

# Effects of Recruiting Maneuvers in Patients with Acute Respiratory Distress Syndrome Ventilated with Protective Ventilatory Strategy

Salvatore Grasso, M.D.,\* Luciana Mascia, M.D.,† Monica Del Turco, M.D.,‡ Paolo Malacarne, M.D.,‡  
 Francesco Giunta, M.D.,§ Laurent Brochard, M.D.,|| Arthur S. Slutsky, M.D.,# V. Marco Ranieri, M.D.\*\*

**Background:** A lung-protective ventilatory strategy with low tidal volume ( $V_T$ ) has been proposed for use in acute respiratory distress syndrome (ARDS). Alveolar derecruitment may occur during the use of a lung-protective ventilatory strategy and may be prevented by recruiting maneuvers. This study examined the hypothesis that the effectiveness of a recruiting maneuver to improve oxygenation in patients with ARDS would be influenced by the elastic properties of the lung and chest wall.

**Methods:** Twenty-two patients with ARDS were studied during use of the ARDSNet lung-protective ventilatory strategy:  $V_T$  was set at 6 ml/kg predicted body weight and positive end-expiratory pressure (PEEP) and inspiratory oxygen fraction ( $FiO_2$ ) were set to obtain an arterial oxygen saturation of 90–95% and/or an arterial oxygen partial pressure ( $Pao_2$ ) of 60–80 mmHg (baseline). Measurements of  $Pao_2/FiO_2$ , static volume-pressure curve, recruited volume (vertical shift of the volume-pressure curve), and chest wall and lung elastance ( $Est_w$  and  $Est_l$ ; esophageal pressure) were obtained on zero end-expiratory pressure, at baseline, and at 2 and 20 min after application of a recruiting maneuver (40 cm  $H_2O$  of continuous positive airway pressure for 40 s). Cardiac output (transesophageal Doppler) and mean arterial pressure were measured immediately before, during, and immediately after the recruiting maneuver. Patients were classified *a priori* as responders and nonresponders on the basis of the occurrence or nonoccurrence of a 50% increase in  $Pao_2/FiO_2$  after the recruiting maneuver.

**Results:** Recruiting maneuvers increased  $Pao_2/FiO_2$  by 20 ± 3% in nonresponders (n = 11) and by 175 ± 23% (n = 11; mean ± standard deviation) in responders. On zero end-expi-

ratory pressure,  $Est_l$  ( $28.4 \pm 2.2$  vs.  $24.2 \pm 2.9$  cm  $H_2O/l$ ) and  $Est_w$  ( $10.4 \pm 1.8$  vs.  $5.6 \pm 0.8$  cm  $H_2O/l$ ) were higher in nonresponders than in responders ( $P < 0.01$ ). Nonresponders had been ventilated for a longer period of time than responders ( $7 \pm 1$  vs.  $1 \pm 0.3$  days;  $P < 0.001$ ). Cardiac output and mean arterial pressure decreased by  $31 \pm 2$  and  $19 \pm 3\%$  in nonresponders and by  $2 \pm 1$  and  $2 \pm 1\%$  in responders ( $P < 0.01$ ).

**Conclusions:** Application of recruiting maneuvers improves oxygenation only in patients with early ARDS who do not have impairment of chest wall mechanics and with a large potential for recruitment, as indicated by low values of  $Est_l$ .

TRADITIONAL respiratory support for the acute respiratory distress syndrome (ARDS) involves the use of relatively large (10–15 ml/kg) tidal volumes ( $V_T$ ) to minimize atelectasis and positive end-expiratory pressure (PEEP) to improve arterial oxygenation by means of low inspiratory oxygen fractions ( $FiO_2$ ).<sup>1</sup> More recently, lung-protective ventilatory strategies have been proposed<sup>2</sup> that are based on the large body of animal data indicating that mechanical ventilation with high  $V_T$  is associated with pulmonary injury indistinguishable from ARDS.<sup>3</sup> Cycling end-expiratory collapse with tidal inflation may exacerbate this process.<sup>4</sup> Three recent randomized controlled trials supported these experimental findings, showing that a lung-protective ventilatory strategies based on low  $V_T$  is able to decrease markers of pulmonary and systemic inflammation<sup>5</sup> and decrease mortality among patients with ARDS.<sup>6,7</sup>

The American-European consensus conference on ARDS proposed periodic use of recruiting maneuvers to prevent atelectasis when small  $V_T$  and/or low PEEP levels are used.<sup>8</sup> Alveolar derecruitment may occur during mechanical ventilation with low  $V_T$ , depending on the  $FiO_2$ , the regional ventilation/perfusion ratios, and the end-expiratory lung volume.<sup>9,10</sup> On the basis of these recommendations, several studies have investigated the physiologic effects of recruiting maneuvers in patients with ARDS.<sup>6,10–14</sup>

