Quantification of Asymmetric Lung Pathophysiology as a Guide to the Use of Simultaneous Independent Lung Ventilation in Posttraumatic and Septic Adult Respiratory Distress Syndrome

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The management of impaired respiratory gas exchange in patients with nonuniform posttraumatic and septic adult respiratory distress syndrome (ARDS) contains its own therapeutic paradox, since the need for volume-controlled ventilation and PEEP in the lung with the most reduced compliance increases pulmonary barotrauma to the better lung. A computer-based system has been developed by which respiratory pressure-flow-volume relations and gas exchange characteristics can be obtained and respiratory dynamic and static compliance curves computed and displayed for each lung, as a means of evaluating the effectiveness of ventilation therapy in ARDS. Using these techniques, eight patients with asymmetrical posttraumatic or septic ARDS, or both, have been managed using simultaneous independent lung ventilation (SILV). The computer assessment technique allows quantification of the nonuniform ARDS pattern between the two lungs. This enabled SILV to be utilized using two synchronized servo-ventilators at different pressure-flow-volumes, inspiratory/expiratory ratios, and PEEP settings to optimize the ventilatory volumes and gas exchange of each lung, without inducing excess barotrauma in the better lung. In the patients with nonuniform ARDS, conventional ventilation was not effective in reducing shunt ($\dot{Q}S/\dot{Q}T$) or in permitting a lower FIO_2 to be used for maintenance of an acceptable PaO_2. SILV reduced per cent v-a shunt and permitted a higher PaO_2 at lower FIO_2. Also, there was x-ray evidence of ARDS improvement in the poorer lung. While the ultimate outcome was largely dependent on the patient's injury and the adequacy of the septic host defense, by utilizing the SILV technique to match the quantitative aspects of respiratory dysfunction in each lung at specific times in the clinical course, it was possible to optimize gas exchange, to reduce barotrauma, and often to reverse apparently fixed ARDS changes. In some instances, this type of physiologically directed ventilatory therapy appeared to contribute to a successful recovery.

RESPIRATORY FAILURE in patients with asymmetric lung disease is not well treated by conventional methods of ventilatory support, which apply their volume and pressure characteristics indiscriminately to all lung regions. This has lead to a resumption of interest in techniques of independent lung ventilation.[1-4]

In unilateral adult respiratory distress syndrome (ARDS) or atelectatic lung disease, there is a mismatch of ventilation to perfusion between the two lungs. Ordinarily, hypoxic vasoconstriction in the atelectatic portion of the diseased lung has a tendency to shift perfusion to the more normally ventilated lung. However, in areas of lung with inflammatory pneumonitis[5] or with posttraumatic or postseptic ARDS pathology, local vasodilation and the hyperdynamic systemic cardiovascular response tend to overcome this vasoconstrictive response. Thus, increased perfusion of dependent lung segments with low ventilation/perfusion ratios occurs with a resulting large percentage of pulmonary venoarterial admixture.[6]

The therapeutic doctrine in these instances has been to use controlled inspiratory volumes at increased positive end-expiratory pressures (PEEP)[7,8] to overcome the pathologically increased small airway resistance (SAR) and reduced alveolar compliance, which together alter the time constant for expansion of the diseased lung.[9] While this technique has generally been effective in bilaterally equal lung disease, it may in itself produce a compounding of the ventilation/perfusion ($\dot{V}/\dot{Q}$) mismatch in asymmetric or unilateral lung pathology.[1-4,10,11] However, because of the differing time constants for expansion in normal *versus* diseased lung, the gas volumes and pressures are not uniformly distributed between the two lungs. The result of this maldistribution of tidal volume is to overdistend the more compliant lower SAR lung, with transmission of the pressures to the distended normal alveolar capillary beds. This increases effective capillary resistance and diverts a share of the normal lung's perfusion to the pathologic alveolar capillary beds, which have a low $\dot{V}/\dot{Q}$ ratio.

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As a consequence, the parameters of gas exchange that reflect pulmonary venoarterial admixture (alveolar-arterial O_2 gradient, Respiratory Index, and per cent shunt) may be worsened, and arterial oxygen tension (PaO_2) falls at any inspired oxygen concentration (FIO_2).

This problem is also seen in bilateral ARDS disease when there is a marked disparity in disease severity between lung segments. Consequently the $\dot{V}/\dot{Q}$ mismatch is distributed nonuniformly within both lungs because of regional differences in compliance and resistance. Under these circumstances, the application of PEEP to prevent small airway closure and alveolar collapse also unintentionally may result in a greater $\dot{V}/\dot{Q}$ mismatch, for the same reasons as occur in unilateral asymmetric lung disease.[3,4]

In acute unilateral asymmetric lung disease, it has been proposed that the technique of simultaneous independent lung ventilation (SILV) could be used to better match the ventilatory volume to the perfusion of each lung.[1,2] This technique results in a better gas exchange by tailoring the ventilatory pressures and time patterns of the volume delivery to each lung so as to alter perfusion to obtain better $\dot{V}/\dot{Q}$ distribution and to interfere less with cardiac filling and cardiac output levels.[12,13] In nonuniform bilateral ARDS syndromes, the SILV technique has also been advocated. It has been suggested that the asymmetric aspects of the pathophysiologic ARDS phenomena may be better isolated by placing the patient in the lateral position.[15] In this circumstance, gravity will redistribute most of the perfusion to the dependent lung. This change in posture leads to a change in the functional residual capacity (FRC) level for each lung. In the dependent lung, there will be a reduction in FRC, due to airway closure, in comparison to the FRC in the nondependent lung. This leads to an increase in ventilation to the nondependent lung at the expense of the dependent lung, thus creating a situation more like that of unilateral asymmetric lung disease, which can then also be more effectively treated by SILV.

While the clinical use of SILV techniques has become possible by virtue of the commercial development of an easily placed double lumen endobroncheal tube that can atraumatically isolate the right and left lungs,[16] no clear and easily applied guidelines have been established for initiating and quantifying the need for SILV. Different approaches to diagnosis have been suggested, including the use of radioisotopic[14] or inert gas[17] studies of $\dot{V}/\dot{Q}$ distribution, or the evaluation of lung capillary perfusion using radio-opaque contrast injected through a pulmonary artery catheter.[1] Unfortunately, while valuable, these methods are cumbersome, expensive, and often require the transport of a critically ill patient from an ICU to a radiologic facility. Also, they cannot be repeated frequently to permit fine tuning of ventilatory control on an hour-by-hour basis.

This paper addresses the application of a computer-based pulmonary evaluation technique linked to the use of a Servo Ventilator 900C (Siemens-Elema, Shaumberg, Illinois) for quantifying the mechanical properties of each lung, so as to assess the static and dynamic compliance changes by the delineation of flow, pressure, and volume relationships. These measurements can be easily repeated as frequently as desired without interrupting ventilatory support, to assure that ventilator adjustment produces the best possible gas exchange. This technique provides a set of quantitative criteria for determining when SILV should be instituted and for assessing the optimum ventilatory techniques that should be applied to each lung.

Methods

Analytic System for Analysis of Respiratory Data

A computer-based analytic system (Fig. 1) was developed for the evaluation of the dynamic respiratory pressures, flows, and volume data for intubated and ventilated patients.[18] In most cases, the inspired and expired respiratory gas partial pressures of O_2, CO_2, and N_2 were also measured by mass spectrometry (Perkins-Elmer MGA 1100, Perkins-Elmer, Pomona, CA). All of these data were entered into the computer system (VAX 11/780, Digital Equipment Co., Mainard, MA) and integrated with the pressure-flow-volume data obtained by the analytic system. The processed data is presented in graphic form on a Tektronix color terminal (Tektronix, Beaverton, OR) for interactive graphic analysis by the physician or technician performing the patient study. A range of standard plots are available to analyze the simultaneously obtained data, depending on the physiologically relevant, therapeutically related questions to be asked.

Figure 2 shows the graphic output of the analytic system. The top data line presents the inspired and expired ventilatory flows measured by ultrasonic flow meter (Perkin-Elmer VMS 1155, Perkin-Elmer, Pomona, CA). The second line demonstrates the dynamic airway pressures, including the peak and plateau airway pressures (the latter obtained by introducing an end-inspiratory pause). Shown, in addition, is the PEEP pressure above zero (atmospheric) pressure. The third line presents the volume obtained by integrating the flow signals. Also shown is the static compliance in liters/cm H_2O, computed from end-inspiratory volume/(plateau pressure-PEEP). By using a Servo Ventilator 900C as the means of ventilatory support, it is possible to do a rapid static compliance curve over the range of possible tidal volumes. This is shown in Figure 3, where the breath rate is changed at constant minute volume, thus producing a series of breaths of different tidal volumes.

