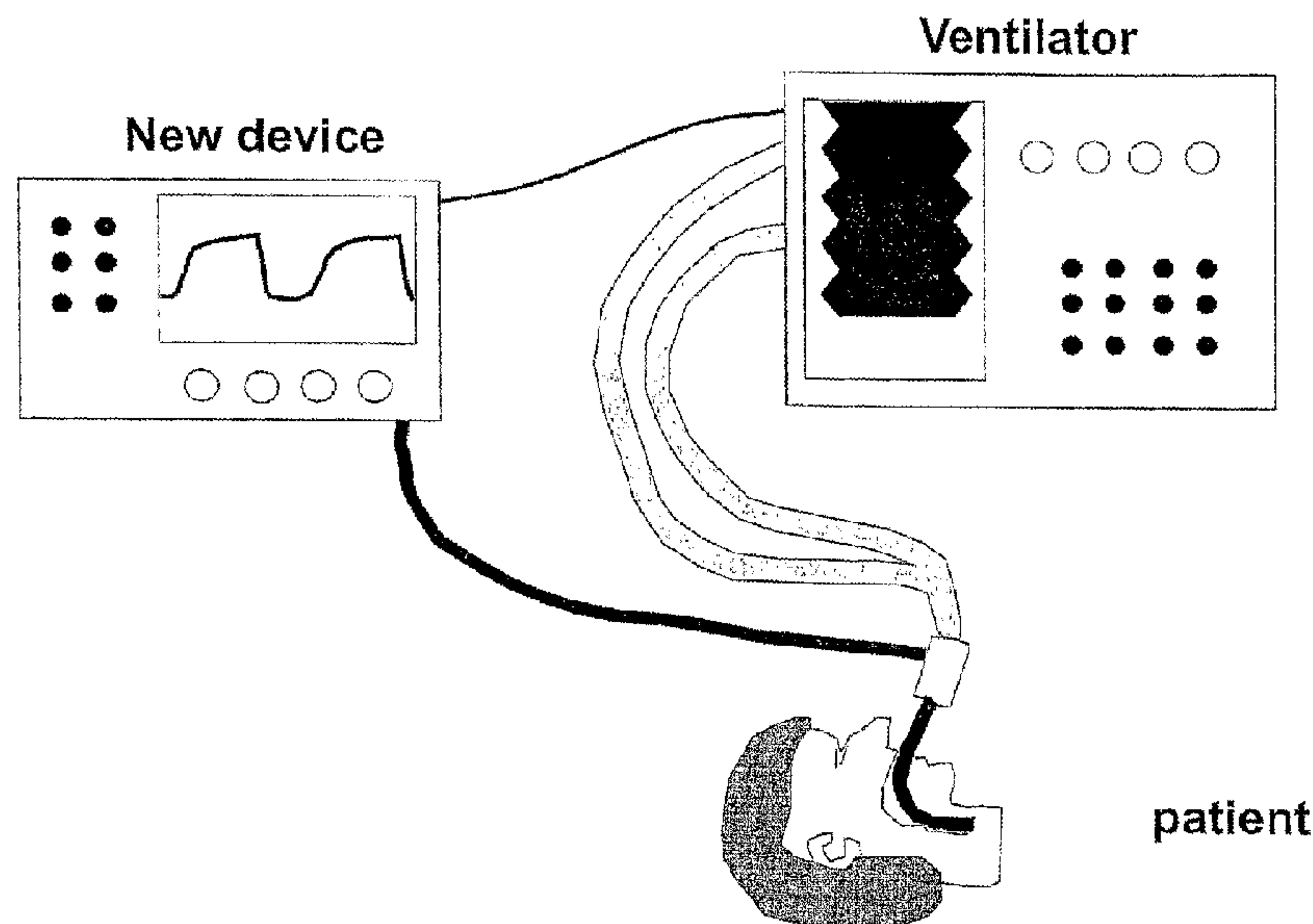




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(54) **Titre : PROCÉDE ET APPAREIL NON INVASIFS POUVANT OPTIMISER LA RESPIRATION DE POUMONS ATELECTASIQUES**
(54) **Title: NON-INVASIVE METHOD AND APPARATUS FOR OPTIMIZING THE RESPIRATION OF ATELECTATIC LUNGS**



(57) **Abrégé/Abstract:**

The invention concerns a method and apparatus for determining the status of a ventilated lung. For determining the status of a lung ventilated, which enables in real time optimal ventilatory settings for a recruitment maneuver of an ailing lung, the invention comprises a sensor for measuring a gas concentration in the expired gas during a single breath, an analog to digital converter for obtaining data samples of said gas concentration in the time domain, means for selecting a plurality of data samples, means for calculating a mean tracing value being sensitive to changes of alveolar dead space based on said samples, and a data processor which detects during a change of the airway pressure of the ventilator from the resulting course of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the PEEP at which lung open condition or alveolar closing occurs.

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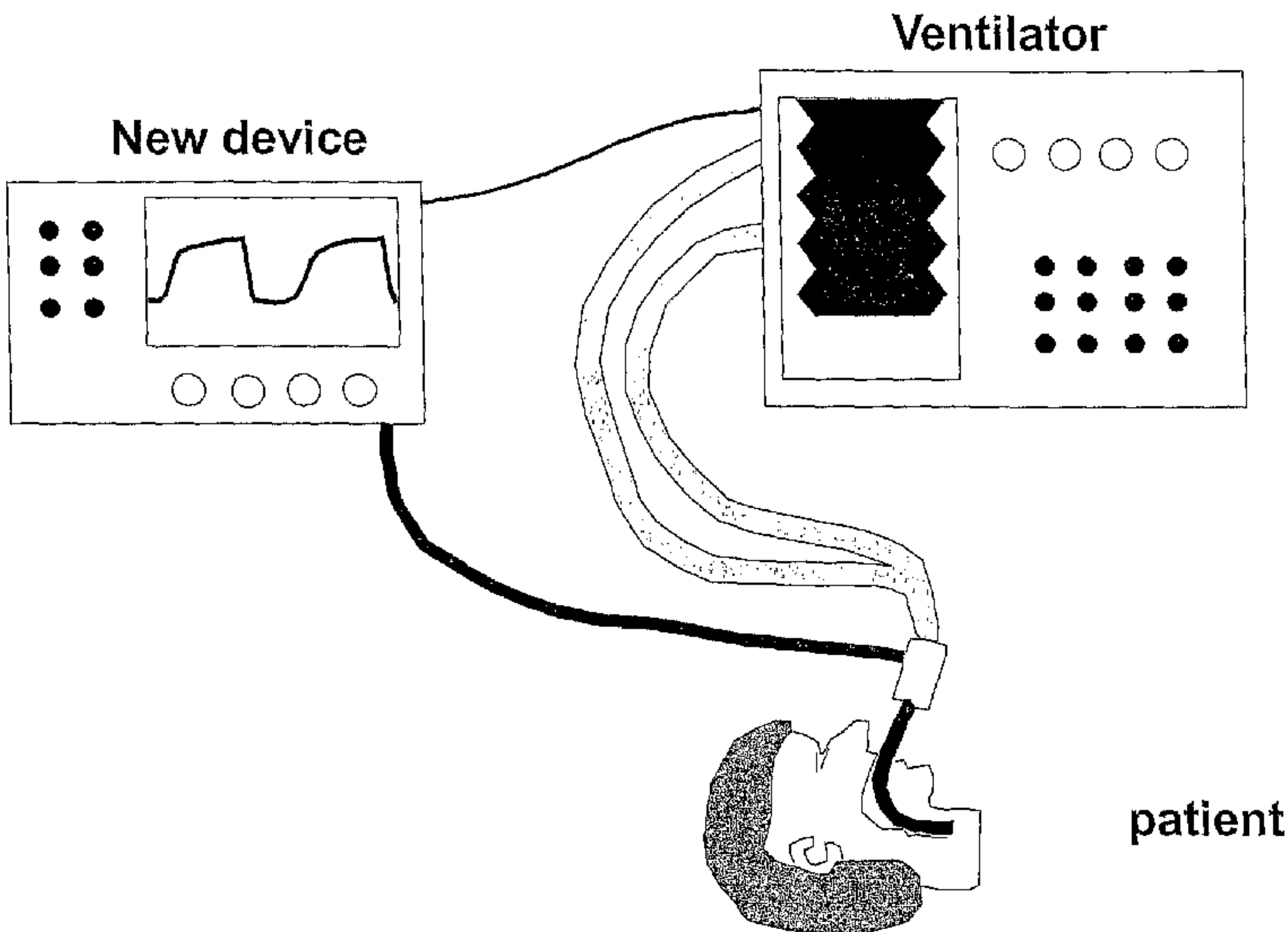
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(54) Title: NON-INVASIVE METHOD AND APPARATUS FOR OPTIMIZING THE RESPIRATION OF ATELECTATIC LUNGS