Alterations in respiratory mechanics parallel the time course of ARDS.<sup>15,16</sup> Most patients with early ARDS who have been on the ventilator for only a few days have a static volume pressure (V-P) curve with a marked lower inflection point (LIP) and an upper inflection point (UIP) that occurs well above tidal inflation. By contrast, most patients with late ARDS who have been on the ventilator for several days often have a static V-P curve with an absent LIP and a UIP that occurs within tidal inflation.<sup>15,16</sup>

Impairment of chest wall mechanics in patients with ARDS has been demonstrated<sup>17</sup>; recent studies suggest

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\* Clinical attending, Servizio di Anestesiologia e Rianimazione, Ospedale Di Venere. † Doctoral student, Dipartimento di Neuroscienze-Sezione di Fisiologia, Università di Torino. ‡ Clinical attending, § Professor, and \*\* Associate Professor, Dipartimento di Chirurgia-Terapia Intensiva, Cattedre di Anestesiologia e Rianimazione, Ospedale S. Chiara, Università di Pisa. || Professor, Service de Réanimation Médicale, Hôpital Henri Mondor, Université Paris XII. # Professor, St. Michael's Hospital, University of Toronto.

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Address reprint requests to Dr. Ranieri: Università Di Torino, Sezione Di Anestesiologia e Rianimazione Ospedale S. Giovanni Battista, Corso Dogliotti 19, 10126, Torino, Italy. Address electronic mail to: marco.ranieri@unito.it. Individual article reprints may be purchased through the Journal Web site, www.anesthesiology.org.

that alterations of chest wall mechanics may influence the effects of PEEP on arterial oxygenation<sup>18</sup> and respiratory mechanics.<sup>19</sup>

The current study set out to examine the hypothesis that the effectiveness of the recruiting maneuver to improve oxygenation in patients with ARDS could be influenced by the elastic properties of the lung and chest wall.

## Methods

### Patient Selection

Twenty-two patients with ARDS were recruited from the intensive care units (ICUs) of the Di Venere, Policlinico (University of Bari), and S. Chiara (University of Pisa) hospitals. The review boards of all three hospitals approved the research protocol, and informed consent was obtained from all patients or next of kin. Inclusion criteria were age >18 yr and diagnosis of ARDS.<sup>20</sup> Exclusion criteria were cardiogenic pulmonary edema (clinically suspected or pulmonary artery occlusion pressure >18 mmHg), history of ventricular fibrillation or tachyarrhythmia, unstable angina or myocardial infarction within the preceding month, preexisting chronic obstructive pulmonary disease, mean arterial pressure (MAP) <65 mmHg (despite attempts to increase blood pressure with fluid and vasopressors, as clinically indicated), anatomic chest wall abnormalities, chest tube with persistent air leak, pregnancy, and intracranial abnormality.

All patients were intubated and ventilated with a Siemens Servo Ventilator 300 (Siemens Elema AB, Solna, Sweden). The investigation was performed in the semirecumbent position after sedation (diazepam, 0.1–0.2 mg/kg, and fentanyl, 2–3 µg/kg) and paralysis (vecuronium, 4–8 mg). A physician not involved in the research aspects of the study was always present to provide patient care.

### Study Protocol

Before enrollment, patients were ventilated according to the ARDSNet protective ventilatory strategy:  $V_T$  was set at 6 ml/kg predicted body weight; PEEP and  $F_{iO_2}$  were set to obtain an arterial oxygen saturation ( $S_{aO_2}$ ) value of 90–95% or an arterial oxygen partial pressure ( $P_{aO_2}$ ) of 60–80 mmHg (baseline),<sup>7</sup> or both.

At baseline, static inspiratory V-P curves of the respiratory system, chest wall, and lung were obtained with and without PEEP. A recruiting maneuver was then performed by setting the ventilator on the continuous positive airway pressure mode and applying a pressure of 40 cm H<sub>2</sub>O for 40 s.<sup>6</sup> After termination of the recruiting maneuver, the previous breathing pattern was reestablished, and measurements of  $P_{aO_2}/F_{iO_2}$  ratio, V-P curve, and respiratory mechanics were obtained 2 min and 20 min after application of the recruiting maneuver.