In Figure 4, the dynamic data from single breaths taken at the actual and trial ventilator settings, the entire static

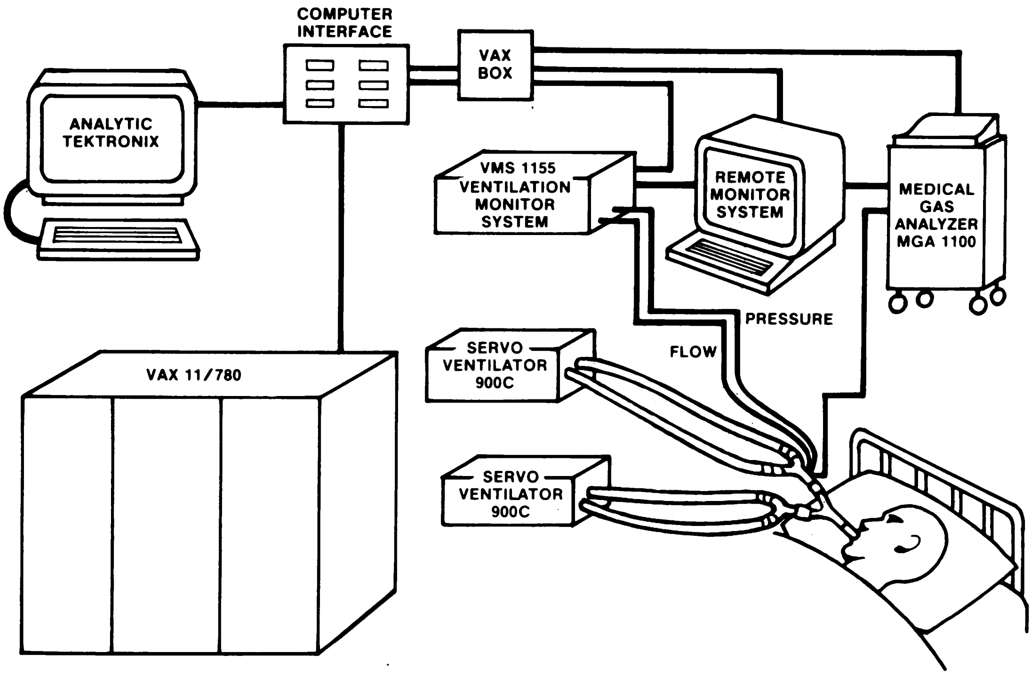


FIG. 1. Computer-based respiratory monitoring and evaluation system.

total compliance curve obtained by spline fit of the individual volume and pressure data points, and the blood gases, pH, cardiac output (CO) and computed variables (for instance, respiratory index (RI) = alveolar-arterial O_2 difference/PaO_2; per cent shunt = $\dot{Q}S/\dot{Q}T$; etc.) at the actual ventilator setting are also shown. This standard plot allows for the integration of all data and also allows the physician to see graphically the point on the static total compliance curve at which the present ventilatory support setting is maintained (actual setting *vs.* trial settings) with regard to optimizing ventilation for the particular lung mechanics demonstrated by the patient. The program will automatically subtract intrathoracic pressure from airway pressure when an esophageal balloon is used. However, since in these patients with posttraumatic lung contusion and ARDS, chest wall compliance is also an important variable modulating the response to therapy, only the total compliance data are shown. All patients were paralyzed or sedated so that no spontaneous breathing efforts were made.

Therapeutic System for SILV

The system to carry out SILV is shown in Figure 5A. In this therapeutic system, two advanced Servo Ventilators 900C are synchronized for the start of inspiration. Each

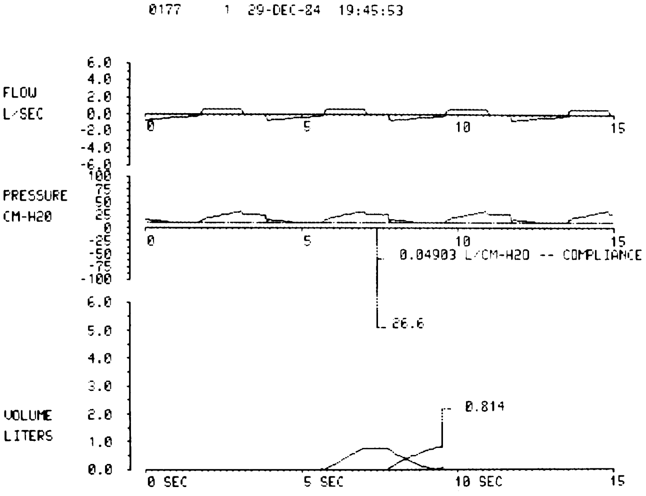


FIG. 2. Primary respiratory flows, pressures, and volume data.

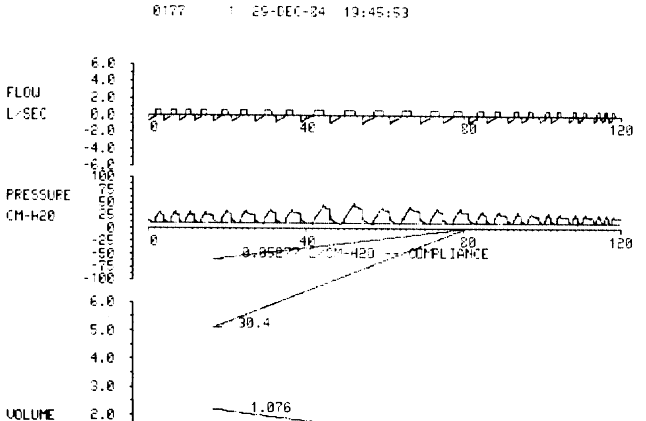
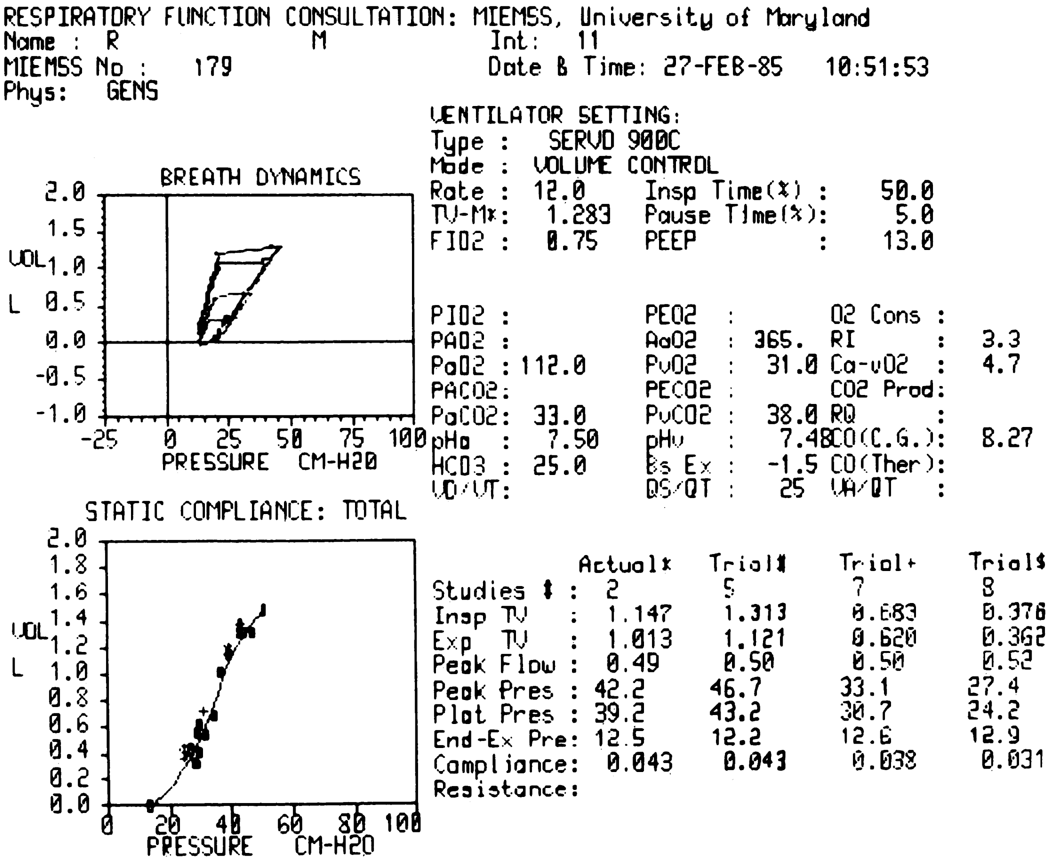


FIG. 3. Evaluation of the total static compliance curve, using the Servo-Ventilator at constant minute volume and changing the respiratory rate and end inspiratory pause, produces a series of breaths at different tidal volumes.