(57) Abstract: The invention concerns a method and apparatus for determining the status of a ventilated lung. For determining the status of a lung ventilated, which enables in real time optimal ventilatory settings for a recruitment maneuver of an ailing lung, the invention comprises a sensor for measuring a gas concentration in the expired gas during a single breath, an analog to digital converter for obtaining data samples of said gas concentration in the time domain, means for selecting a plurality of data samples, means for calculating a mean tracing value being sensitive to changes of alveolar dead space based on said samples, and a data processor which detects during a change of the airway pressure of the ventilator from the resulting course of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the PEEP at which lung open condition or alveolar closing occurs.

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5

**Non-Invasive Method and Apparatus for Optimizing the
Respiration of Atelectatic Lungs**

The invention refers to a method and an apparatus for
10 determining the status of a lung ventilated by an
artificial ventilator.

Such a method and such an apparatus are known from WO
00/44427 A1. WO 00/44427 A1 deals with the problem of the
15 artificial ventilation of patients with an ailing lung. The
basic patho-physiological mechanism of an ailing lung is
the lack of surfactant (substance which reduces surface
tension) which can cause a collapse of major lung fractions
and a dramatically reduced gas exchange area. Hence, to
20 prevent undesirable sequelae and consecutive multiorgan
failure, an important goal of protective ventilator therapy
is a gentle and early „reopening" of the lung. Through the
identification of the alveolar opening and especially of
the alveolar closing pressures, a distressed lung may be
25 kept open by proper choice of the airway pressure. However,
the manual determination of opening and closing pressures
is arduous and time consuming. Therefore, WO 00/44427 A1
suggests to use the partial pressures of oxygen (paO_2) as
an indicator for determining the opening and closing
30 pressures of the lung. WO 00/44427 A1 has recognized that
there is a significant hysteresis behaviour of the paO_2 as
a function of the ventilation pressure.

Fig. 1 shows the paO_2 hysteresis of the same healthy (left)
35 and ailing (right) lung. While there is almost no

hysteresis in the healthy lung and the choice of ventilation pressures has no visible impact on the quality of gas exchange, the hysteresis is even more severe in an ailing lung. In many cases, gas exchange may be reduced so strongly that at typical ventilation pressures, a sufficient hemoglobin oxygen saturation (> 85 mm Hg) may only be reached if high oxygen concentrations (e.g. 90 ... 100 %) are delivered to the patient.

For such an ailing lung, a ventilation strategy could be to first open the lung with a temporary high inspiratory airway pressure and then ventilate on the descending branch of the hysteresis such that a sufficient tidal volume is reached and gas exchange is maintained. This so called recruitment maneuver has become a common strategy in operating rooms and in the intensive care medicine. In general, to achieve a sufficient tidal volume it is necessary to ventilate the lung with a certain delta pressure, which is defined as:

$$\text{delta pressure} = \text{PIP} - \text{PEEP}$$

PIP is the peak inspiratory pressure and PEEP is the positive end expiratory pressure. The aim of the recruitment maneuver is to find the alveolar opening pressure and the alveolar closing pressure. It is then possible to set the peak inspiratory pressure slightly higher than the alveolar opening pressure and to set the positive end expiratory pressure slightly higher than the alveolar closing pressure. In this way ideally all previously closed lung units will be re-opened and at the same time all open lung units will be kept open.

During a recruitment maneuver the peak inspiratory pressure is stepwise increased so that as many lung units as

possible are re-opened, while at the same time the positive end expiratory pressure is increased in order to keep the newly recruited lung units open. When recruiting a lung, some lung units open up and become overdistended, while
5 other lung units are still closed. Thus, when increasing the peak inspiratory pressure in order to re-open as many lung units as possible, most of the opened lung units will be overdistended.

10 Due to the hysteresis behaviour of the lung, the values obtained for peak inspiratory pressure and for the positive end expiratory pressure during this process of a stepwise increase are too high to further ventilate the lung once the lung units are opened. Thus they need to be reduced
15 systematically.

At first the excessive peak inspiratory pressure is reduced while the positive end expiratory pressure is maintained at its level. This reduction is performed until an adequate
20 tidal volume is reached. From this point onwards both the peak inspiratory pressure and the positive end expiratory pressure are reduced simultaneously. The aim is to find the lowest value for the positive end expiratory pressure that would just maintain all re-opened lung units open. At this
25 stage the peak inspiratory pressure is a secondary variable of interest. Noticeably, the tidal ventilation will change during this simultaneous reduction of the peak inspiratory pressure and the positive end expiratory pressure, since the relief of overdistension will initially increase the
30 lung's compliance. Once the positive end expiratory pressure is too low to keep all previously re-opened lung units open, the point of alveolar closing is reached.

Having identified the values of the peak inspiratory
35 pressure corresponding to the alveolar opening pressure and

the positive end expiratory pressure corresponding to the alveolar closing pressure as outlined above, it is then possible to ventilate the lung in an optimal condition. First, all lung units are re-opened by choosing a peak
5 inspiratory pressure which is slightly higher than the alveolar opening pressure, i.e. 2 - 5 cmH₂O higher, and choosing a positive end expiratory pressure which is slightly higher than the alveolar closing pressure, i.e. 2 - 3 cmH₂O higher. Afterwards the peak inspiratory pressure
10 is reduced again to achieve the desired tidal volume. The corresponding ventilation stage corresponds to the optimal condition. An optimal compliance is achieved, since all lung units are opened, and no major overdistension is present.

15

By way of an example, Fig. 2 shows a typical recruitment maneuver in detail. As shown in Fig. 2, the recruitment maneuver is carried out on the basis of a pressure controlled ventilation. Before the final recruitment
20 maneuver takes place, the alveolar opening pressure and the alveolar closing pressure have to be identified. In a first step (step 1), PIP and PEEP are stepwise increased by means of an incremental limb until the alveolar opening pressures have been detected with regard to PIP and PEEP (steps 2 and
25 3). The alveolar opening pressure with regard to PIP is usually about 40 cmH₂O in normal lungs and in the range of 55-60 cmH₂O in sick lungs. After a successful alveolar opening, a decremental limb or stepwise decrease of PIP and PEEP is done (step 4) to determine the alveolar closing
30 pressure (step 5). As outlined above initially only PIP is reduced as indicated at the transition from step 3 to step 4 in Fig. 2. After having identified the pressures for alveolar opening and alveolar closing, the final recruitment maneuver (step 6) is done with these new target
35 pressures over 10 breaths and PEEP is set above the

alveolar closing pressure to avoid pulmonary re-collapse.
For example, PEEP is set 2 cmH₂O above the alveolar closing
pressure, i.e.

$$5 \quad \text{PEEP} = \text{PEEP}_{\text{close}} + 2 \text{ cmH}_2\text{O}$$

Alternatively, a volume controlled ventilation can be
carried out having the advantage that the ventilated volume
remains constant and that all changes of the lung status
10 can be related to changes within the alveoli.