### Measurements

Flow was measured with a heated pneumotachograph (Fleisch no. 2; Fleisch, Lausanne, Switzerland), connected to a differential pressure transducer (Diff-Cap, ±1 cm H<sub>2</sub>O; Special Instruments, Nordlingen, Germany) inserted between the Y-piece of the ventilator circuit and the endotracheal tube. The pneumotachograph was linear over the experimental range of flow. Airway opening pressure ( $P_{ao}$ ) was measured proximal to the endotracheal tube with a pressure transducer (Digima-Clic, ±100 cm H<sub>2</sub>O; Special Instruments). Changes in intrathoracic pressure were evaluated by assessment of esophageal pressure ( $P_{es}$ ). Esophageal pressure was measured with a thin latex balloon-tipped catheter connected by a polyethylene catheter to a pressure transducer (Digima-Clic, ±100 cm H<sub>2</sub>O). The esophageal balloon was filled with 1–1.5 ml of air and correctly positioned by means of an occlusion test performed before sedation and paralysis.<sup>17–19</sup> Transpulmonary pressure was calculated as  $P_{ao}-P_{es}$ . All the variables described above were displayed and collected on a personal computer through a 12-bit analog-to-digital converter board (DAQCard 700; National Instrument, Austin, TX) at a sample rate of 200 Hz (ICU Lab, KleisTEK Engineering, Bari, Italy). Arterial blood samples were analyzed (ABL 330; Radiometer, Copenhagen, Denmark).

The difference between end-expiratory lung volume during mechanical ventilation and the elastic equilibrium volume of the respiratory system on zero end-expiratory pressure (ZEEP) was assessed by reducing respiratory rate to the lowest value possible during a baseline breath, while decreasing PEEP to zero.<sup>21</sup> To standardize volume history, immediately after the prolonged expiration to ZEEP, five consecutive pressure control breaths with an inspiratory pressure of 40 cm H<sub>2</sub>O and an inspiratory time of 5 s were applied before reestablishing the baseline ventilatory pattern.<sup>11,14,22</sup> Total PEEP ( $PEEP_{tot}$  = applied PEEP plus intrinsic PEEP) of the respiratory system (rs) and of the chest wall (W) were measured as the plateau pressure in  $P_{ao}$  and  $P_{es}$  during an end-expiratory occlusion, referenced to their values at the elastic equilibrium point of the respiratory system.  $PEEP_{tot}$  applied to the lung (L) was evaluated as  $PEEP_{tot,L} = PEEP_{tot,rs} - PEEP_{tot,W}$ .<sup>17</sup>

Static inflation V-P curves were obtained by performing single-breath occlusions at different inflating volumes, achieved by changing inflation volumes in random order, and altering the respiratory frequency of the ventilator.<sup>21</sup> Twelve to 15 experimental points were collected.<sup>21</sup> Each occlusion was maintained until an apparent plateau in  $P_{ao}$  was observed (3–4 s). The static end-inspiratory pressures of the respiratory system ( $P_{st,rs}$ ) and chest wall ( $P_{st,W}$ ) were measured as the end-inspiratory plateau pressure on  $P_{ao}$  and  $P_{es}$ , referenced to their values at the elastic equilibrium volume of the

respiratory system. The static end-inspiratory pressure of the lung ( $P_{st_L}$ ) was calculated as the difference between  $P_{st_{rs}}$  and  $P_{st_w}$ . Values of pressures at the upper and lower inflection points of the V-P curve of the lung on ZEEP ( $UIP_L$  and  $LIP_L$ , respectively) were quantified by means of a step-by-step regression analysis on samples of 4–5 consecutive experimental points, as previously described.<sup>22</sup> Recruited volume at baseline and 2 and 20 min after application of the recruiting maneuver was identified as the upward shift of the V-P curves of the lung, relative to the curve on ZEEP at a fixed pressure (20 cm  $H_2O$ ).<sup>21</sup>

Static elastance ( $Est$ ) of the respiratory system was calculated as  $Est_{rs} = (P_{st_{rs}} - PEEP_{cocrs})/V_T$ . Static elastance of the chest wall ( $Est_w$ ) was calculated as  $Est_w = (P_{st_w} - PEEP_{cocw})/V_T$ . Static elastance of the lung ( $Est_L$ ) was calculated as  $Est_{rs} - Est_w$ .

All patients had a radial artery and central venous catheters for measurements of systemic blood pressure and right atrial pressure. To evaluate the instantaneous effects of the recruiting maneuver on cardiac output, transesophageal continuous-wave Doppler (Doptek-ODM1; Deltex Medical, Chichester, UK) of the descending aorta was measured before and during application of the recruiting maneuver (20–25 s after the onset of the maneuver) and immediately (within 20–25 s) after reestablishment of baseline ventilation. This technique measures blood flow velocity in the descending thoracic aorta, with use of a transducer inserted in the esophagus.<sup>23</sup> Stroke volume may then be derived with an algorithm based on (1) the beat-to-beat maximum velocity-time integral (stroke distance); (2) the cross-sectional area of the descending aorta; and (3) a correction factor that transforms descending aortic blood flow into global cardiac output.<sup>23</sup> The validity of this approach in mechanically ventilated critically ill patients has recently been established.<sup>23</sup>

Patients were defined *a priori* as responders if they had an increase in  $PaO_2/FiO_2$  of  $\leq 50\%$  2 min after application of the recruiting maneuver; otherwise, they were considered to be nonresponders.<sup>11</sup> On the basis of history, clinical presentation, and microbiologic results,<sup>11,19</sup> ARDS was classified as pulmonary or extrapulmonary by three independent physicians blinded to the study results.