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RESPIRATORY FUNCTION CONSULTATION: MIEMSS, University of Maryland
Name : R                M          Int:  11
MIEMSS No :   179                  Date & Time: 27-FEB-85   10:51:53
Phys:   GENS
                              VENTILATOR SETTING:
                              Type :   SERVO 900C
                              Mode :  VOLUME CONTROL
                              Rate :  12.0     Insp Time(%) :    50.0
                              TV-Mx:   1.283   Pause Time(%):     5.0
                              FIO2 :   0.75    PEEP         :    13.0

                              PIO2 :           PEO2   :        O2 Cons :
                              PAO2 :           AaO2   :  365.  RI      :   3.3
                              PaO2 : 112.0     PvO2   :   31.0 Ca-vO2  :   4.7
                              PACO2:           PECO2  :        CO2 Prod:
                              PaCO2:  33.0     PvCO2  :   38.0 RQ      :
                              pHa  :   7.50    pHv    :    7.48CO(C.G.):   8.27
                              HCO3 :  25.0     Bs Ex  :   -1.5 CO(Ther):
                              VD/VT:           QS/QT  :    25  VA/QT   :

                                       Actual*   Trial#   Trial+   Trial$
                              Studies # :  2        5        7        8
                              Insp TV   :  1.147    1.313    0.683    0.376
                              Exp  TV   :  1.013    1.121    0.620    0.362
                              Peak Flow :  0.49     0.50     0.50     0.52
                              Peak Pres : 42.2     46.7     33.1     27.4
                              Plat Pres : 39.2     43.2     30.7     24.2
                              End-Ex Pre: 12.5     12.2     12.6     12.9
                              Compliance:  0.043    0.043    0.038    0.031
                              Resistance:
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FIG. 4. Standard graphic output from a computer program showing respiratory dynamics, static compliance curve, and blood gas data. Actual ventilator setting data can be compared with trial settings at different volumes with regard to their points on the static compliance curve.

complete system is connected to one lumen of a dual lumen Broncho-cath® (National Catheter Corp., Argyle, NY) catheter. Regardless of the side of greatest pathology, the long arm of a left angled Broncho-cath is placed in the left mainstem bronchus to avoid obstruction to the right upper lobe segmental bronchus. The proximal balloon occludes the trachea, providing a closed system. When the distal balloon is inflated, the right and left lungs can be independently ventilated by the two Servo Ventilators, using different tidal volumes, PEEPs, inspiratory/expiratory (I:E) ratios, pause times, and, in some instances, totally different ventilatory modes (*i.e.*, volume controlled in one lung *vs.* pressure controlled in the other). To start the SILV process, initially the total tidal volume is divided in half, the pressures monitored, and a compliance curve done for each lung. Then, adjustment to an appropriate pressure-volume point for each lung is carried out. The value of this approach is seen in Figure 5B, where the different static total compliance curves of the right and left lungs mandate two different volume optimization points at different PEEPs.

Other Measurements

Cardiac output (CO) was measured by thermodilution (Ther) or cardiogreen dye (C.G.) dilution at frequent intervals and after all major ventilatory changes (Fig. 4). Arterial and mixed venous O_2 saturations and the blood partial pressures of respiratory gases (PO_2, PCO_2) and pH were measured (IL-CO-Oximeter 282, IL 813 pH Blood Gas Analyzer, Instrumentation Laboratory, Lexington, MA) at the same time. The oxygen content difference ($Ca - \bar{v}O_2$), per cent pulmonary venoarterial admixture ($\dot{Q}S/\dot{Q}T$), and the respiratory index (the alveolar-arterial O_2 gradient/PaO_2 ratio) were computed as described elsewhere.[19,20]

Patient Population

Eight patients with severe asymmetrical lung pathology secondary to massive trauma or septic ARDS, or both, were treated with SILV. These cases (Table 1) all represented critically injured or ill patients with major life-threatening conditions being treated in a critical care resuscitation unit. Six of the eight died, but in all cases the cause of death was secondary either to one of the preexistant injuries (brain injury or myocardial contusion) or to refractory sepsis or its complications, including progressive refractory ARDS. All patients were either improved on SILV, or SILV allowed temporary stabilization of a deteriorating ventilatory status. In no case was SILV the cause of deterioration in pulmonary status. However, in one instance, SILV was discontinued because of diffi-

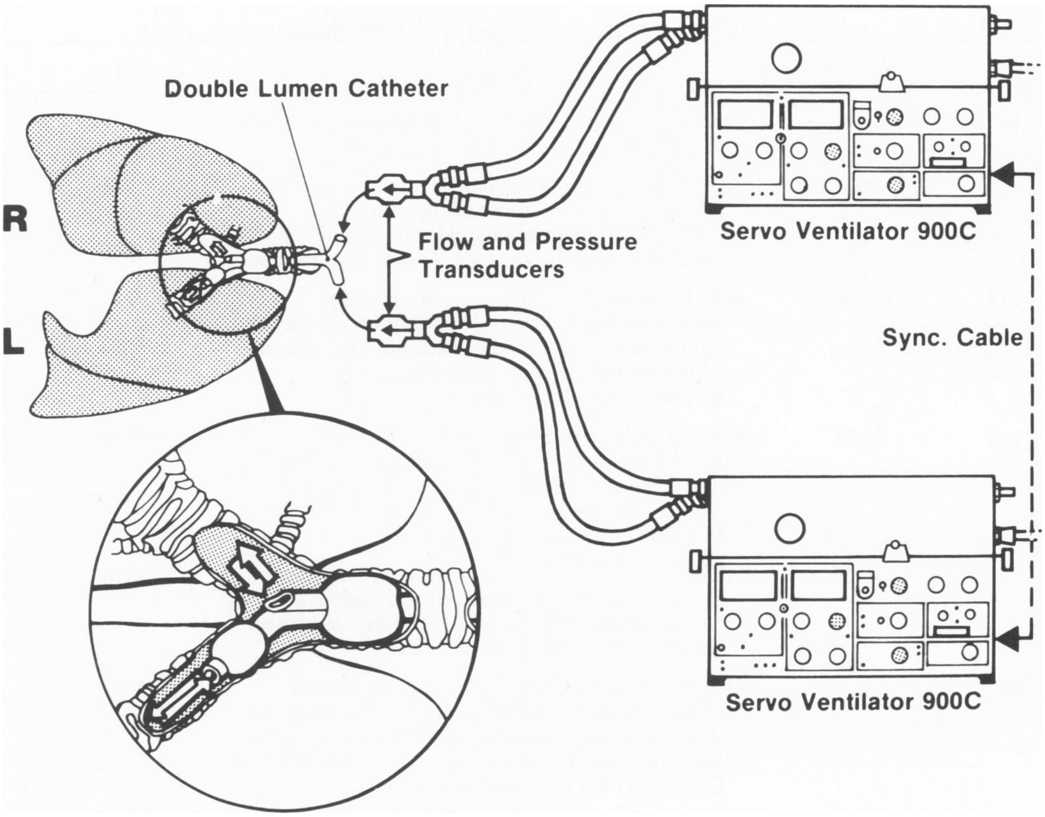


FIG. 5A. Therapeutic system for Simultaneous Independent Lung Ventilation.

culty in obtaining adequate endobronchial toilet by suctioning through the narrower tube lumens. The two cases who survived were unquestionably improved by SILV, one having sustained improvement with resolution of a unilateral posttraumatic ARDS. In the other, a patient requiring pneumonectomy for unilateral necrotizing pneumonitis, SILV provided adequate ventilation, reduced $\dot{Q}S/\dot{Q}T$ and enabled prevention of endobronchial contamination of the opposite "good" lung until definitive surgery could be successfully completed.

Results

Decisions for the Use of SILV

The static compliance curves generated by the analytic system provided means of quantifying the degree of abnormality and response to changes in therapeutic modalities. The configuration of the curves obtained during conventional ventilation together with clinical findings suggested that SILV might be beneficial in the patients presented.

Optimization of PEEP as a Test for Initiating SILV

An example of this technique is shown in patient GN: 153 (Fig. 6), who had sustained multiple traumatic injuries including a major closed head injury, myocardial contusion, and a severe right lung contusion. Total static compliance curves for both lungs together were obtained at 50 hours after injury at three different PEEP levels (15, 22, and 25 cm H_2O) to determine the optimal or "Best"[11,21] PEEP and ventilatory volume settings. In-

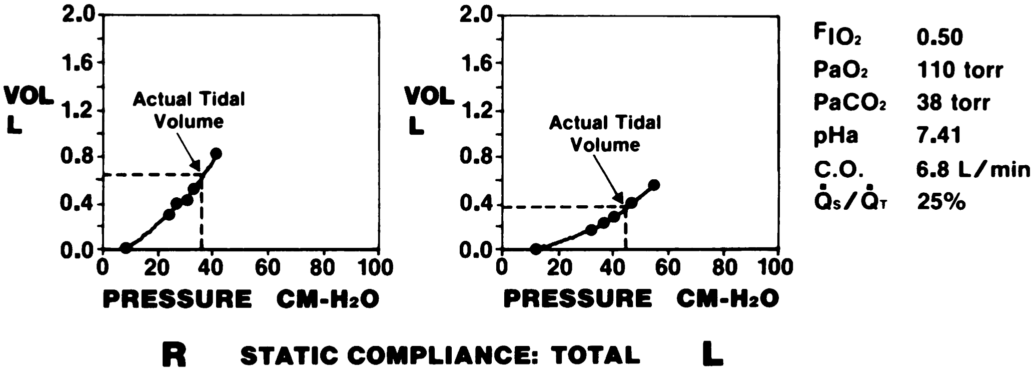


FIG. 5B. Different total static compliance curves for right and left lungs showing optimization points at different tidal volumes and PEEP levels. (Respiratory Function Consultation: MIEMSS, University of Maryland.)

TABLE 1.