In order to avoid the invasive measurement of paO₂, WO
00/44427 A1 utilizes according to a first embodiment the
endtidal CO₂ concentration (etCO₂) and/or the CO₂ output as
15 feedback signals for identification of the optimal
ventilator settings for ailing lungs. Both feedback signals
can be measured non-invasively. etCO₂ can be obtained by
measuring the CO₂ concentration at the end of an expiration
cycle. CO₂ output (unit [ml CO₂/min]) can be obtained from
20 continuous measurements of the CO₂ concentration (unit [%])
and air flow (unit [ml/min]) and subsequent breathwise
computation of

$$\dot{V}_{\text{CO}_2 \text{ Atem}} = RR \cdot \int_0^{T_e} [\text{CO}_2](t) \cdot \dot{V}_{\text{Atem}}(t) DT$$

25

during one expiration cycle. According to a second
embodiment of WO 00/44427 A1, the hemoglobin oxygen
saturation (SO₂) is measured non-invasively and is used as
a feedback signal for identification of optimal ventilation
30 parameters for ailing lungs.

In summary, WO 00/44427 A1 discloses a non-invasive method
for determining the alveolar opening or closing of a lung
based on one of the measurement of the parameters CO₂

concentration (etCO₂), CO₂ output or hemoglobin oxygen saturation (SO₂). However, practical tests have shown various disadvantages of this method. One disadvantage is the fact that a single parameter is subject of various
5 disturbances so that an average value of several parameters has to be taken over several breath cycles which causes a delay in the feed back path. Another disadvantage is the fact that the detection of alveolar opening cannot be clearly distinguished from an overdistension of the lung
10 which could cause severe damages to the lung during the recruitment maneuver.

Therefore, it is an object of the invention to provide a method and an apparatus for determining the status of a
15 lung ventilated by an artificial ventilator which enables in real time optimal ventilatory settings for a well-conducted recruitment maneuver of an ailing lung.

A method for determining the
20 status of a lung ventilated by an artificial ventilator comprises the following steps:

- a) obtaining data samples of a gas concentration of the expired gas over a single breath,
25
- b) selecting a plurality of data samples from said obtained data samples,
- c) calculating a tracing value being sensitive to
30 changes of alveolar dead space on the basis of said selected data samples,
- d) repeating steps a), b) and c) for obtaining a plurality of tracing values, and

e) changing the peak inspiratory pressure and the positive end expiratory pressure of the artificial ventilator, wherein from the observation of the resulting course of the plurality of calculated tracing values the
5 peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.

10 An apparatus according to the invention for determining the status of a lung ventilated by an artificial ventilator comprises the following features:

a sensor for measuring a gas concentration in the expired
15 gas during a single breath,

an analog to digital converter for obtaining data samples of said gas concentration of the expired gas over a single breath in the time domain,
20

means for selecting a plurality of data samples from said obtained data samples,

means for calculating a tracing value being sensitive
25 to changes of alveolar dead space on the basis of said selected data samples, and

a data processor which detects during a change of the airway pressure of the artificial ventilator from the
30 resulting course of a plurality of calculated tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs.

According to a preferred aspect of the invention, the gas concentration represents the CO₂ concentration. The CO₂ concentration can be obtained using a CO₂ single breath test as described below. However, the CO₂ single breath
5 test was developed for specific applications and therefore was restricted to evaluate the CO₂ concentration over a single breath. In contrast to that, it was found out that other gas concentrations over a single breath could be also used for the purpose of the invention since the invention
10 is based on the hypothesis that a lung recruitment maneuver would reduce alveolar dead space. Starting from this hypothesis, the basic principle of the invention is to derive a tracing value from the gas concentration the expired gas during a single breath which is sensitive
15 to changes of alveolar dead space. As mentioned above, in the following the CO₂ concentration will be used exemplary.

The meaning of alveolar dead space with regard to the CO₂ concentration in the expired gas was already studied by R.
20 Fletcher, G. Johnson and J. Brew in: "The Concept of Deadspace with Special Reference to Single Breath Test for Carbon Dioxide." Br. J. Anaesth., 53, 77, 1981 and will be explained further below with regard to Fig. 3.

25 Fig. 3 shows a plot of expiratory gas CO₂ concentration against expired volume, which can be obtained by combining a CO₂ concentration measurement against time and a volume rate measurement against time. This plot is called the CO₂ single breath test and shows three distinct phases in
30 breath CO₂ gas concentration during the patient exhale cycle. Phase I represents CO₂ free gas expired from the airway conduction structures where gas exchange does not occur. Phase II is characterized by an S-shaped upswing and represents the transition from airway to alveolar gas.
35 Phase III reflects the exhalation of unmixed gas from

regions of the lung which normally are in active exchange with the alveolar tissue and thus closely resembles at least in healthy patients gas properties associated with arterial blood in contact with the lung for gas exchange, i.e. CO₂ release and O₂ absorption. In normal lungs, Phase III is characterized by a horizontal level since ventilated and perfused alveolar regions are closely matched. In a diseased lung, Phase III may not appear horizontal due to a mismatch in ventilation and perfusion of this lung region.

10

The variables of the graph according to Fig. 3 have the following meaning:

- paCO₂ is the partial pressure of carbon dioxide.
- 15 etCO₂ is the endtidal CO₂ concentration of a single breath.
- X is the alveolar tidal volume and represents true alveolar gas which is the result of a gas exchange in the alveoli.
- 20 Y is the alveolar deadspace which is that part of inspired gas which reaches the alveoli but does not take part in gas exchange.
- Z is the airway deadspace which is that part of inspired gas which does not reach the alveoli and therefore does not take part in gas exchange either.
- 25

The plot according to Fig. 3 is formed by the exhaled partial pressure of CO₂ against the expiratory tidal volume. Its analysis can be performed, e.g., using a side-stream infrared capnometer and a pneumotachograph of the Capnomac Ultima (e.g. Datex-Engstrom Instrument, Corp., Helsinki, Finland) or a main-stream CO₂ sensor (e.g. Novamatrix, USA). Furthermore, a computer is provided to

35 record and analyze data.

Before anesthesia and ventilating a patient, capnograph and blood gas analyzer should be calibrated using the same CO₂ concentration (5%). Airway flow can be measured and
5 integrated to obtain volume. A corresponding device automatically normalizes airway volumes from standard condition to body temperature, ambient pressure and water vapor saturation (BTPS). Before anesthesia and ventilating a patient, induction the volume calibration can be done
10 with e.g. a 700 ml super-syringe following the manufacturer's guidelines.

The side-stream CO₂ signal has a time delay with respect to the flow signal. A corresponding software can correct the
15 CO₂ delays automatically using mathematical algorithms. The VTCO_{2,br} or area under the curve can be computed by integrating expired flow and CO₂ in each breath. Analysis of dead space can be done on-line and/or off-line using Fowler's analysis and adding arterial PCO₂ values to the
20 CO₂ curve of the single breath test.

A well known application of the CO₂ single breath test is the so called capnography, which is a technique to assess the arterial carbon dioxide content, expressed as partial
25 pressure of CO₂ (paCO₂), and which is disclosed in detail in WO 92/04865 A1 and WO 96/24285 A1. Since alveolar dead space cannot be derived directly from the CO₂ single breath test, both WO 92/04865 A1 and WO 96/24285 A1 assume alveolar dead space as a constant variable which has to be
30 determined or estimated by other means, e.g. by a separate blood sample. Hence, according to WO 92/04865 A1 and WO 96/24285 A1 any changes of alveolar dead space are seen as a disturbance variable, since these changes result in a faulty estimate of paCO₂.