**Statistics**

Data are expressed as mean  $\pm$  standard deviation of the mean. Data within groups were compared by analysis of variance for repeated measures with a Bonferroni correction. If significant ( $P \geq 0.05$ ), the values at different experimental conditions were compared with those at baseline with use of a paired *t* test, as modified by Dunnett. Comparisons of data between groups were performed at each experimental condition by the Fisher exact test for categorical variables and the Wilcoxon test

**Table 1. Demographic and Clinical Characteristics in Nonresponders and Responders**

	Patient	Age	Gender	Underlying Disease	Time on MV (days)
Nonresponders	4	67	M	Pancreatitis	10
	6	38	M	Polytrauma	6
	7	61	F	Peritonitis	7
	8	52	F	Pneumonia	6
	10	28	M	Pneumonia	7
	11	49	F	Peritonitis	6
	14	49	F	Peritonitis	7
	16	63	M	Pneumonia	10
	18	45	F	Peritonitis	5
	21	40	F	Pneumonia	7
	22	30	M	Pneumonia	9
	Mean		47		
SD		13			1.5
Responders	1	63	F	Pancreatitis	1
	2	19	M	Polytrauma	1
	3	35	M	Polytrauma	1
	5	25	M	Pneumonia	1
	9	37	F	Pancreatitis	1
	12	41	F	Pneumonia	1
	13	22	F	Pneumonia	1
	15	33	F	Pancreatitis	1
	17	68	M	Pneumonia	1
	19	62	F	Pneumonia	1
20	62	M	Pneumonia	2	
Mean		42			1.0*
SD		18			0.3

Data are mean  $\pm$  SD.

\* $P < 0.001$ , Wilcoxon for unpaired data Nonresponders vs. Responders.

MV = mechanical ventilation; M = male; F = female.

for continuous variables. Regression analysis was performed with the least-squares method. Analysis was carried out with the StatView software package (Abacus, Berkeley, CA).

**Results**

Two minutes after the application of the recruiting maneuver,  $PaO_2/FiO_2$  increased  $20 \pm 3\%$  in 11 nonresponders and  $175 \pm 23\%$  in the responders (11 patients).

Before application of the recruiting maneuver,  $V_T$  ( $6.1 \pm 0.1$  and  $6.0 \pm 0.2$  ml/kg) and PEEP ( $9.4 \pm 2.2$  and  $9.1 \pm 2.7$  cm  $H_2O$ ) did not differ between nonresponders and responders. Age ( $47 \pm 13$  [nonresponders] and  $42 \pm 18$  yr [responders]), sex (five and six males), underlying disease (five and six cases of pulmonary ARDS), and  $PaO_2/FiO_2$  ratio on ZEEP ( $111 \pm 38$  vs.  $105 \pm 38$ ) were similar for nonresponders and responders. Time on mechanical ventilation (including time on ventilator in other ICUs before admission to the study centers) was significantly longer ( $P < 0.001$ ) for the nonresponders (table 1).

Values of LIP ( $8.7 \pm 1.2$  vs.  $10.6 \pm 1.0$  cm  $H_2O$ ) and UIP ( $24.2 \pm 1.4$  vs.  $27.8 \pm 2.2$  cm  $H_2O$ ) on the static V-P

**Table 2. Respiratory Mechanics in Nonresponders and Responders on Zero End-expiratory Pressure**

		LIP <sub>L</sub>	UIP <sub>L</sub>	Est <sub>L</sub>	Est <sub>w</sub>
	Patient	(cm H <sub>2</sub> O)	(cm H <sub>2</sub> O)	(cm H <sub>2</sub> O/L)	(cm H <sub>2</sub> O/L)
Nonresponders	4	8.1	22.8	33.64	9.90
	6	9.1	23.5	29.06	10.70
	7	10.8	25.1	25.11	11.60
	8	6.9	24.5	30.23	9.30
	10	8.7	22.9	27.50	11.50
	11	9.5	26.7	26.00	9.70
	14	8.4	22.7	31.00	10.90
	16	7.6	22.9	28.50	9.30
	18	7.8	24.2	27.90	6.40
	21	10.2	26.4	26.80	12.90
	22	8.5	23.5	31.80	11.90
Mean		8.7	24.2	28.4	10.4
SD		1.2	1.4	2.2	1.8
Responders	1	10.1	27.5	25.67	5.30
	2	9.8	26.6	23.55	6.60
	3	10.7	24.3	28.82	5.20
	5	9.2	26.3	27.92	6.80
	9	10.8	28.8	23.10	5.50
	12	11.5	31.1	27.20	4.30
	13	12.5	25.7	24.50	5.50
	15	10.3	26.9	22.40	6.10
	17	11.8	28.5	19.90	6.20
	19	10.4	30.8	21.90	5.80
	20	9.8	29.8	20.80	4.30
Mean		10.6*	27.8*	24.2*	5.6*
SD		1.0	2.2	2.9	0.8

Data are mean ± SD.

