of Pes suggesting that the major portion of their airway resistance resided in their airways and endotracheal tube. When patients hyperinflated during spontaneous ventilation, large negative distending pressures were required to generate adequate tidal volumes, and Pes decreased.

Reducing intra-thoracic pressure during SV₁ augments venous return, CI, right and left ventricular filling pressures, and end-diastolic volumes of COPD patients (table 2). Studying patient groups with different diseases, others have documented similar but smaller changes accompanying a change from MV to SV.^{2,††}

PAOP increased in each patient during SV₁ (table 4). We have obtained evidence in four patients that the PAOP closely reflects the LVEDP during MV and SV (fig. 3); Lockhardt *et al.* has reported a similar correspondence of pressures in five patients with COPD during exercise.¹⁸ Many of our patients studied with a

TABLE 4. Factors Increasing PAOP during Unsuccessful Weaning from MV

1. Increased Preload
Increased venous return
• Decreased pleural pressure
• Sympathetic discharge (stress, hypercapnia)
Reduced LV compliance
• Myocardial ischemia
O ₂ Supply reduced
↓PaO ₂ , ↓SaO ₂
↑LVEDP and ↑HR, reducing coronary blood flow
O ₂ Demand increased
↑Catecholamines
↑HR, ↑Systolic BP
↑Work of breathing
• LV Enlargement
• RV Enlargement (ventricular interdependence)
• Compression of heart chambers by regionally hyperinflated lung
2. Reduced Contractility
Ischemia
3. Increased Afterload
↑Systolic BP
↓Pleural Pressure

gamma camera had PAOP increases with minimal augmentation of LVEDVI, suggesting reduced LV diastolic compliance.¹⁹ There are several possible causes of a reduced diastolic compliance. Ischemic heart disease was documented in seven of the 15 patients by a history and ECG evidence of myocardial infarction, or by autopsy examination showing severe atherosclerosis of the coronary vessels. LV ischemia can reduce the diastolic compliance, although we noted the lead II ECG was unchanged during weaning.²⁰

During SV, several factors favor ischemia due to reduced myocardial O₂ delivery: arteriosclerosis, mild arterial desaturation (84% mean SaO₂ during SV₁), and an increased LVEDP impeding coronary artery flow. Ischemia was also promoted by an increasing myocardial oxygen demand through tachycardia, left and right ventricular systolic hypertension, and catecholamine release.²¹ Rasanen *et al.*²² observed angina and ischemic ECG changes concomitant with an increased PAOP from 15 to 20 mmHg in patients weaned rapidly from MV to SV after acute myocardial infarction. Three of our patients (patients 1, 3, and 9) had evidence of coronary atherosclerosis and pre-existing abnormal LV and wall motion during MV that became more severe during SV₁ (fig. 4A). Scharf *et al.* reported that patients with coronary artery disease develop LV dyskinesia during a Mueller maneuver.²³ During SV₁, the markedly negative inspiratory pleural pressure augmented LV afterload and may have promoted LV dyskinesia by the same mechanism.

Robotham and Mitzner have demonstrated that RV engorgement can cause septal flattening and impairment of LV filling with an elevated LVEDP.²⁴ Re-

†† Fernandez E, Navarrete P, Hinojosa R, Alvarez E, Fornieles H, Valquez G: Trabajo respiratorio y variaciones hemodinamicas tras la supresion de la ventilacion mecanica en pacientes afectados de EPOC. *Medicina Intensiva* 11:123-128, 1987

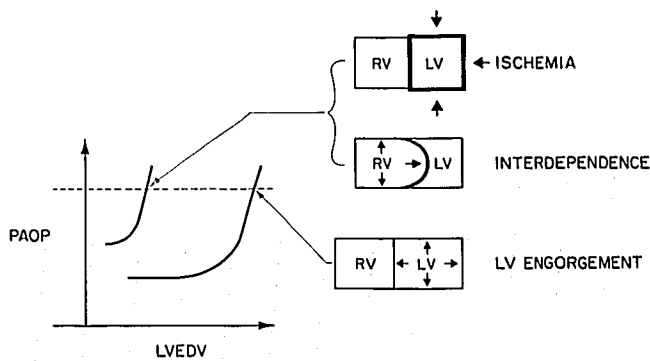


FIG. 5. A schema of several possible mechanisms causing the increased pulmonary artery occlusion pressure (PAOP) during weaning from mechanical ventilation. Increases of PAOP at a smaller left ventricular end-diastolic volume (LVEDV) suggest a reduced ventricular compliance possibly caused by ischemia or right ventricular (RV) enlargement. Increases of PAOP at a larger LVEDV suggest ventricular engorgement.

strained by an indistensible pericardium, both ventricles are interdependent; thus, another possible cause of reduced LV compliance in some of our patients was encroachment upon the left ventricle by a dilated right ventricle. Although the mean values for RVEDVI during SV_1 were not abnormally large, all the patients increased their RVEDVI and six patients developed an RVEDVI exceeding 100 ml/M^2 .