In contrast to that the invention takes a new course for evaluating the CO₂ single breath test, since the invention uses now a tracing value which is sensitive to changes of alveolar dead space in order to determine certain lung conditions, namely alveolar opening or lung overdistension or lung open condition or alveolar closing. Hence, changes of alveolar dead space are no longer seen as a disturbance variable but are now taken as an indicator for certain lung conditions.

10

Since the meaning of alveolar dead space despite the well investigated single breath test with regard to the detection of alveolar opening or lung overdistension or lung open condition or alveolar closing of a ventilated lung was not recognized so far, the physiologic concept for alveolar dead space will be explained further below.

15

Fig. 4 shows the anatomical and functional units of the lungs, namely the lung acinus. The meaning of the abbreviations is as follows:

20

Cap = pulmonary capillary

alv = alveolus

Calv = alveolar duct

25 Salv = alveolar sac

RB = respiratory bronchiole.

30

The lung acinus is constituted of the respiratory bronchioli, alveolar ducts, alveolar sacs, alveoli and pulmonary capillaries. To maintain a normal function, this acinus must be well-ventilated and perfused, i.e must be maintained in an open condition. If this acinus becomes collapsed, it loses its normal capacity for gas exchange and makes itself prone to injury during artificial ventilation, as stated previously.

35

Diffusion is a process fundamental to life because it is responsible for blood oxygenation and CO₂ removal within the lungs. Fig. 5 shows the diffusion phenomenon for CO₂ which is defined as a passive movement of CO₂ molecules through the alveolar-capillary membrane due to a gradient of concentration or partial pressures.

Diffusion is studied by Fick's law:

10

$$J = D_{mol} A \frac{Dc}{Dx}$$

where J is the instantaneous flux of CO₂, Dmol represents the gas-phase molecular diffusivity of CO₂ in air, A is the area of gas exchange, and Dc the gas concentration gradient for CO₂ and Dx is the distance.

During normal physiology and in most of the pathological states, Dmol, Dc, and Dx remain roughly constant. This means that the area (A) becomes the main factor responsible for changes in the diffusion process within the lung.

The area of gas exchange depends on a normal acinar structure. Reduction in A is the consequence of pathologic three-dimensional changes in acinar morphology. Thus, a decrease in A as during lung collapse results in a decrease of the CO₂ and O₂ diffusion at the alveolar-capillary membrane. Opposite to that, the recovery of a normal acinar morphology by a recruitment maneuver normalizes A and thus diffusion.

According to the invention, the three-dimensional structural changes of the lung acini are reflected in a change of alveolar dead space during a CO₂ single breath test, wherein a suitable tracing value is used to

detect these changes. The tracing value represents a data fusion of the data samples of the CO₂ concentration using an average data algorithm. Examples of average data algorithms are a least squares linear regression, a
 5 weighted sum calculation or a FIR (finite impulse response) filter.

In contrast to WO 00/44427 A1 the method and the apparatus according to the invention has the advantage that an
 10 averaged value within one single breath is obtained which still yields a good accuracy for determining certain lung conditions. An important cognition of the invention compared to WO 00/44427 A1 is the fact that a plurality of data samples from said obtained data samples are selected
 15 which enables a selective evaluation of the CO₂ concentration within one single breath.

According to a preferred aspect of the invention, the data samples according to step a) are obtained in the time
 20 domain. This can be achieved by a conventional analog to digital converter. According to another preferred aspect of the invention, the obtained data samples are converted from the time domain into the volumetric domain. This is particularly useful for obtaining the well known plot of
 25 the CO₂ single breath test.

Fig. 6 shows some possible tracing values within a plot of a CO₂ single breath test, which are

slope III or endtidal mean slope	determined by the mean slope (either over time or over volume) of the CO ₂ concentration in the expired gas towards the final stage of a single breath,
slope II or steepest mean slope	determined by the steepest mean slope (either over time or over volume) of the CO ₂

	concentration in the expired gas in vicinity of the point of inflection,
angle II-III	determined by the angle between slope II and slope III,
intercept II	determined by the intersecting point of slope II with the X-axis, and
intercept III	determined by the intersecting point of slope III with the Y-axis.

The following table shows an overview of these and some more tracing values together with their sensibility with regard to the lung stages "recruitment",

5 "overdistension", "open-lung" and "re-collapse":

Variable	recruitment	overdistension	open-lung	Re-collapse
VD^{aw}	↑↑ (+++)	↑↑↑ (+++)	↓↓ (+)	↓↓ (+)
VD^{aw}/VT	↑↑ (+++)	↑↑↑ (+++)	↓↓ (+)	= ↓ (+)
VCO_2	↑↑ (+++)	↓↓ (+++)	↑ (+)	= ↓ (+)
$PAECO_2$	↑↑ (+++)	↓↓ (+++)	↑ (+)	= ↓ (+)
$etCO_2$	↑↑ (+)	= ↓ (-)	= ↓ (-)	↓ (-)
$VT_{CO_2,br}$	↑↑ (+++)	↓↓ (+++)	↑↑ (+)	= ↓ (+)
VT^{alv}	↓ (+)	↓ (-)	↑ (-)	= (+)
Angle II-III	↓↓↓ (+++)	↑↑↑ (+++)	↓↓ (+)	↑↑↑ (+++)
Slope II	↑↑↑ (+++)	↓↓ (+)	↑↑ (+)	↓↓ (+)

Variable	recruitment	overdistension	open-lung	Re-collapse
Slope III	↓↓↓ (+++)	↑ (-)	↓ (+)	↑↑ (+++)
Vol I	↑↑↑ (+++)	↑ (-)	↓ (+)	↓ (+)
Vol II	↑↑ (+++)	↑ (+)	↓↓ (+)	= ↑ (++)
Vol III	↓↓↓ (++)	↓ (+)	↑↑ (+)	= ↓ (+)
Intercept II	↓↓↓ (+++)	= ↓ (-)	↑ (+)	= ↑ (++)
Intercept III	↑↑↑ (+++)	↓ (+)	↑ (+)	= ↑ (-)

with:

5 =: no change

1 arrow: small change

2 arrows: moderate change

3 arrows: large change

(-): no sensitivity

10 (+): low sensitivity

(++): moderate sensitivity

(+++): high sensitivity.

15 The meaning of the variables with regard to their use as
tracing values is as follows:

20 VD^{aw}: airway dead space. Is the dead space created by the
convective airways to the point where mixing with alveolar
gas takes place (Fig. 3, Z area). The midpoint of phase II
is the limit between anatomical dead space and alveolar gas
(Fowler's method). This midpoint is calculated as 50 % of

numerical data from slope II. It represents the gas inside the lung transported by convection.

VCO₂: is the production of CO₂ per minute (ml/min) and is
5 calculated as the product of the expired concentration of CO₂ by the alveolar minute ventilation.

VT_{CO₂, br}: or area under the curve, it represents the volume
of CO₂ expired in a single breath measured by flow
10 integration (Fig. 3, X area). It is useful to calculate CO₂ production. It represents the alveolar gas, which is in contact with pulmonary capillary blood.

Phase I: begins with the start of expiration (detection by
15 a negative inflection on flow signal), and ends when the concentration of CO₂ in the CO₂ single breath test increases above 0,1 % from baseline (Fig. 3, Fig. 6).

Phase II: starts at the end of phase I (from 0,1 % CO₂
20 concentration) and continues to the intersection of the predictive slope lines for phases II and III (Fig. 3, Fig. 6).

Phase III: or alveolar plateau begins at the intersection
25 of the predictive slopes lines for phase II and III and terminates at the end of expiration, defined by an abrupt positive deflection on flow signal (Fig. 3, Fig. 6).

Volume of phase I: Is the volume of gas contained in the
30 phase I. It determines the largest part of the airway dead space and represents the gas in the proximal airway and the compressive gas in the ventilatory circuit (Fig. 3, Fig. 6).