Patient	Age/Sex	Diagnosis	SILV	LOS⁺/SILV⁺⁺	Outcome
152	22/M	Crush injury: Hepatic fracture, left pulmonary contusion, fractured right humerus, fractured left tibia	90 hrs.	48/19	S
158	38/M	Fall: CHI§, epidural hematoma, multiple rib fractures, left pulmonary contusion with necrotizing pseudomonas pneumonitis and empyema, left pneumonectomy for removal of septic necrotic lung	50 hrs.	195/14	S
153	18/M	MVA* motorcyclist: CHI§ occipital contusion neurogenic shock, myocardial contusion, fractured right humerus, right pulmonary contusion, sepsis and empyema with thoracotomy drainage and debridement of necrotic clot	91 hrs.	58/4	D
165	66/M	Referred for HBO** after clotted aortofemoral graft: necrotizing fascitis of right hip, requiring eventual hip disarticulation, COPD†† with septic ARDS, torsion of left lung with necrosis of lung, left pneumonectomy, PE† with inferior vena cava clipping	66 hrs.	100/19	D
174	27/M	MVA*: CHI,§ brain contusion, contusion, myocardial contusion, left diaphragmatic rupture, gastric and hepatic contusion, left humeral fractures, sepsis and septic ARDS, MOFS‡ with DIC‡‡, PE†	48 hrs.	5/4	D
167	24/M	MVA* Pedestrian: CHI,§ epidural hematoma and cerebral contusion, basilar skull fractures, left pneumo thorax with lung contusion open bilateral, tibia and fibula fractures, Pseudomonas, pneumonitis, PE† with Greenfield filter in inferior vena cava	46 hrs.	17/12	D
176	16/M	Blast injury: face and chest contusions, right pulmonary contusion, myocardial contusion with pericardial tamponade, renal failure	53 hrs.	23/1	D
179	18/M	MVA*: Hemopneumothorax left lung contusion, splenic laceration and splenectomy, necrotizing Staphalococcus pneumonitis, renal failure sepsis, and MOFS‡	90 hrs.	24/3	D

⁺ LOS = Total length of stay (days) until discharge (S) or death (D).
⁺⁺ SILV = Day on which SILV begun during LOS.
* MVA = Motor vehicle accident.
† PE = Pulmonary embolus.
‡ MOFS = Multiple organ failure syndrome.
§ CHI = Closed head injury.
** HBO = Hyperbaric oxygen therapy.
†† COPD = Chronic obstructive lung disease.
‡‡ DIC = Disseminated intravascular coagulation.
Unit numbers were altered to prevent patient identification.

spection of the total static compliance curves (CST) shows that there are marked changes in compliance at the different inspired volumes and PEEP levels used to generate these curves (Fig. 6). At an inspired volume of 0.9 L, a PEEP of *15* cm H_2O resulted in a CST of 0.041 L/cm H_2O; a PEEP of *22* cm H_2O resulted in a CST of 0.047 L/cm H_2O, as shown by the steeper slope of the pressure volume relation; and at a PEEP of *25* cm H_2O, the CST was 0.027 L/cm H_2O. When the inspired volume was increased to 1.2 L, CST was increased to 0.052 L/cm H_2O at a PEEP of 15 cm H_2O. However, there was no significant change in CST at any inspired volume when the PEEP was 25 cm H_2O. At a PEEP of 25 cm H_2O, the compliance curve was essentially linear, and CST was equal to 0.027 L/cm H_2O *at all inspired volumes.*

These data were interpreted to mean that, at a PEEP of *15* cm H_2O, the increase in CST from 0.041 L/cm H_2O to 0.052 L/cm H_2O, as volume was increased, indicated that additional lung units were being opened at the higher inspired volumes. This is the result of the increased airway pressure required to deliver volumes above the critical opening pressure of the contused lung units. However, on expiration to these compromised lung units again deflated since the PEEP level was not sufficient to keep them open.

When the PEEP level was increased from 15 to *22* cm H_2O at an inspired volume of 0.9 L, the CST increased from 0.041 to 0.047 L/cm H_2O, indicating that additional lung units were now being ventilated at the same tidal volume. However, a further increase in inspired volume to 1.2 L resulted in a decrease in compliance to 0.029 L/cm H_2O. There was a flattening of the compliance curve above an inspired volume of 1.0 L, indicating that at higher inspired volumes the lung was being overdistended and therefore its compliance was decreasing. Below this critical volume, however, the compliance was at its optimal level, and thus this volume point was chosen as the "optimal" point for ventilatory support at "best" PEEP by conventional volume-controlled ventilation.

If one looks at the actual airway pressure levels necessary to insure an optimum compliance at a PEEP of *15*, or of *22* cm H_2O, there was essentially no difference. However, using the higher end-expiratory pressure of 22 cm H_2O was more beneficial since those lung units with a higher critical opening pressure did not close during expiration because the airway pressure was not permitted to fall below this level, as occurred when using a lower end-expiratory pressure and a higher tidal volume. This beneficial effect can be seen in the increase in the PaO_2 and the decrease in $PaCO_2$ and RI with the increase in PEEP from 15 to 22 cm H_2O (Table 2). This suggests a more uniform alveolar ventilation and $\dot{V}/\dot{Q}$.

Criteria for Identifying Asymmetric Lung Disease from "Best" PEEP Studies

Small changes in PEEP may have major deleterious effects in acute asymmetrical lung pathology if they rise above the optimal compliance level. This is shown by the static compliance curve (Fig. 6) obtained at a PEEP of 25 cm H_2O. There is now a marked decrease in the total static compliance with a disproportionate rise in pressure as tidal volume was increased, indicating overdistention of lung units. This overdistention leads to an increase in the physiologic dead space, as evidenced by the increase in $PaCO_2$ (Table 2) from 36 to 40 mmHg at the same minute ventilation. Although oxygenation is maintained, as shown by the unchanged PaO_2, there was no further improvement in either RI or $\dot{Q}S/\dot{Q}T$, indicating that the optimum level was reached at 22 cm H_2O. Further increases in PEEP in this type of patient are likely to lower cardiac index or result in increases in dead space and further $\dot{V}/\dot{Q}$ disparity because of increases in capillary resistance caused by the Starling resistance effect of excess pressure on the more normal alveolar capillary beds.

Studies of this nature that use different PEEP levels to show the multicomponent nature of the compliance curve, and where there is a disparity in the compliance and blood gas response to changes in the PEEP level, suggest that the disease process is nonuniform. If the clinical findings also suggest that the disease process is asymmetric, a trial of SILV is indicated. This patient had sustained a contusion to his right lung. Studies performed on the fourth day after the trauma showed a further deterioration in the patient's status with an increase in $\dot{Q}S/\dot{Q}T$ from 28 to 47% and a decrease in total static compliance from 0.047 L/cm H_2O to 0.023 L/cm H_2O. The contused right lung continued to bleed and, in an effort to prevent further spillover into the left lung, a Broncho-cath tube was inserted and the patient was placed on SILV.

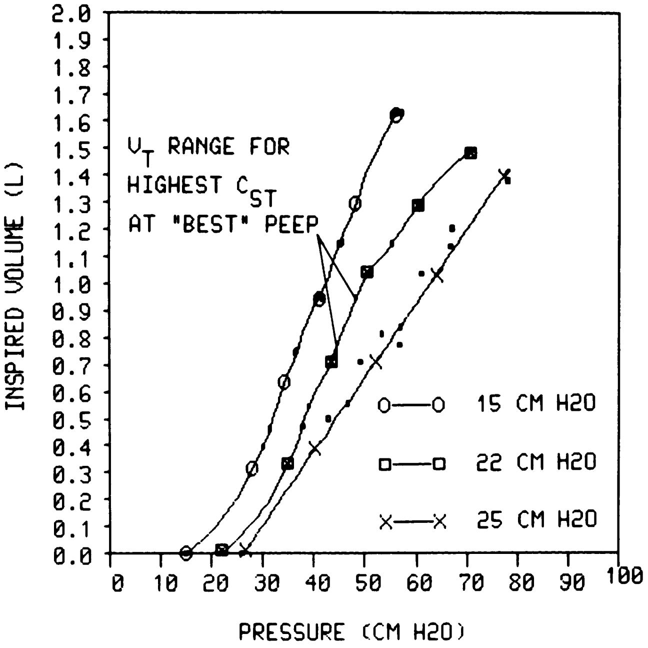


FIG. 6. Optimization of pressure-volume relations at different PEEP levels. "Best" PEEP and ventilatory volume setting chosen as described in the text (patient 153).

Asymmetric Lung Pathology

Compliance studies were performed on each lung individually (Fig. 7) as a guide to the selection of the appropriate tidal volume, flow pattern, and PEEP level for the right and left lungs. The total static compliance of the right or damaged lung was 0.011 L/cm H_2O at 20 cm PEEP (Fig. 7) at V_T of 0.303 L. The better left lung initially had a CST of 0.017 L/cm at the same PEEP level, but upon reducing the PEEP level to 15 cm H_2O on the left lung, its total static compliance increased to 0.022 L/cm H_2O (Fig. 7) at a V_T of 0.677 L. This clearly shows the differences in the mechanical properties of the two lungs.