\*  $P < 0.01$ , Wilcoxon for unpaired data Nonresponders vs. Responders.

LIP<sub>L</sub> = lower inflection point on the static pressure-volume curve of the lung;

UIP<sub>L</sub> = upper inflection point on the static pressure-volume curve of the lung;

Est<sub>L</sub> = static elastance of the lung; Est<sub>w</sub> = static elastance of the chest wall.

curve of the lung on ZEEP were lower for nonresponders than responders ( $P < 0.01$ ); values of Est<sub>L</sub> ( $28.4 \pm 2.2$  vs.  $24.2 \pm 2.9$  cm H<sub>2</sub>O/l) and Est<sub>w</sub> ( $10.4 \pm 1.8$  vs.  $5.6 \pm 0.8$  cm H<sub>2</sub>O/l) on ZEEP were higher for nonresponders than responders ( $P < 0.01$ ) (table 2).

Two minutes after the application of the recruiting maneuver, the PaO<sub>2</sub>/Fio<sub>2</sub> ratio increased to  $180 \pm 46$  in nonresponders and to  $440 \pm 60$  in responders ( $P < 0.001$ ); 20 min after application of the recruiting maneuver, values of PaO<sub>2</sub>/Fio<sub>2</sub> tended to return toward baseline values in both groups (fig. 1, top). Values of Est<sub>L</sub> ( $25.1 \pm 2.2$  vs.  $18.9 \pm 2.4$  cm H<sub>2</sub>O/l) at baseline were higher in nonresponders than responders ( $P < 0.01$ ). Two minutes after application of the recruiting maneuver, Est<sub>L</sub> decreased to  $22.7 \pm 1.9$  cm H<sub>2</sub>O/l in nonresponders ( $8 \pm 3\%$ ) and to  $14.8 \pm 2.3$  cm H<sub>2</sub>O/l in responders ( $21 \pm 2\%$ ) ( $P < 0.01$ ). Est<sub>L</sub> returned toward baseline values 20 min after application of the recruiting maneuver in both groups (fig. 1, middle). At baseline, the amount of recruited volume with PEEP was smaller in nonresponders than in responders ( $199 \pm 80$  vs.

$284 \pm 37$  ml, respectively;  $P < 0.01$ ) and increased after application of the recruiting maneuver to  $296 \pm 99$  ml in nonresponders and  $482 \pm 80$  ml in responders ( $P < 0.01$ ). Twenty minutes after application of the recruiting maneuver, the recruited volume was  $263 \pm 99$  ml in nonresponders and  $322 \pm 64$  ml in responders ( $P < 0.01$ ; fig. 1, bottom).

Physiologic variables in one representative nonresponder and responder are shown in figure 2. Relative to baseline conditions, application of the recruiting maneuver increased the end-expiratory position of the volume and Pes signals only in the responder. At similar V<sub>T</sub>, tidal swings of Pes were larger for nonresponders than for responders. Transpulmonary pressure during the sustained inflation was lower in nonresponders than in responders. The reduction in blood pressure and the increase in right atrial pressure after application of the recruiting maneuver were more evident in nonresponders than responders.

On average, heart rate remained unchanged during application of the recruiting maneuver (20–25 s after onset), and cardiac output, stroke volume, and MAP decreased by  $31 \pm 2$ ,  $27 \pm 1$ , and  $19 \pm 3\%$  in nonresponders and by  $2 \pm 1$ ,  $5 \pm 1$ , and  $2 \pm 1\%$  in responders, whereas right atrial pressure increased by  $19 \pm 3$  and  $2 \pm 1\%$ , respectively ( $P < 0.01$ ). All hemodynamic variables returned to baseline values right after ventilation was reestablished after the recruiting maneuver (within 20–30 s; table 3).

## Discussion

All ventilatory strategies used to minimize alveolar recruitment-derecruitment and overdistension based on mechanical properties use Pst<sub>rs</sub> as a surrogate for transpulmonary pressure. However, the lung and the chest wall are in series, and Pst<sub>rs</sub> equals the sum of Pst<sub>L</sub> and Pst<sub>w</sub>. Our study shows that a substantial part of the pressure applied to the respiratory system during a recruitment maneuver (to reexpand collapsed alveoli) can be dissipated against a stiff chest wall; we found that the pressure applied to the lung during a fixed recruitment maneuver of 40 cm H<sub>2</sub>O was  $18.4 \pm 3.3$  and  $28.6 \pm 2.1$  cm H<sub>2</sub>O in nonresponders and responders, respectively.