Volume of phase II: Is the volume of gas contained in the phase II: The midpoint of phase II (50% of slope) is the limit between anatomical dead space and alveolar gas, and represents an interface when convective gas transport changes to diffusion transport in lung acini. Thus, phase II is part of both, airway dead space and alveolar gas. Phase II is highly influenced by the acinar emptying time: the more homogeneous the gas emptying for the acini the lower is the phase II volume (Fig. 3, Fig. 6).

10

Volume of phase III: This volume represents the gas inside the alveoli in contact with pulmonary capillary blood. It is considered as efficient volume for gas exchange within the tidal volume (Fig. 3, Fig. 6).

15

Slope of phase II: It is derived i.e. from least squares linear regression using data points collected between 25-75 % of the phase II, expressed as fraction (Fig. 6). The phase II slope of individual breaths is normalized by dividing the slope value by the corresponding mean alveolar fraction of CO₂ or PAECO₂ (expressed in %). Similar to volume of phase II, the slope represents the spread of acinar expiratory times. If all acini were emptying at almost the same time the ventilation would be more homogeneous and the slope increases. An opposite change in slope II represents an inhomogeneous gas emptying as observed i.e during atelectasis (lung collapse) (Fig. 6).

Slope of phase III: It is derived from e.g. least squares linear regression using data points collected between 25-75 % of the phase III, expressed as fraction (Fig. 6). The phase III slope of individual breaths is normalized by dividing the slope value by the corresponding mean alveolar fraction of CO₂ or PAECO₂ (expressed in %). Phase III slope is the most useful variable to measure a recruitment

35

effect. It is related to the ventilation/perfusion relationship (V/Q): when the V/Q ratio is more efficient the phase III slope decreases, representing a decrease in CO_2 diffusional resistance. When slope III increases, a V/Q mismatch is found.

Mathematical models have described the variables that can change phase III slope. They are: tidal volume, respiratory rate (only in the extreme of normal values), area of gas exchange, and gas diffusivity. Maintaining all variables stable that can change phase III slope, any change in the area of gas exchange can thus affect this slope. Fick's first law of diffusion can easily explain this statement.

Angle II-III: It is defined as the angle of intersection between slope of phase II and III. Changes in this angle represent changes of the shape of the CO_2 single breath test related to the efficiency/inefficiency state of ventilation and gas exchange. When the angle decreases, as after lung recruitment, ventilation and gas exchange improve. Increasing angles II-III are related to an inhomogeneous (and worse) ventilation/perfusion relationship (Fig. 6).

Intercept of phase II slope: It is defined as the intersection of the line of phase II slope with the X axis (Fig. 6).

Intercept of phase III slope: It is defined as the intersection of the line of phase III slope with the Y axis (Fig. 6).

V_T^{alv} : It represents the portion of tidal volume that is located distal to the interface, it is true alveolar gas.

This volume is constituted by the sum of $VT_{CO_2}^{alv}$ plus VD^{alv} . VT^{alv} is derived by Fowler analysis as $VT - VD^{alv}$.

PAECO₂: or mean expired concentration of CO₂, constitutes
5 the mean partial pressure of CO₂ in alveolar air. It is defined as the partial pressure of CO₂ at the middle of the slope III. This value represents the partial pressure of all CO₂ molecules in the expired volume.

10 etCO₂: is the end tidal partial pressure of CO₂ (Fig. 3).

Pet-AECO₂: is the difference between end tidal CO₂ and mean expired partial pressure. It is an index of alveolar dead space: the higher the differences between these two values,
15 the higher is the inefficiency of lung function.

VDBohr: is the dead space formed by anatomical dead space plus part of the alveolar dead space (ml), defined as the lower portion of the alveolar dead space.

20

Vdaw/VT: the ratio between airway dead space to tidal volume, is an index of lung efficiency / inefficiency. The higher this index is the more inefficient the lung becomes.

25 It should be noted that Volume I, II, III and phase III slope are normalized by dividing them by the tidal volume to make comparison among different breaths possible.

According to a preferred aspect of the invention the
30 endtidal mean slope is taken as a tracing value and is determined by the mean slope (either over time or over volume) of the CO₂ concentration in the expired gas towards the final stage of a single breath. The calculation of the endtidal mean slope can be carried out on the basis of a
35 least squares linear regression using suitable constraints,

wherein a suitable constraint could be a minimum mean square error of the regression result over a predetermined range. On the basis of such a constraint the calculation of the endtidal mean slope would be carried out as follows:

5

Step 1: Performing on the basis of the data points of the measured CO₂ concentration of a single breath a running least squares linear regression over a predetermined range (either with regard to volume or time), wherein the predetermined range is a certain percentage of the expired volume or of the respiratory period, e.g. 20%.

10

Step 2: Identifying the range for which the mean square error of the running least squares linear regression becomes a minimum towards the final stage of a single breath.

15

Step 3: Setting the slope of the least squares linear regression over the identified range of step 2 as the tracing value of said single breath.

20

According to a preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined first tracing values reaches a minimum.

25

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined first tracing values reaches a maximum.

30

35

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting
5 from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined first tracing values reaches a minimum.

According to another preferred aspect of the invention, the
10 positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined first tracing values
15 reaches a maximum.

According to another preferred aspect of the invention a second tracing value is represented by the steepest mean slope of the CO₂ concentration in the expired gas
20 during a single breath. The steepest mean slope is determined by the mean slope (either over time or over volume) of the CO₂ concentration in the expired gas in the vicinity of the point of inflection. The calculation of the steepest mean slope can be carried out again on the basis
25 of a least squares linear regression using suitable constraints, wherein a suitable constraint could be a minimum mean square error of the regression result over a predetermined range. On the basis of such a constraint the calculation of the steepest mean slope would be carried out
30 as follows:

Step 1: Performing on the basis of the data points of the measured CO₂ concentration of a single breath a running least squares linear regression over a
35 predetermined range (either with regard to volume

or time), wherein the predetermined range is a certain percentage of the expired volume or of the respiratory period, e.g. 20%.

- 5 Step 2: Identifying the range for which the mean square error of the running least squares linear regression becomes a minimum in the vicinity of the point of inflection.
- 10 Step 3: Setting the slope of the least squares linear regression over the identified range of step 2 as the tracing value of said single breath.

According to another preferred aspect of the invention, the
15 peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined second tracing values reaches a maximum.

20

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the
25 negative gradient of the resulting course of the plurality of determined second tracing values reaches a minimum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial
30 ventilator is decreased stepwise breath by breath starting from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined second tracing values reaches a maximum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the negative gradient of the resulting course of the plurality of determined second tracing values reaches a minimum.

According to another preferred aspect of the invention a third tracing value is represented by the angle between the endtidal mean slope and the steepest mean slope of the CO₂ concentration in the expired gas during a single breath.

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined third tracing values reaches a minimum.

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined third tracing values reaches a maximum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined third tracing values reaches a minimum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined third tracing values reaches a maximum.

According to another preferred aspect of the invention, a plurality of different types of tracing values are calculated in parallel and wherein from the resulting course of the plurality of different types of tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.

According to another preferred aspect of the invention, during a recruitment maneuver of the lung the peak inspiratory pressure is set above the peak inspiratory pressure at which alveolar opening has been detected and the positive end-expiratory pressure is set above the positive end expiratory pressure at which alveolar closing has been detected.

Other objects and features of the invention will become apparent by reference to the following specification and to the drawings in which Fig. 1 to Fig. 6 have been referred to already in the introductory part of the description and in which Fig. 7 to Fig. 12 will be explained now in further detail.