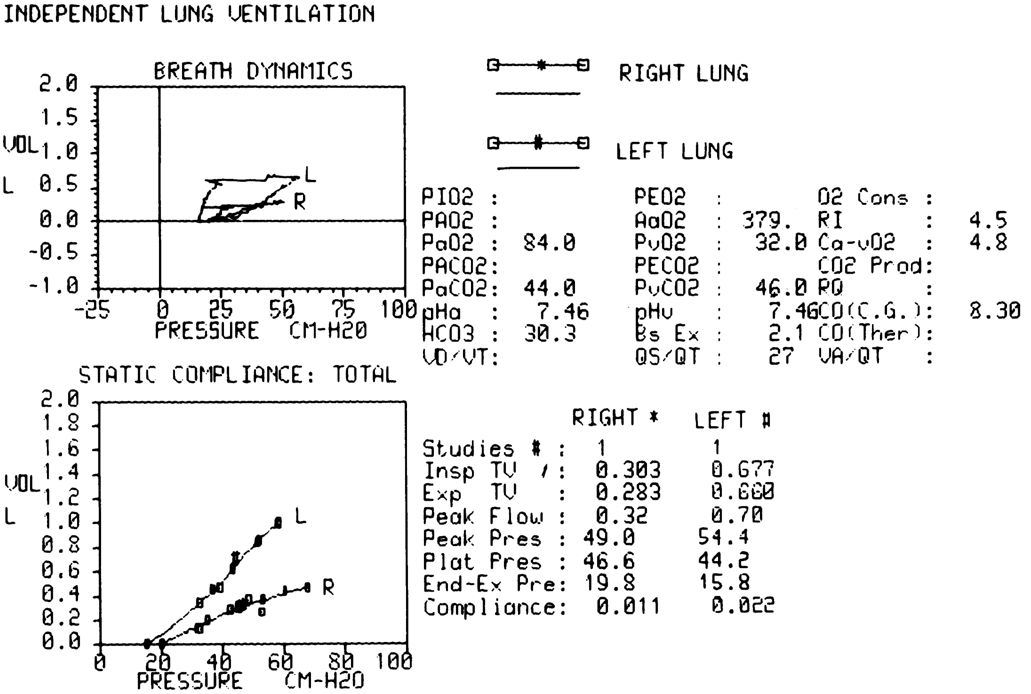
Figures 8 and 9 show the changes in the total static compliance curves induced by SILV for the right and the left lungs, respectively.

In the right lung (Fig. 8), the PEEP level was maintained at 20 cm H_2O for the 91 hours of therapy. By applying

TABLE 2. *Patient 153*

		BEST	
PEEP	15	22*	25 cm H_2O
CST (VT = 0.9 L)*	0.041	0.047*	0.027 L/cm H_2O
CST (VT = 1.2 L)	0.052	0.029	0.027 L/cm H_2O
FIO_2	0.50	0.50	0.50
$PaCO_2$	41	36	40 mmHg
PaO_2	62	76	77 mmHg
RI	3.3	2.6	2.5
$\dot{Q}S/\dot{Q}T$	—	28	28%

* "Best" PEEP and V_T relationship.



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PIO2  :            PEO2    :          O2 Cons  :
PAO2  :            AaO2    :  379.    RI       :   4.5
PaO2  :  84.0      PvO2    :   32.0   Ca-vO2   :   4.8
PACO2:             PECO2   :          CO2 Prod:
PaCO2:  44.0       PvCO2   :   46.0   RQ       :
pHa   :   7.46     pHv     :    7.46CO(C.G.):   8.30
HCO3  :  30.3      Bs Ex   :    2.1   CO(Ther):
VD/VT:             QS/QT   :    27    VA/QT    :

                  RIGHT *   LEFT #
Studies #  :       1         1
Insp TV  / :     0.303     0.677
Exp  TV    :     0.283     0.660
Peak Flow  :     0.32      0.70
Peak Pres  :    49.0      54.4
Plat Pres  :    46.6      44.2
End-Ex Pre:     19.8      15.8
Compliance:      0.011     0.022
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FIG. 7. Individual dynamic and static compliance relations for right and left lungs in patient 153 at beginning of SILV. (Date: 10/19/83).

this sustained high PEEP and progressively raising the tidal volume to the optimum point, as described earlier, an improvement in the mechanical properties of the right lung was achieved, with the compliance increasing from 0.009 L/cm H_2O to 0.015 L/cm H_2O during the period of SILV therapy.

The PEEP level was set to 15 cm H_2O for the left lung. Selected total static compliance curves of the less damaged left lung are shown in Figure 9. The middle curve was obtained at a PEEP of 15 cm H_2O and is representative of the studies obtained daily while on SILV at this PEEP level. On October 20, 1983, the PEEP level was increased to 20 cm H_2O in this lung to assess the necessity for continuation of SILV. There was a slight decrease in the total static compliance from 0.023 to 0.021 L/cm H_2O at the "optimum" tidal volume of 0.7 L. Above this tidal vol-

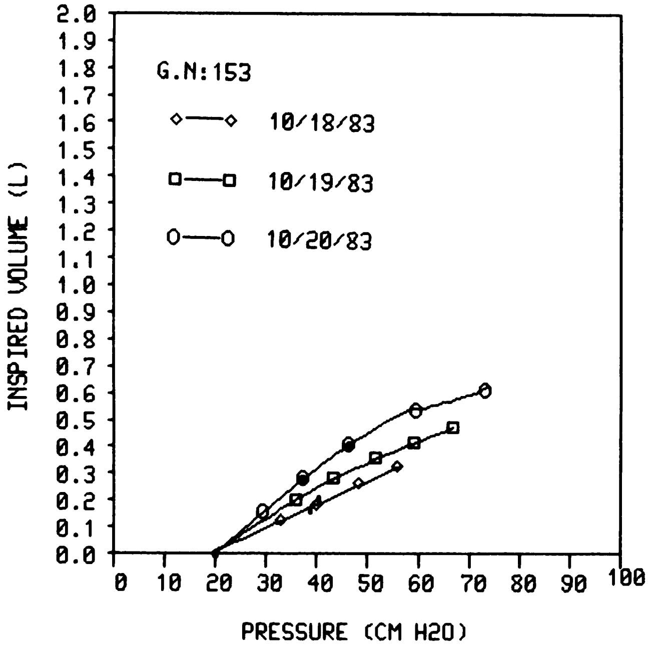

FIG. 8. Changes in static compliance curves induced by SILV in right lung (patient 153).

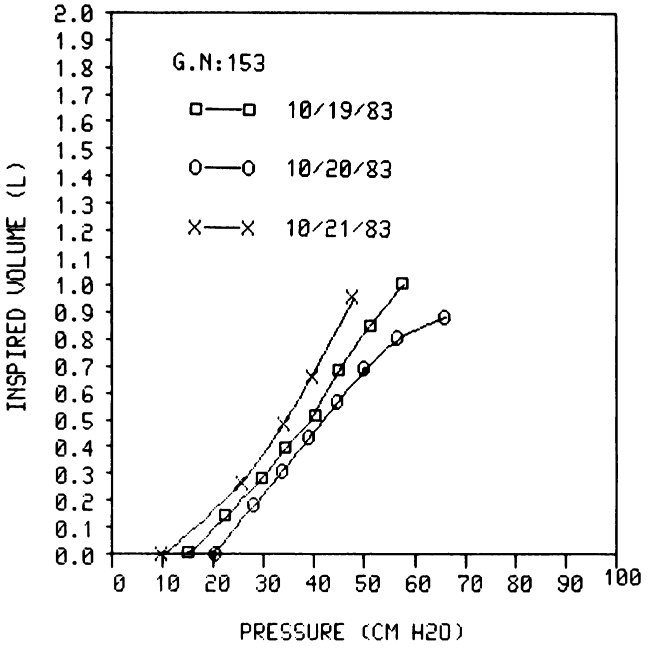

FIG. 9. Changes in static compliance curves induced by SILV in left lung (patient 153).

TABLE 3. *Response of Patient 153 to SILV Therapy*

	SILV Start		SILV	SILV	SILV End	
	10/18/83		10/19/83	10/20/83	10/21/83	10/22/83
FIO_2	1.0*	1.0	0.70	0.60	0.50	0.55
PaO_2	59*	71	84	102	81	64 mmHg
$\dot{Q}S/\dot{Q}T$	47*	40	27	21	31	41%
RI	10.3*	8.5	4.9	2.7	3.1	5.3
CST (right)	—	0.009	0.012	0.015	0.015	—
CST (left)	—	0.022	0.023	0.021	0.024	—
CST (right and left)	.023	0.031	0.035	0.036	0.039	0.041 l/cm H_2O

* Gas exchange values immediately prior to SILV Therapy.

ume, however, there was a readily apparent difference in the slope of the compliance curve, indicating overdistention of the left lung at the PEEP level found necessary to prevent airway closure and alveolar collapse in the right lung. SILV was continued. The following day a "trial" lowering of the PEEP level to 10 cm H_2O resulted in a deterioration in oxygenation, although there was no change in the total static compliance, indicating that a PEEP level of 15 cm H_2O was optimal for the left lung.