Matamis *et al.*<sup>15</sup> found that alterations in respiratory mechanics paralleled the evolution of ARDS. In patients on the ventilator for a prolonged period of time and with signs of interstitial fibrosis on a chest radiograph, static V-P curves differed substantially from those observed in patients at an early stage and at the onset of mechanical ventilation. Our study included patients transferred from other ICUs and on mechanical ventilation for 5–10 days (nonresponders) and patients admitted from the emergency department or from the ward and on mechanical ventilation for 1–2 days (responders). Patients in whom

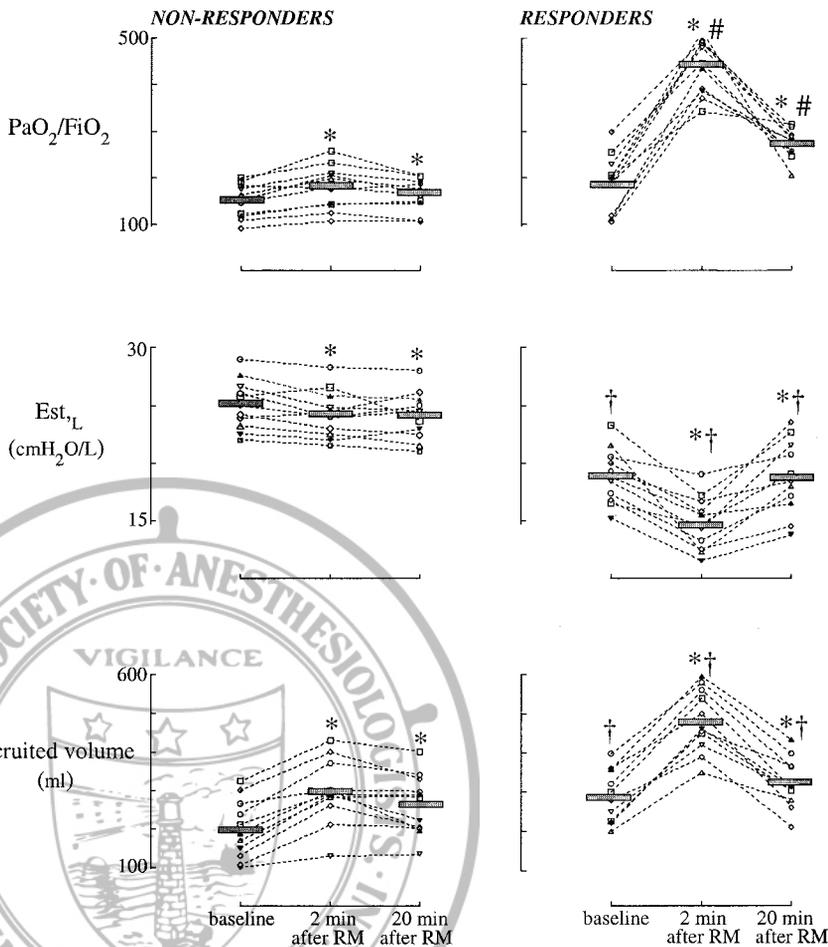


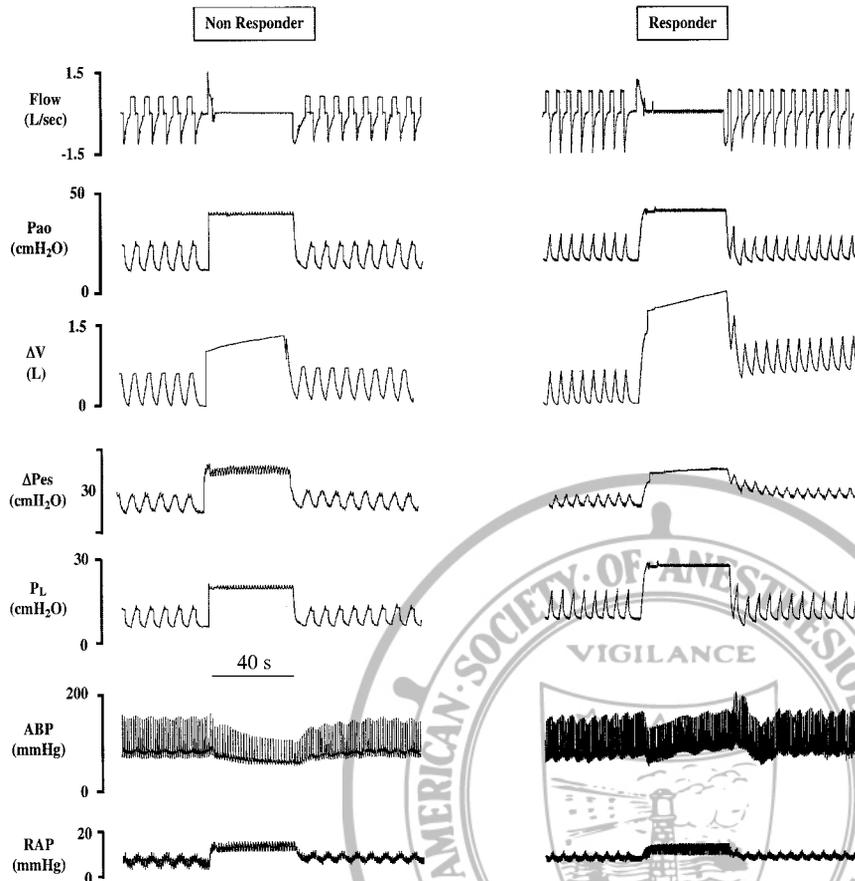
Fig. 1. Individual values of arterial oxygen partial pressure or inspiratory oxygen fraction ( $PaO_2/FiO_2$ ; top) ratio static elastance of the lung ( $Est_L$ ; middle) and recruited volume (bottom) during the different experimental conditions in nonresponders and responders (RM = recruiting maneuver; horizontal bars indicate mean values; \* $P < 0.01$  [analysis of variance for repeated measures with Bonferroni correction vs. baseline]; † $P < 0.05$ ; # $P < 0.01$  [Wilcoxon test, nonresponders vs. responders]).

application of a recruiting maneuver caused a substantial improvement in oxygenation were those studied within 1–2 days after initiation of mechanical ventilation. In these patients,  $Est_L$  on ZEEP was smaller and  $LIP_L$  and  $UIP_L$  occurred at higher pressures than in patients studied after 5–10 days of mechanical ventilation. This suggests that the potential for alveolar recruitment with recruiting maneuvers may be reduced in patients with late ARDS.

Recent studies have demonstrated impaired chest wall mechanics in many patients with ARDS consequent to major abdominal surgery<sup>17</sup> and in patients in whom ARDS is caused by extrapulmonary causes.<sup>19</sup> These studies suggested that a great part of the alteration in chest wall mechanics can be explained by abdominal distension.<sup>17,19</sup> It has been shown that in patients with ARDS, chest wall mechanics can be significantly altered by the presence of pleural effusions due to a positive fluid balance.<sup>11,24–27</sup> Mattison *et al.*<sup>26</sup> found that pleural effusions were seen only in patients on the ventilator for  $7 \pm 1$  days, not in patients on the ventilator for only  $2 \pm 1$  days. We found a positive correlation ( $R^2 = 0.72$ ;  $P < 0.0001$ ) between  $Est_w$  on ZEEP and days on mechanical ventilation, suggesting that impairment of chest wall mechanics may occur, independently from the underlying