Fig. 1 shows two graphs of the paO_2 hysteresis of the same healthy (left) and ailing (right) lung,

- Fig. 2 shows a plot of the airway pressures over time of a typical recruitment maneuver,
- Fig. 3 shows a plot of the CO₂ single breath test with three distinct phases in breath CO₂ gas concentration during the patient exhale cycle,
- Fig. 4 shows a schematic diagram of the anatomical and functional units of the lungs,
- Fig. 5 shows a schematic diagram of the diffusion phenomenon for CO₂ in a human's lung,
- Fig. 6 shows some possible tracing values within a plot of a CO₂ single breath test,
- Fig. 7 shows two plots of a CO₂ single breath test in the states of atelectasis and recruitment,
- Fig. 8 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the steepest mean slope as a tracing value,
- Fig. 9 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the volume of phase II as a tracing value,
- Fig. 10 shows measurements of the partial pressure of oxygen (paO₂) with 12 patients at three different lung stages,
- Fig. 11 shows measurements of the end-expiratory lung volume (EELV), the partial pressure of oxygen

(paO_2) and the compliance at three different ventilation modes,

5 Fig. 12 shows a draft of an apparatus according to the invention connected in series with the ventilator to the patient,

10 Fig. 13 shows a plot of the O_2 single breath test depicting the O_2 gas concentration during the patient exhale cycle,

15 Fig. 14 shows a plot comparing the CO_2 gas concentration during a CO_2 single breath test with the O_2 gas concentration during an O_2 single breath test during the patient exhale cycle, and

Fig. 15 shows some possible tracing values within a plot of an O_2 single breath test.

20 Fig. 7 shows two plots of a CO_2 single breath test in the states of atelectasis and recruitment. As it can be seen, an increase in the area of gas exchange due to recruitment alters the shape of the plot of a CO_2 single breath test, wherein the endtidal mean slope (slope III) decreases and
25 the steepest mean slope (slope II) increases. Hence, taking into account the above theoretical explanation, the reversible and dynamic acinar change in morphology can be manipulated by treatment. Normalizing acinar morphology in a mechanically ventilated patient by a recruitment maneuver
30 produces a normalisation in the physiology of the lung. A normalisation in acinar morphology by the recruitment maneuver causes an improvement in gas exchange and in gas emptying during expiration.

Fig. 8 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the steepest mean slope (slope II) as a tracing value.

The algorithm for diagnosing the lung's open-collapse state is described with regard to the steepest mean slope as follows:

1. Analysis of the baseline situation

An analysis of the CO₂ single breath test is performed before the recruitment maneuver. This data are considered as the control values for comparison with values observed during and after the recruitment maneuver.

2. Analysis of lung recruitment

During the recruitment maneuver the behavior of the steepest mean slope in each breath is observed and typical recruitment effects are detected.

3. Analysis of lung-overdistension

At the end of the incremental limb of the recruitment maneuver the behavior of the steepest mean slope in each breath is observed and typical overdistension effects are detected.

4. Analysis of the open-lung condition

During the decreasing limb of the recruitment maneuver the steepest mean slope is analyzed in every breath searching for changes representing the open-lung condition.

5. Analysis of the lung re-collapse

During the decreasing limb of the recruitment maneuver the steepest mean slope is analyzed in every breath searching for changes representing lung re-collapse.

6. Final recruitment maneuver

A new recruitment maneuver is done with the known opening and closing pressure.

Although the algorithm merely has been described with
5 regard to the steepest mean slope as a tracing value,
it goes without saying that any other suitable tracing
values as listed above or combinations thereof can be taken
as a basis for carrying out the algorithm.

10 Fig. 9 shows a plot of the airway pressures over time of a
typical recruitment maneuver together with the response of
the volume of phase II as a mean tracing value. Lung
recruitment, overdistension, open-lung condition and re-
collapse are seen during the recruitment maneuver. The
15 inflection point represents the change of direction of the
volume of phase II from the open-lung condition to the
beginning of the collapsed state. Furthermore, the
inflection point represents the pulmonary closing pressure.

20 In the following, a first study concerning the effect of an
alveolar recruitment strategy (ARS) on gas exchange and
lung efficiency during one-lung ventilation (OLV) is
discussed using the single breath test of CO₂.

25 A total of 12 patients were studied during general
anesthesia for elective open thoracic surgery or
thoracoscopy. Patients with acute or chronic uncompensated
cardiopulmonary disease were not included in the study.

30 Only for open thoracotomies, a thoracic epidural catheter
was placed at T2 to T4 and a total volume of 0,1 ml/kg of
bupivacaine 0,5% without epinephrine were administered.
Prior to the epidural anesthesia, intravascular volume was
expanded by infusing 7 ml/kg of a colloidal solution

(HaemacellTM) and maintained at 8 ml kg⁻¹ h⁻¹ of normal saline solution.

After 3 minutes of breathing 100 % oxygen, general
5 anesthesia was induced with fentanyl 5 µg/kg, thiopental 3 mg/kg and vecuronium 0,08 mg/kg iv. Anesthesia was maintained with isofluorane 0,5-0,6 MAC and epidural lidocaine 1 % boluses of 5 ml for open thoracotomies. For
10 thoracoscopies and minimal invasive coronary artery by-pass graft (mini-CABG), anesthesia was maintained with isofluorane 0,7-1 MAC and boluses of fentanyl 2 µg/kg and vecuronium 0,015 mg/kg as clinically necessary.

The trachea and the left bronchus were intubated with a left double lumen tube (DLT) of the appropriate size
15 (Broncho-CathTM, Mallinckrodt Laboratories, Atholone, Ireland). Air leakage were assessed by introducing the capnograph's side stream sensor into each lumen of the DLT while maintaining ventilation through the other lumen. Bronchoscopy confirmed the correct position of the DLT
20 before and after positioning the patients in the lateral position. During OLV, the lumen of the non-ventilated side was left open to atmosphere.

Lungs were ventilated with a Servo 900 C in a volume
25 control ventilation mode and an inspired oxygen fraction (FiO₂) of 1.0. The ventilator delivered a square-wave flow with an inspiratory time of 33% with no end-inspiratory pause. The respiratory rate was set between 10-14 breaths/min, tidal volumes (VT) were maintained at 8 ml/kg,
30 and PEEP was 8 cmH₂O throughout the study.

During OLV, tidal volume was reduced to 6 ml/kg to avoid peak pressures higher than 30 cmH₂O. Respiratory rate was increased to 15-18 breaths/min to maintain the same minute
35 ventilation as during TLV.

Standard monitoring was performed with the Cardiocap II monitor. A Capnomac Ultima monitor was used to measure the following ventilation parameters and gas concentrations:

- 5 Peak inspiratory pressure (PIP), PEEP, expired tidal volume (VTe), respiratory rate, expired minute volume, O₂ and CO₂ fractions.

Carbon dioxide elimination (VCO₂) was calculated as the
10 product of alveolar ventilation times the mean expired alveolar fraction of CO₂ (FAECO₂ %). Oxygen consumption (VO₂) was calculated as the product of alveolar ventilation times the inspiratory-expiratory O₂ difference. Respiratory quotient (RQ) was calculated dividing VCO₂ by VO₂. The
15 single breath analysis for CO₂ was performed using the sidestream infrared capnometer and the pneumotachograph of the Capnomac Ultima and a signal processor. Data were recorded and analyzed by a computer.

20 Capnograph and blood gas analyzer were calibrated using a known gas concentration of CO₂ (5%). This calibration was performed in each patient before the induction of anesthesia. Airway flow and pressure measurements are based on the measurement of kinetic gas pressure, and are
25 performed using the Pitot effect. Flow rate is measured and integrated to obtain VT. The Capnomac device restores normal airway volumes from standard condition to body temperature, ambient pressure and water vapor saturation (BTPS) automatically. Volume calibration was done with a
30 700 ml super-syringe before anesthesia induction following the manufacturer's guidelines.

The sidestream CO₂ signal has a time delay compared to the flow signal. The software automatically corrected the CO₂
35 delay using commonly known mathematical algorithms. The

VTCO_{2,br} or area under the curve was computed by integrating expired flow and FCO₂ in each breath.