Whereas we measured a 12 mmHg absolute increase of PAOP during weaning, Butler *et al.* reported a rise of 4.9 mmHg during exercise of COPD patients.²⁵ They postulate that the localized regions of hyperinflation that they observed radiographically compress the heart and raise the wedge pressure.

During SV_1 , LVEDVI was increased in all patients, minimally in eight, and markedly in four (fig. 2). This places the LVEDP on the steeply ascending portion of the LV pressure-volume compliance curve (fig. 5). Increased LV volume was promoted by a combination of increased venous return and augmented afterload. Afterload was increased by catecholamine release. Increased sympathetic activity was reflected by tachycardia, increased systemic blood pressure, and augmented blood levels of epinephrine and norepinephrine. Kennedy *et al.* also measured increased catecholamines during weaning.²¹ LV afterload was also increased by the reduction of pleural pressure.^{24,26} Another reason for increasing LVEDVI is an augmentation of venous return, due to the low pleural pressure and peripheral venoconstriction with central translocation of blood volume.

Increased LV filling pressure is a major component of the cascade of events leading to weaning failure. Increased LVEDP may narrow small airways, increasing

airway resistance and the work of breathing, and, thus, precipitating respiratory muscle fatigue. Figure 1 illustrates a decreasing and markedly varying peak negative inspiratory pressure after 9 min of SV_1 , suggesting diaphragmatic fatigue. Diaphragmatic fatigue during weaning may occur if the increased blood supply requirements of working respiratory muscles are not provided. Deloos *et al.*²⁷ and Wolff *et al.*²⁸ studied patients after heart surgery, and reported that an increase of CI predicted successful weaning. Two of our patients (patients 1 and 6) did not increase their CI during weaning, and neither weaned from the ventilator.

The basis of our treatment with diuretics was to reduce the circulating blood volume, and reduce central transfusion by venoconstriction. Diuretics may also reduce airway edema and resistance.²⁹ After diuresis (mean weight loss 5 kg), eight patients successfully weaned from the ventilator. At that time (SV_2), their tidal volume, respiratory rate, minute ventilation, and negative inspiratory pressure were not different from SV_1 , suggesting that their respiratory function had not improved at the time of restudy (SV_2); however, their $PAOP_{tm}$ was stably maintained at $9 \pm 3 \text{ mmHg}$ and hemodynamic values were close to those measured during MV.

We believe that forced diuresis allowed many of our patients to wean from the ventilator; however, lacking a control group that was not treated with diuretics, we cannot prove this point. As we learned more about the adverse cardiopulmonary dynamics that occur during weaning, we found ourselves unwilling to withhold therapy and possibly prolong the weaning period. It is possible that, during the week-long period of study, our patients spontaneously improved due to rest of their respiratory muscles or some other unspecified therapeutic event. However, due to the long period of mechanical ventilation in many patients prior to diuretic therapy, we believe spontaneous improvement was most unlikely.

The present studies add a new dimension to the observations of Sladen *et al.*,³⁰ who demonstrated that water retention during prolonged mechanical ventilation resulted in impaired blood gas exchange. Our studies demonstrate that patients with impaired left ventricular function and chronic obstructive airways disease may suffer a combination of acute left ventricular dysfunction and acute respiratory failure when transferring from MV to SV, despite the lack of evidence of hemodynamic abnormalities during MV. This can be prevented by decreasing the circulating blood volume, indicating that translocation of blood from the peripheral to the central circulation in the presence of LV diastolic dysfunction is probably a major contributing factor to unsuccessful weaning.

The authors would like to thank Drs. Edward Lowenstein, Richard Teplick, James Robotham, and H. William Strauss for helpful discussions, Dr. David Hoaglin for statistical advice, and Mrs. S. Barry and F. Delcampe for typing the manuscript.