ing disease, because of pleural effusions in patients on the ventilator for a prolonged period of time. Further studies are required to prospectively confirm this hypothesis.

Pelosi *et al.*<sup>11</sup> showed that recruiting maneuvers improved lung mechanics and oxygenation only in patients with extrapulmonary ARDS. In our study, the underlying disease responsible for ARDS did not influence the amount of improvement in arterial oxygenation after application of the recruiting maneuver. The relation between baseline  $V_T$  and effects of PEEP and recruiting maneuvers on alveolar recruitment may explain such apparently conflicting data. In the study of Pelosi *et al.*,<sup>11</sup>  $V_T$  and  $Pst_{rs}$  during baseline ventilation were  $0.56 \pm 0.11$  L (approximately 10 ml/kg) and  $31.6 \pm 3.6$  cm H<sub>2</sub>O, whereas in the present study they were  $0.38 \pm 0.05$  L ( $6.1 \pm 0.1$  ml/kg) and  $23.3 \pm 2.8$  cm H<sub>2</sub>O, respectively. Several studies have shown that lung mechanics vary considerably with volume history.<sup>28–30</sup> When relatively large  $V_T$  (10–12 ml/kg) are used, most alveolar recruitment may occur during tidal inflation, and the potential for further recruitment with PEEP or recruiting maneuvers may be limited.<sup>31</sup> This is confirmed by the observation that alveolar recruitment with PEEP decreases with increasing magnitude of  $Pst_{rs}$  on ZEEP.<sup>21,32,33</sup> The larger



**Fig. 2.** Physiologic variables in a representative nonresponder and responder before, during, and after application of a recruiting maneuver. From top to bottom: flow, airway opening pressure (Pao), and changes in lung volume ( $\Delta V$ ), esophageal pressure ( $\Delta P_{es}$ ), transpulmonary pressure ( $P_L$ ), arterial pressure (ABP), and right atrial pressure (RAP).

potential for alveolar recruitment due to the lower  $V_T$  used in the current study could therefore explain the improvement in arterial oxygenation with recruiting maneuvers that was also noted in responders with pulmonary ARDS.