Analysis of dead space was done off-line using Fowler's
5 analysis and adding PaCO₂ value to the CO₂ curve of the
single breath test (Fig. 3). The mean value of 3
consecutive CO₂ single breath tests was used for each
variable. The dead space of the apparatus was 60 ml (10 ml
from D-LITETM plus 50 ml from DLT connections) and was
10 subtracted from the airway dead space value.

All measurements were performed with the patient in the
lateral position. Arterial blood gases, CO₂ single breath
test data, ventilatory and hemodynamic data were recorded
15 at three points:

- a) TLV: 15 minutes after placing the patient in the
lateral position with the chest still closed.
- b) OLV_{PRE}: after 20 minutes of OLV ventilation, before
20 applying the ARS.
- c) OLV_{ARS}: 20 minutes after applying the ARS selectively to
the dependent lung.

Patients were studied during OLV prior to any vascular
25 interruption in the non-dependent lung. During OLV patients
were studied at the moment of highest shunt prior to any
vascular clipping in the nondependent lung.

The recruitment maneuver was applied selectively to the
30 dependent lung immediately after the measurement at point
b. First, the ventilator was switched to pressure control
ventilation, adjusting the level of pressure to obtain the
same tidal volume as during volume control ventilation.
Ventilation was then allowed to equilibrate for three
35 minutes. Thereafter, the ARS was performed based on an

established concept. The critical alveolar opening pressure was assumed to be at 40 cmH₂O as described for healthy lungs.

5 ARS protocol:

1. Inspiratory time was increased to 50 %.
2. Respiratory frequency was set to 12 breaths/min.
3. The inspiratory pressure gradient was limited to 20
10 cmH₂O in order to avoid large tidal volumes during the maneuver. PIP and PEEP were sequentially increased from 30/10 to 35/15 in steps of five breaths. The recruitment pressure of 40/20 cmH₂O was applied for 10 breaths.
4. Airway pressures were then gradually decreased,
15 returning to baseline settings but maintaining a PEEP level of 8 cmH₂O.

After completing the ARS, the ventilator was set back to volume control. The ARS took about 3 minutes. Prior to the
20 recruitment maneuvers central venous pressure values were maintained above 10 mmHg to avoid hemodynamic side effects caused by the increased intrathoracic pressures. Hemodynamic and ventilatory variables were monitored closely while performing the ARS. If mean arterial pressure
25 and/or heart rate changed by more than 15 % from baseline, the ARS was discontinued and 500 ml of crystalloid solution were administered. After regaining hemodynamic stability the ARS was tried again.

30 During surgery, oxygen saturation was maintained above 90% at all times. If during OLV SpO₂ fell below 90%, surgery was temporarily interrupted to resume TLV (intermittent ventilation) until oxygen saturation recovered to at least 97 %. Blood samples were processed within 5 minutes of
35 extraction by the blood gas analyzer known as ABL 520 and

values were corrected for body temperature. The calibration of this device was done with the same CO₂ concentration as the capnograph (5%).

5 Comparison of variables between points was carried out using repeated-measure analysis of variance. If the analysis of the variance F-statistic was significant the Student-Newman-Keuls post-test detected significant differences. Values are reported as mean $\pm$ SD and a p < 10 0,05 was considered significant.

Twelve patients, 10 men and 2 women, were included in this study. The following table shows the patients data. Only patient number 7 received inhaled bronchodilators 15 sporadically as needed.

P	Age (yrs)	Gender	BMI (Kg/h ²)	FEV ₁ (Lts/%)	pH	PaO ₂ (mmHg)	PaCO ₂ (mmHg)	Smoking (p/Year)	Surgery
1	71	M	26	2,1/84	7.39	64	36	50	RUL
2	48	M	28	3,0/93	7.43	101	39	NO	RUL
3	57	F	24	2,4/101	7.43	91	40	NO	RML
4	65	M	23	---	7.40	84	44	NO	Thoracoscopy
5	66	M	29	2,5/85	7.36	95	39	30	Mini-CABG
6	72	F	23	1,8/73	7.44	81	39	25	Mini-CABG
7	73	M	26	1,7/67	7.50	73	38	41	LUL
8	73	M	27	1,9/78	7.35	84	42	22	Thoracoscopy
9	19	M	23	---	7.44	99	37	NO	Thoracoscopy
10	58	M	30	2,9/89	7.34	89	43	NO	RLL
11	74	M	28	2,2/79	7.48	75	41	45	RUL/RML
12	66	M	27	2,6/96	7.34	83	39	NO	Mini-CABG
Mean	62		26		7.41	85	40		
SD	15		2,4		0,06	11	2,3		

Age (years), BMI = body mass index (kg m⁻²)

FEV₁ (absolute values in liters and % of normal values),

20 smoking history measured in total pack-year (N° cigarettes smoked per day / 20 x N° years of smoking). PaO₂, PaCO₂ and

pH awake values at room air. In patients 4 and 9 respiratory tests were not performed due to pneumothoraces. L-L =left lung, R-L = right lung, L = lower lobe, U = upper lobe, M = median lobe.

5 Mini-CABG = minimal invasive coronary by-pass graft.

The following table shows the results with regard to the most relevant tracing values and at three different lung stages:

10

Variables	TLV	OLV before ARS	OLV after ARS
Absolute values (ml):			
VD ^{aw}	160 ± 28	123 ± 29 *	107 ± 30 †
VD ^{alv}	106 ± 31	107 ± 24	97 ± 23
VD ^{phys}	266 ± 42	230 ± 39	204 ± 34 †
VT ^{alv}	392 ± 42	260 ± 39 *	279 ± 40 †
VT _{CO₂,br}	19 ± 2,8	13 ± 2,7	14 ± 2,5
Ratios:			
VD / VT	0,50 ± 0,04	0,60 ± 0,05 *	0,53 ± 0,04 †
VD ^{aw} /VT	0,30 ± 0,05	0,33 ± 0,07	0,29 ± 0,08
VD ^{alv} /VT ^{alv}	0,28 ± 0,07	0,43 ± 0,1 *	0,35 ± 0,07
Vol I / VT	0,23 ± 0,03	0,24 ± 0,06	0,19 ± 0,04 †
Vol II / VT	0,29 ± 0,05	0,30 ± 0,05	0,25 ± 0,04 †
Vol III / VT	0,48 ± 0,07	0,47 ± 0,1	0,56 ± 0,07 †
Slope II (%/L)	16 ± 3,5	15 ± 3,9	18 ± 3,9
Slope III/N (1/L)	0,58 ± 0,3	1,08 ± 0,3 *	0,72 ± 0,2 †

wherein:

TLV = two lung ventilation

OLV_{PRE} = one lung ventilation before the recruitment maneuver

5 OLV_{ARS} = one lung ventilation after an alveolar recruitment strategy (ARS).

VD^{aw} = airway dead space

VD^{alv} = alveolar dead space

VD^{phys} = physiological dead space.

10 VT^{alv} = alveolar tidal volume

VT_{CO₂,br} = expired volume of CO₂ per breath

VD/VT = physiological dead space to tidal volume

VD^{aw}/VT = airway dead space to tidal volume

VD^{alv}/VT^{alv} = alveolar dead space to alveolar tidal volume,

15 Vol I, II and III/VT = volume of phase I, II and III to tidal volume respectively, slope II = phase II slope (%/L) and slope III/N = normalized phase III slope (1/L) dividing absolute value by the mean alveolar fraction of CO₂ (FAECO₂, in %).

20

The physiological dead space (VD^{phy}) was calculated by Enghoff's modification of the Bohr equation, where VD^{phy}/VT = PaCO₂ - PAECO₂/PaCO₂. Alveolar dead space (VD^{alv}) was calculated by subtracting physiological from airway dead
25 space.

* TLV against OLV_{PRE}, p < 0,05; † OLV_{ARS} against TLV, p < 0,05; and ‡ OLV_{ARS} against OLV_{PRE}, p < 0,05.