References

1. Sahn SA, Lakshminarayan S, Petty TL: Weaning from mechanical ventilation. *JAMA* 235:2208-2212, 1976
2. Mathru M, Rao T, El Etr A, Pifarre R: Hemodynamic response to changes in ventilatory patterns in patients with normal and poor left ventricular reserve. *Crit Care Med* 10:423-426, 1982
3. Robotham JL, Lixfeld W, Holland L, McGregor D, Bryan C, Rabson J: Effects of respiration on cardiac performance. *J Appl Physiol* 44:703-709, 1978
4. Morgan BC, Martin WE, Hornberger JF, Crawford FW, Guntheroth WC: Hemodynamic effects of intermittent positive pressure respiration. *ANESTHESIOLOGY* 27:584-590, 1966
5. Buda AJ, Pinsky MR, Ingels NB, Daughters GT, Stinson EB, Alderman EL: Effect of intrathoracic pressure on left ventricular performance. *N Engl J Med* 301:453-459, 1979
6. Sahn SA, Lakshminarayan S: Bedside criteria for discontinuation of mechanical ventilation. *Chest* 63:1003-1005, 1973
7. Pierson DJ: Weaning from mechanical ventilation in acute respiratory failure: Concepts, indications and techniques. *Respir Care* 28:646-662, 1983
8. Mead J, McIlroy MB, Silverstone NJ, Kriete BC: Measurement of intra-esophageal pressure. *J Appl Physiol* 7:491-495, 1955
9. International Committee for Standardization in Haematology: Recommended methods for measurement of red-cell and plasma volume. *J Nucl Med* 21:793-800, 1980
10. Fouat FM, MacIntyre WJ, Tarazi RC: Noninvasive measurement of cardiopulmonary blood volume. Evaluation of the centroid method. *J Nucl Med* 22:201-205, 1981
11. Dhainaut JF, Devaux JY, Monsallier JF, Brunet F, Villemant D, Huyghebaert MF: Mechanisms of decreased left ventricular preload during continuous positive pressure ventilation in ARDS. *Chest* 90:74-80, 1986
12. Brown MJ, Jenner DA: Novel double-isotope technique for enzymatic assay of catecholamines, permitting high precision, sensitivity and plasma sample activity. *Clin Sci* 61:591-598, 1981
13. Scheffe H: *Analysis of Variance*. New York, John Wiley and Sons, 1959, p 80
14. Pepe PE, Marini JJ: Occult positive end expiratory pressure in mechanically ventilated patients with airflow obstruction. *Am Rev Respir Dis* 126:166-170, 1982
15. Rossi A, Gottfried SB, Zocchi L, Higgs BD, Lennox S, Calverley PMA, Begin P, Grassino A, Milic Emili J: Measurement of static compliance of the total respiratory system in patients with acute respiratory failure during mechanical ventilation. *Am Rev Respir Dis* 131:672-77, 1985
16. Permutt S: Some physiological aspects of asthma: Bronchomuscular contraction and airways caliber. Ciba Foundation Study Group Symposium #38. London, Churchill Livingstone, 1971, pp 63-87
17. Katz JA, Kraemer RW, Gjerde GE: Inspiratory work and airway pressure with continuous positive airway pressure delivery systems. *Chest* 88:519-526, 1985
18. Lockhart A, Tzareva M, Nader F, LeBlanc P, Schrijen F, Sadoul P: Elevated pulmonary artery wedge pressure at rest and during exercise in chronic bronchitis: Fact or fancy. *Clin Sci* 37:503-517, 1969
19. Chin WDN, Cheung HW, Driedger AA, Cunningham DG, Sibbald WJ: Assisted ventilation in patients with pre-existing cardiopulmonary disease. *Chest* 88:503-511, 1985
20. Gaasch WH, Levine HJ, Quinone MA, Alexander JK: Left ventricular compliance: Mechanisms and clinical implications. *Am J Cardiol* 38:645-653, 1976
21. Kennedy SK, Weintraub WB, Skillman JJ: Cardiorespiratory and sympathoadrenal responses during weaning from controlled ventilation. *Surgery* 82:233-240, 1977
22. Rasanen J, Nikki P, Heikkila J: Acute myocardial infarction complicated by respiratory failure: The effects of mechanical ventilation. *Chest* 85:21-28, 1984
23. Scharf SM, Bianco JA, Tow DE, Brown R: The effects of large negative intrathoracic pressure on left ventricular function in patients with coronary artery disease. *Circulation* 63:871-874, 1981
24. Robotham JL, Mitzner W: A model of the effects of respiration on left ventricular performance. *J Appl Physiol* 46:411-418, 1979
25. Butler J, Enriquez A, Schrijen F, Polu JM, Poincelot F, Albert RK: The abnormal rise in wedge pressure during exercise in obstructed airflow disease may be due to gas trapping. *Am Rev Respir Dis* 135:A304, 1987
26. Scharf SM, Brown R, Tow DE: Cardiac effects of increased lung volume and decreased pleural pressure in man. *J Appl Physiol* 47:257-262, 1979
27. Deloos HH: Factors influencing successful discontinuance of mechanical ventilation after open heart surgery: A clinical study of 41 patients. *Crit Care Med* 4:265-270, 1976
28. Wolff G, Gradel E: Haemodynamic performance and weaning from mechanical ventilation following open-heart surgery. *Eur J Intensive Care Med* 1:99-104, 1975
29. Shannon DC: *Chronic complications of respiratory therapy in the newborn: Neonatal Pulmonary Care*. Edited by Thibeault DW, Gregory GA. Menlo Park, Addison Wesley, 1978, pp 401-409
30. Sladen A, Laver MB, Pontoppidan H: Pulmonary complications and water retention in prolonged mechanical ventilation. *N Engl J Med* 279:448-453, 1968