The results of SILV therapy can be seen from the values of FIO_2, PaO_2, $\dot{Q}S/\dot{Q}T$, RI, and compliance at the optimum point for each lung shown in Table 3. The PaO_2 rose from *59* mmHg on October 18, 1983, before SILV to *81* mmHg on October 21, 1983, during SILV as FIO_2 was decreased from 1.0 to 0.50. Shunt fell from 47 to 31%, and RI decreased from 10.3 to 3.1. The increases in right lung compliance, total (right plus left) static compliance, and oxygenation suggested that SILV was able to influence resolution of the postcontusive element of ARDS without further increase in the risk for barotrauma or compounding $\dot{V}/\dot{Q}$ mismatching. However, when the patient was placed back on conventional ventilation, the shunt increased to 41%, suggesting that this patient may have benefited from longer treatment on SILV. Unfor-

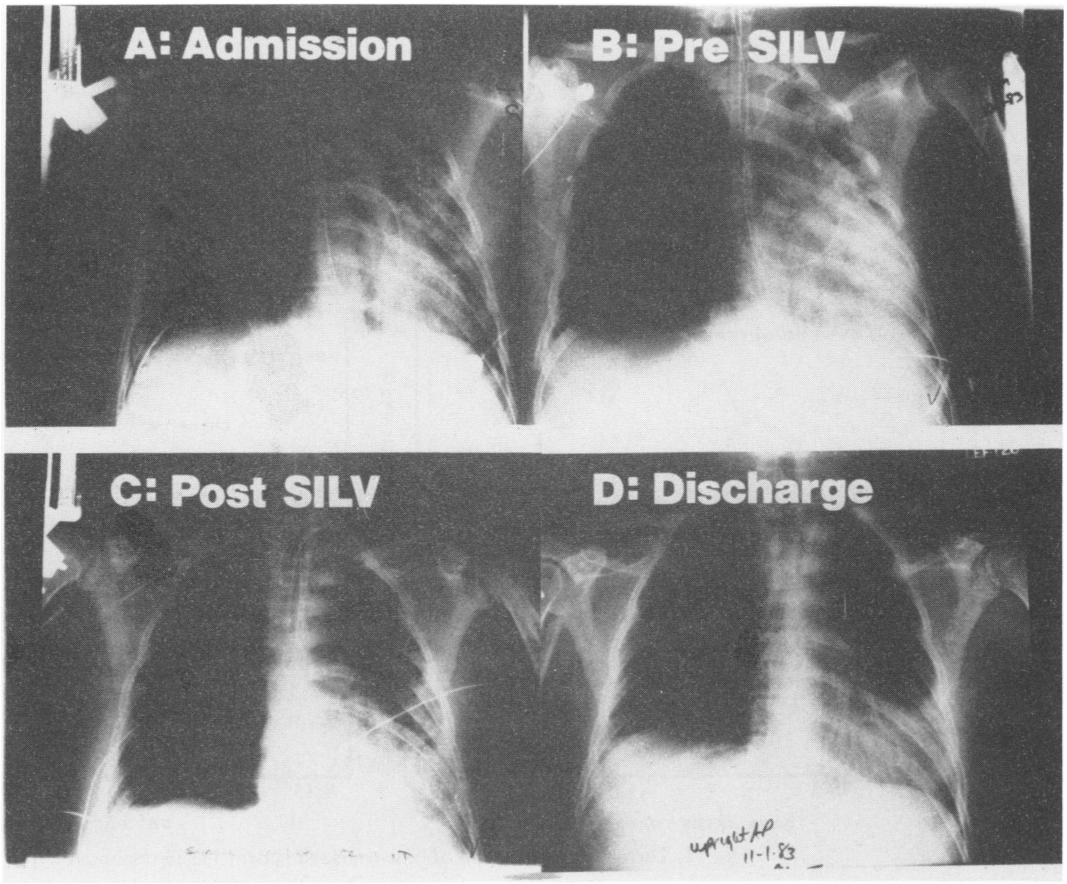

FIG. 10. Radiologic examination of posttraumatic unilateral atelectasis (patient 152). *A*, (9–14–83) Admission, post-resuscitation, post-injury to left lung; *B*, (10–3–83) Persistant atelectatic ARDS with hyperexpansion of right lung on conventional ventilation, immediately prior to SILV; *C*, (10–5–83) Improvement in aeration of left lung on SILV; *D*, (11–1–83) Sustained resolution of ARDS immediately before discharge from hospital.

TABLE 4. *Response of Patient M.C.:152 to SILV Therapy*

	SILV Start	SILV	SILV	SILV End
	10/3/83	10/4/83	10/5/83	10/6/83
FIO_2	0.50*	0.34	0.34	0.30
PaO_2	103*	135	175	122 mmHg
$\dot{Q}S/\dot{Q}T$	20*	13	5	10 %
RI	2.1*	0.2	0.1	0.3
CST (right)	0.020	0.020	0.018	0.020 l/cm H_2O
CST (left)	0.005	0.013	0.011	0.012 l/cm H_2O

* Gas values immediately before SILV therapy.

tunately, this patient succumbed 51 days after SILV as a consequence of complications related to his neurologic injury and late progressive septic pneumonitis due to aspiration and secondary infection of the injured lung.

Reversing Anatomic and Physiologic Changes of Persistent Atelectatic Unilateral Posttraumatic ARDS

In addition to providing a physiologically directed therapy aimed at the reduction of posttraumatic ventilation/perfusion abnormality, the use of SILV in selected instances can reverse persistent atelectatic changes associated with ARDS. This can take place even late in the clinical course, provided irreversible fibrotic or necrotic changes have not occurred. This is shown in patient 152 (Fig. 10A), where a persistent ARDS pattern was seen despite the continuous use of PEEP and high tidal volumes with conventional ventilation. Attempts to re-expand the left lung while on conventional ventilation brought about marked increases in airway pressure to the right lung as well, resulting in overdistention barotrauma (Fig. 10B). There was also a diversion in blood flow from the relatively compliant area, which produced an increase in shunt fraction (Table 4 and Fig. 11). With the initiation of SILV, there was improvement in the shunt fraction from 20 to 10% and in the RI from 2.1 to 0.3 (Table 4 and Fig. 11).

A comparison of the static compliance relations for the total lung and the individual right and left lung compliances are shown for the period corresponding to the start of SILV (Fig. 12) on October 3, 1983, and the period at the end of SILV (Fig. 13) on October 6, 1983. The quantitative gas exchange and compliance data are presented in Table 4. The initial study before SILV (October 3, 1983) demonstrated marked difference in the mechanical properties of the right and left lung. The chest x-ray (Fig. 10B) at this time showed a marked dissimilarity in aeration between the lungs. This correlated with the total compliance curve for both lungs obtained immediately before the initiation of SILV, which had two distinct slopes (Fig. 12) with tangents equivalent to compliances of 0.029 at a V_T of 0.6 L and 0.011 L/cm H_2O at a V_T of 1.2 L, indicating unilateral or asymmetrical lung pathology. Ini-

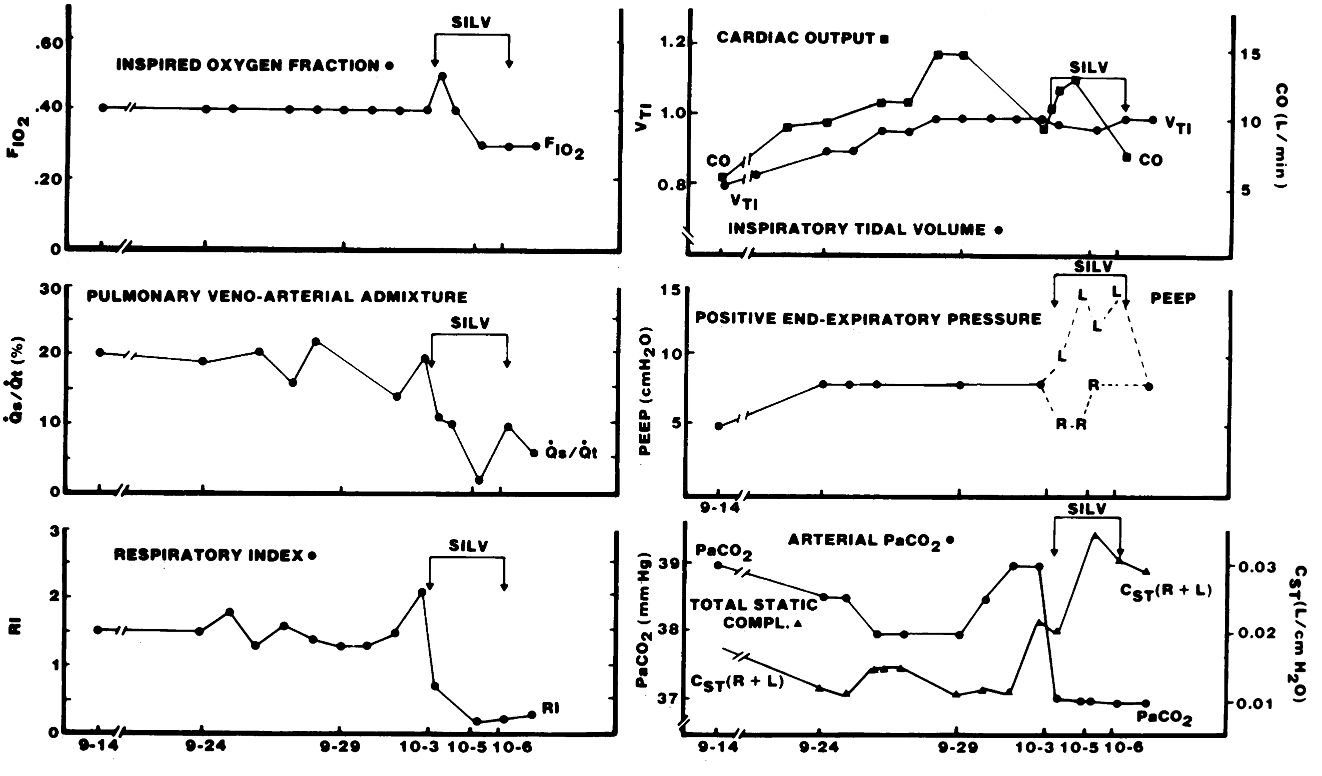

FIG. 11. The physiologic aspects of time course of patient 152 in response to SILV.