Concerns have been voiced about the potential risk of hemodynamic impairment during application of recruiting maneuvers.<sup>34</sup> Our data show that in nonresponders, application of a recruiting maneuver caused a substantial (20–30%) reduction in MAP and cardiac output. The effects of recruiting maneuvers on MAP and cardiac output include a reduced preload due to transmission of Pao to intrathoracic vasculature and/or an increased afterload due to increased lung volume.<sup>35,36</sup> In patients

with a stiff chest wall, the degree of Pao transmitted to the pleural space would be larger than in patients with a normal chest wall<sup>35,36</sup>; thus, the decrease in the pressure gradient for venous return ( $19 \pm 3\%$  increase in right atrial pressure) observed in nonresponders during application of recruiting maneuvers might explain the reduction in cardiac output. The more compliant chest wall observed in the responders may induce a smaller transmission of pressure within the thorax, with a larger amount of pressure transmitted to the lung. The smaller decrease in the pressure gradient for venous return ( $2 \pm 1\%$  increase in right atrial pressure) may explain the minimal hemodynamic consequences due to recruiting maneuvers observed in responders.

**Table 3. Hemodynamic Variables before, during, and Immediately after Application of a Recruiting Maneuver**

	Nonresponders			Responders		
	Before RM	During RM	After RM	Before	During RM	After RM
HR (beats/min)	95 ± 10	103 ± 10	97 ± 7	93 ± 11	98 ± 10	95 ± 9
CO (L · min <sup>-1</sup> )	10.1 ± 0.5	6.1 ± 0.7*	9.45 ± 0.8	10.6 ± 1.7	10.5 ± 1.6	10.8 ± 1.8
SV (ml)	116 ± 15	58 ± 13*	104 ± 12	118 ± 19	110 ± 15	116 ± 20
MAP (mmHg)	85 ± 10	70 ± 5*	86 ± 6	90 ± 6	88 ± 7	91 ± 8
RAP (mmHg)	15.2 ± 1.5	24 ± 2.9*	14.7 ± 0.9	14.2 ± 3.3	16.1 ± 2.7	14.5 ± 5.1

\*  $P < 0.01$ , analysis of variance (ANOVA) for repeated measures with Bonferroni's correction versus before RM.

Data are mean ± SD.

RM = recruiting maneuver; HR = heart rate; CO = cardiac output; SV = stroke volume; MAP = mean arterial pressure; RAP = right atrial pressure.

However, cyclic right ventricle afterload occurring during the inspiratory phase has been demonstrated in mechanically ventilated patients.<sup>37</sup> In a recent study, Vieillard-Baron *et al.*<sup>38</sup> found that when  $Est_w$  was increased by chest strapping and transpulmonary pressure was reduced by decreasing  $V_T$  without changing Pao, the right ventricle was unloaded. In our study the increase in lung volume and transpulmonary pressure during the recruiting maneuver was smaller in nonresponders with worsening hemodynamics (fig. 2). Under these circumstances, the increase in right ventricle afterload would not likely be the mechanism responsible for the reduction in cardiac output and MAP observed during the application of recruiting maneuvers in nonresponders. Echocardiographic evaluation of hemodynamics, not performed in the present study, may confirm these speculations.

One may argue that application of a higher level of continuous positive airway pressure for a longer period of time may have transformed nonresponders into responders. However, the reduction in cardiac output and MAP observed in nonresponders suggests first that the use of more aggressive recruiting maneuvers may worsen the hemodynamic impairment and therefore limit the clinical use of recruiting maneuvers at a pressures higher than 40 cm H<sub>2</sub>O, and second, in patients with late ARDS, characterized by a focal distribution of loss of aeration,<sup>39</sup> recruiting maneuvers may provide alveolar recruitment with lung overdistension.<sup>40</sup> Loss of beneficial effects of the recruiting maneuver was observed within 30 min. This may be the result of an insufficient level of PEEP to keep open the alveoli recruited by sustained inflation.<sup>34</sup>

In conclusion, this study demonstrates that application of recruiting maneuvers is successful in improving oxygenation only in patients with early ARDS on the ventilator for 1–2 days and without impairment of chest wall mechanics. In patients ventilated for a longer period of time, the presence of a stiff chest wall and the reduction in blood pressure and cardiac output make the recruiting maneuver ineffective and potentially harmful.

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