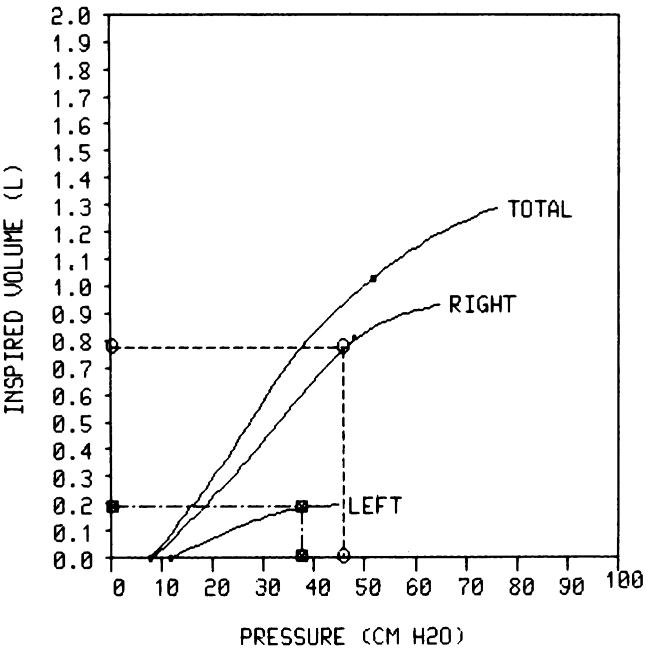

FIG. 12. Comparison of static compliance relations in right and left lungs of patient 152 immediately before SILV.

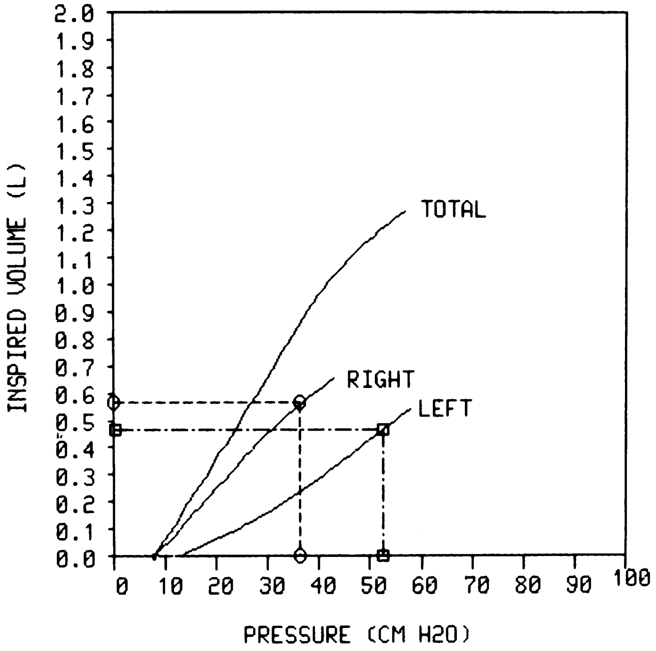

FIG. 13. Comparison of static compliance relations in right and left lungs of patient 152 immediately before termination of SILV.

tially, the compliance of the left lung was 0.005 L/cm H_2O and only a V_T of 0.2 L could be delivered to this lung (Fig. 12). Attempts to increase this volume led to marked increases in airway pressure with minimal improvement in the amount of volume actually delivered, as evidenced by the plateau in the compliance curve for this lung. A V_T of 0.8 ml delivered to the right lung was required to maintain gas exchange. This resulted in hyperinflation, even though low PEEP was applied. The left lung was re-expanded by using a PEEP level of 12 cm H_2O and gradually increasing the tidal volume delivered. It was thus possible to reduce the V_T to the right lung and thereby to lower the distending pressures in this lung to more reasonable levels (Fig. 13). The compliance improved from 0.005 to 0.012 L/cm H_2O, and there was marked improvement in the chest x-ray (Fig. 10C). The improvement was sustained, and the atelectasis continued to resolve upon the discontinuation of SILV (Figs. 10D and 11).

Therapy of Bilateral Asymmetrical ARDS

The use of SILV with lateral positioning is shown for a patient (179) who had diffuse bilateral posttraumatic and septic ARDS with an associated bronchial air leak decompressed by a chest tube on the left side (Table 5). Initially, the patient was placed on SILV and kept in the supine position with deterioration of the patient's pulmonary status, even though many adjustments were made over a 12-hour period (18:35 P.M. to 7:00 A.M. studies) to optimize ventilation settings. It was decided to place the patient in the left lateral position at 9:00 A.M., with

TABLE 5. *Response of Patient 179 to SILV Therapy*

Ventilation	CMV	SILV		SILV		SILV	
Position	Supine	Supine (18:35 P.M.)		Supine (7:00 A.M.)		L Lateral (10:45 A.M.)	
FIO_2	1.0	1.0		1.0		1.0	
PaO_2	66	70		43		88 (mmHg)	
RI	9.1	8.4		14.8		5.9	
$\dot{Q}S/\dot{Q}T$				63		36 (%)	
Lung	Both	R	L	R	L	R	L
Mode	PC	PC	PC	PC	PC	PC	VC
PEEP	12	6	14	10	10	13	12 (cm H_2O)
Mean press	24	17	24			28	33 (cm H_2O)
VTI	0.795	0.490	0.412			0.588	0.563 liter
VTE	0.663	0.456	0.305			0.557	0.502 liter
Compliance	0.026	0.023	0.014			0.015	0.016 (L/cm H_2O)

R = Right; L = Left; PC = Pressure control; VC = Volume control; VTI = Inspired tidal volume; VTE = Expired tidal volume.

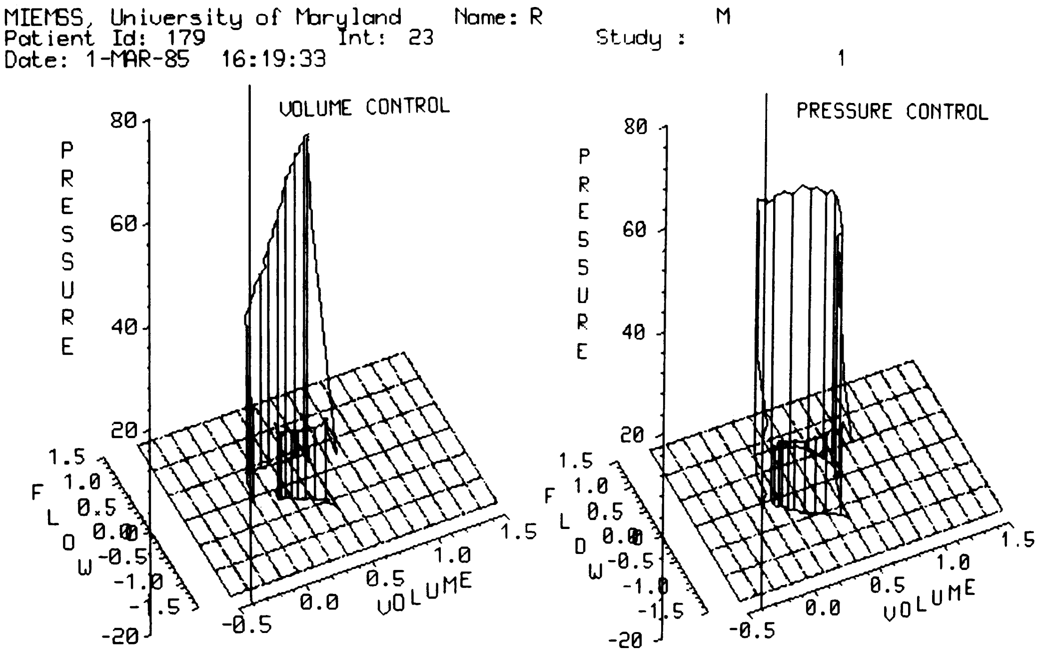

FIG. 14. Comparison of dynamic pressure-flow-volume relations of the left lung in patient 179 while on SILV. Graph shows a reduction in air leak from 164 to 69 ml in response to the change from *volume* control to *pressure* control in the left lung while in the supine position. (The right lung was maintained on pressure control.)

results as shown in the 10:45 study in Table 5. Both lungs were ventilated with *pressure-controlled* ventilation in the supine position. However, when the patient was placed in the left lateral position, the dependent lung was ventilated with *volume-controlled* ventilation to assure a constant volume with a higher mean pressure in the dependent lung. This change in position with pressure adjustment to favor increased perfusion of the superior lung resulted in an apparent improvement in $\dot{V}/\dot{Q}$ distribution. The change in PaO_2 with positioning was from 43 mmHg to 88 mmHg on FIO_2 1.0. There was a further increase in PaO_2 to 129 mmHg on FIO_2 0.80 over the next 24-hour period. The shunt decreased from 63 to 36% initially, with further improvement to 27%, and the RI fell from 14.8 to 3.1 during this period.

Since sufficient improvement had occurred after ventilation in the lateral position, it was possible to place the patient back in the supine position. However, because of the persistant air leak, the left lung was again placed on pressure-controlled ventilation. This led to a more uniform pressure profile as volume expansion occurred, compared to the previous volume-controlled ventilatory mode. This also stopped the air leak. The three-dimensional pressure-flow-volume curves shown in Figure 14 demonstrate the differences between pressure and volume control in the left lung in the supine position. The right lung was maintained on pressure control throughout. By applying a pressure sufficient to overcome the critical airway opening pressure during the early phase of inspiration, a more even volume distribution and more complete expansion of the lung was achieved during pressure-controlled ventilation, which resulted in better control of the air leak. This can be seen in Figure 14, where the gap in the flow-volume plane, representing the nonexpired volume lost *via* the air leak, is reduced.

In eight patients, 20 hours of SILV produced a significant ($p < 0.05$) increase in the net tidal volume that could be delivered to the two lungs if the separate tidal volumes were combined, compared to what could be delivered by conventional therapy to the two lungs considered as a unit (Fig. 15). This occurred while maintaining lower plateau and peak pressures in the less damaged lung and generally produced a higher combined total (right plus left) compliance. $PaCO_2$ was essentially unchanged while the RI (and shunt) tended to fall and the PaO_2 to rise at any FIO_2.

Discussion

Recent studies of patients with acute unilaterally asymmetrical lung disease have suggested the use of independent lung ventilation (SILV) employing a greater level of positive end-expiratory pressure (PEEP) in the diseased lung to overcome the reduced compliance and to effect better ventilation of collapsed alveoli.[1-4] Experimental studies[10] have suggested that pulmonary contusion that reduces ventilation and pulmonary compliance also increases the per cent shunt ($\dot{Q}S/\dot{Q}T$) in the injured lung, but that the resulting increased hypoxic vasoconstriction diverts blood flow to the uninjured side, thus minimizing the effects of the injury. However, the application of PEEP, which assists in opening small airways and alveoli, may alter the balance of perfusion by shifting blood flow back to the low $\dot{V}/\dot{Q}$ and shunt areas. This occurs as a function of its relative effectiveness in opening closed alveoli and because of its effect in reducing perfusion to more compliant alveoli by transmitting the PEEP pressure to the normal alveolar capillaries, thus acting as a Starling resistance at the capillary level.[23,24] West[25] and Hedenstierna[17] have shown that the normal dependent lung has the greatest degree of perfusion. However, with generalized PEEP, the relative perfusion of the dependent lung increased. In the clinical setting, both trauma and sepsis have been shown to induce a hyperdynamic cardiovascular state in which perfusion to the dependent lung is increased. As a consequence, there is a total flow increase relative to the available ventilation to the contused or dependent edematous ARDS lung that tends to increase the magnitude of the $\dot{Q}S/\dot{Q}T$ as a function of the increase in cardiac index.[6]

There is a therapeutic paradox imposed by this pathophysiologic problem; namely, that controlled volume ventilation with generalized PEEP may increase flow through the low $\dot{V}/\dot{Q}$, low compliance lung while reducing that through the high compliance, high $\dot{V}/\dot{Q}$ lung. This occurs at the same time that the PEEP effect assists in opening underventilated alveoli, by raising mean airway pressures above the now increased critical opening pressures in the injured lung. This pathophysiologic sequence has suggested that a technique of independent ventilation of the normal *versus* the injured lung may be beneficial.[14] SILV has been applied with some success to unilateral lung contusion,[4] lobar pneumonia,[2] and refractory unilateral atelectasis.[26] More recently, it has been suggested that even acute asymmetric bilateral lung pathology may be treated by independent lung ventilation in the lateral position,[13-15] thus artificially creating a situation of one lung with increased perfusion (the dependent lung) and the other lung (the nondependent lung) with increased ventilation. Then by using selective PEEP and pressure or volume-controlled ventilation, it may be possible to shift perfusion upwards to the hyperventilated nondependent lung, while simultaneously increasing ventilation to the hyperperfused dependent lung, thereby effecting a more even $\dot{V}/\dot{Q}$ matching.[13-15]

The difficulties in achieving an optimal ventilatory solution to this set of clinical problems have been in three areas. The first has been the need for an easily insertable double lumen bronchial catheter for separation of the two lungs. The second has awaited the development of a suitable dual ventilator system with sufficient flexibility to accommodate all of the variations of PEEP, volume, flow, I:E ratio, and in the modalities of pressure and volume-controlled support required to meet all possible clinical situations. The third need has been for a simple, clinically applicable bedside technique of ventilatory assessment by which the magnitude of the asymmetrical lung pathology can be rapidly assessed, criteria for the initiation of SILV can be established, and management of this therapy effected.

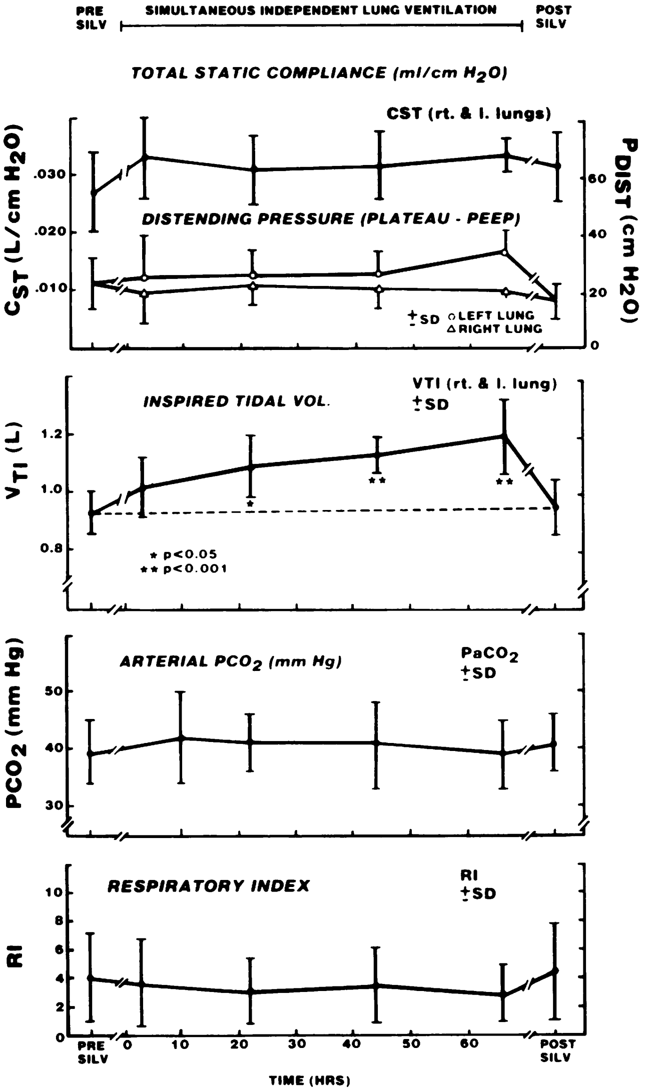

FIG. 15. A summary of the physiologic effects of SILV in eight patients. There is a significant increase in total inspired tidal volume (right and left lung) with no increase in distending pressure (P_{DIST}). Also shown are a trend for improvement in combined (right and left) compliance and respiratory index suggesting improvement in ventilation/perfusion distribution.

The present study suggests that sufficient progress has now been achieved in all of these areas to make the SILV technique a clinically relevant method for early, safe, and effective therapy in selected patients. The full range of indications and limitations has yet to be determined, but the initial guidelines and clinical physiologic justification for its use seem established.

Acknowledgments

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DISCUSSION

DR. LEWIS FLINT, JR. (Buffalo, New York): I enjoyed listening to the data, and, because I have been frustrated on several occasions by this problem, I find that I have several questions to ask Dr. Siegel that do not necessarily relate to the feasibility or the technology of his system but to what we might learn about the pathophysiology of the condition from such a system.

First of all, it has seemed to me that clinically identifiable barotrauma to the lung in a patient receiving high levels of PEEP and adjuvant ventilator therapy has been more or less randomly distributed in patients who have identifiable unilateral worse ARDS *versus* bilateral severe ARDS, and I would ask Dr. Siegel if this system, when applied to patients with bilateral disease, does, in fact, lower the frequency of clinically identifiable barotrauma by the ability to identify the worse lung.

The second question I have has to do with the differences between ARDS hypoxemia produced as a result of pulmonary contusion, which I think is the clinical example he showed us, *versus* ARDS produced by systemic sepsis, and whether the measurements of lung mechanics can help us to differentiate any differences in pathophysiology between these two processes.

And the third question has to do with the explanation for the reduced shunt. In the two examples that were presented in the abstract, there was one marked reduction in intrapulmonary shunting and one relatively modest reduction in intrapulmonary shunting. I would ask whether Dr. Siegel has made some measurements with regard to separating pulmonary blood flow and pulmonary vascular resistance to identify the mechanism that might result in reduced shunt.

DR. RICHARD M. PETERS (San Diego, California): I want to congratulate Dr. Siegel for showing us again what we have come to expect from him—the use of nicely designed, complex methods of analysis—in this presentation of sophisticated pulmonary physiology. I guess that the computer processing involves long and complex programs. Certainly the front end instrumentation is both expensive and intricate.

My first question is, how much is your analysis and decision making dependent on the mechanical measurements and how much requires a gas analysis system? The mechanical sensors are cheaper and more generally available.

My second question is about therapy. You use two ventilators for the patients with one stiff and one compliant lung. These must be coordinated and more than double the cost of and skill required to manage the ventilators. How well would you expect the poor man's ventilators to work? Namely, to position the patient with the good lung down to (1) increase its perfusion, and (2) compress it with the weight of the mediastinum and abdomen so that it is protected from hyperexpansion.

This is a very nice study and demonstrates a combination of measurement of coordination of ventilation and perfusion and analysis of