30 Fig. 10 shows measurements of the partial paO₂ pressure with 12 patients at three different lung stages.

PaO₂ was significantly higher during TLV (379 ± 67 mmHg) compared to OLV_{PRE} (144 ± 73 mmHg, p < 0,001) and OLV_{ARS} (244
35 ± 89 mmHg, p < 0,001). During OLV the difference in PaO₂

before and after the ARS also reached significance. Hemoglobin O₂ saturation was lower at OLV_{PRE} ($95,5 \pm 2,6 \%$) as compared to TLV ($98,7 \pm 0,4\%$, $p < 0,001$) and OLV_{ARS} ($97,8\% \pm 0,9\%$, $p < 0,01$).

5

Only patients 8 needed 4 cycles of intermittent ventilation during OLV before the ARS ($\text{SpO}_2 < 90\%$). Blood gases were taken after the fourth cycle of intermittent TLV immediately before the recruitment maneuver. In these
10 patients the ARS relieved the arterial hypoxemia instantaneously, (SpO_2 from 88% to 98%) and no more episodes of hemoglobin desaturation occurred.

PaCO₂ was 43 ± 6 mmHg during OLV_{ARS} but not significantly
15 different from the other conditions. However, PaCO₂ was higher during OLV_{PRE} (46 ± 6 mmHg) compared to TLV (38 ± 4 mmHg, $p < 0,05$). EtCO₂ and PAECO₂ were stable during the protocol without any significant differences among the measurement points. Pa-etCO₂ difference was significant
20 higher during OLV_{PRE} ($14,2 \pm 4,8$ mmHg) compared to TLV ($8,8 \pm 3,2$ mmHg) and OLV_{ARS} ($11,6 \pm 4,6$ mmHg). The pH_a remained in the normal range throughout the study period.

All tracing values (variables) listed in the table
25 above decreased during OLV_{ARS} compared to OLV_{PRE}, but differences showed statistical significance only for VD/VT, Vol I, II, III/VT and phase III slope.

Tidal volumes were higher during TLV (506 ± 83 ml) compared
30 to OLV_{PRE} (377 ± 45 ml) and OLV_{ARS} (382 ± 42 ml). Minute ventilation was similar between OLV_{PRE} ($5,9$ l/min) and OLV_{ARS} ($5,8$ l/min), but both values were significantly smaller than during TLV (7 l/min). PIP values were higher during OLV_{PRE} ($25,3 \pm 1,7$ cmH₂O) compared with TLV ($20,6 \pm 1,7$

cmH₂O, $p < 0,001$) and OLV_{ARS} ($23,2 \pm 2$ cmH₂O, $p < 0,05$) with no differences between the latter two.

Hemodynamic variables, minute CO₂ elimination, oxygen
5 consumption and respiratory quotient were similar at all time points. The total time of OLV ranged from 50 to 105 minutes. No hemodynamic or ventilatory side effects related to the recruitment maneuver were detected.

10 The results of this study indicate an improved efficiency in gas exchange after a lung recruitment maneuver during OLV. This finding can be explained by a recruitment effect on both, shunt and dead space, taking into account that hemodynamic, metabolic and ventilatory conditions were
15 stable along the protocol.

Arterial oxygenation is a common measurement used to describe the extent of lung collapse. It has been suggested that a PaO₂ higher than 450 mmHg defines an open lung
20 condition during pure O₂ breathing. Arterial oxygenation, however, is an unspecific variable to evaluate the recruitment effect since it depends on the hemodynamic and metabolic status. As these two conditions remained stable throughout the study period, a true recruitment effect is
25 the most likely explanation for the increases seen in PaO₂.

During TLV a mean PaO₂ of 379 ± 67 mmHg indicated some extent of lung collapse, which is a common finding during general anesthesia. Oxygenation was further impaired during
30 OLV_{PRE} but increased after recruiting the dependent lung.

At TLV, the calculated shunt values of the patients ranged from 8 to 22 % (mean 16 %), values typically seen in general anesthesia, during OLV from 18 to 45 % (mean 28 %)
35 and during OLV_{ARS} from 12 to 27 % (mean 21 %). After lung

recruitment oxygenation was sufficient to maintain hemoglobin saturation above 95 %.

PaCO₂ increased during OLV at the same etCO₂ and PAECO₂ values as those observed during TLV. Increases in dead-space during OLV can explain this decrease in the efficiency of CO₂ removal.

During TLV, the values of the dead space related tracing values are higher than normal, due to the double lumen tube, lung collapse, open-chest condition, and the use of positive pressure ventilation.

Surprisingly, alveolar dead space did not change during OLV despite a significant increase in shunt. There is no explanation for the absence of an increase in VD^{alv} despite a marked shunt effect (apparent dead space) during OLV compared to TLV. It is assumed that during TLV a decrease in the perfusion of the nondependent lung can increase VD^{alv} (real alveolar dead space) despite a lower shunt.

Large tidal values during TLV result also in absolute large values for VD^{aw}, VT^{alv} and VD^{phys} larger than the ones observed during OLV, thus making their direct comparison questionable. Nevertheless, when these tracing values (variables) are adjusted to account for differences in tidal volume this comparison may become useful.

The tracing values (variables) that represent efficiency of ventilation and CO₂ exchange (VCO_{2,br}, VD/VT, Pa-etCO₂, VT^{alv}, VD^{alv}/VT^{alv}) were higher during TLV compared to OLV. During OLV all tracing values (variables) improved only after the recruitment maneuver. Even more interesting was the behaviour of the tracing values (variables) that show the distribution of tidal volume

throughout the phases of the CO₂ single breath test. Distribution of volume was most efficient during OLV after the ARS as indicated by a decrease in phase I and II volumes and a concomitant increase in phase III volume. The
5 absolute value of the ratio Phase III/VT observed after recruitment was even higher than during TLV. Phase II represents a transition between alveolar and airway gas transport. An increase in the cross-sectional area of the bronchial tree in the lung periphery decreases the linear
10 velocity of the bulk flow until a point where the two transport mechanisms within the lungs (convection and diffusion) are of equal magnitude. This stationary diffusion front demarcates the transition between airway and alveolar gas. On expiration, this front corresponds to
15 phase II and is used to measure VD^{aw} in Fowler's analysis.

Changes in inspiratory flow, tidal volume and peripheral cross-sectional area of bronchioli have an effect on the diffusion front, and thus on the volume and slope of phase
20 II. If inspiratory flow and tidal volume are constant, as during OLV, any change in phase II must be interpreted as a recruitment related increase in the cross-sectional area of the bronchioli leading to a more homogeneous gas emptying of lung acini. The slope of phase II, which depends on the
25 spread of transit time of different lung units, increased during OLV after the recruitment maneuver when compared to the other study conditions. However, differences were not significant. This increase in phase II slope in combination with a decrease in its volume, can be considered as a more
30 synchronous and homogeneous emptying of acini during expiration. Both, asthma and emphysema would have an opposite effect on phase II. These conditions show a wide dispersion of the transit time of gas emptying among lung units making the slope of phase II flatter and its volume
35 higher.

Diffusion is the most important mechanism of gas transport within the acinus. Phase III volume represents the amount of gas exposed to the capillary bed and therefore depends on an effective pulmonary perfusion and CO₂ production. Phase III slope is directly related to the V/Q relationship and represents the diffusional resistance for CO₂ at the alveolar-capillary membrane. Its positive slope is explained by lung pendelluft, continuous evolution of CO₂ from the blood into the acini, and a stratified inhomogeneity.

As could have been expected, during OLV_{ARS}, phase III volume increased while its slope decreased compared to OLV_{PRE}. Decrease in functional lung acini in emphysema is related to an increase in phase III slope.

The patients included in the study were submitted to different thoracic surgeries including classical thoracotomies (lobectomies), minimal invasive thoracotomies (mini-CABG), and closed-chest surgeries (Thoracoscopies). Possible differences in lung mechanics can account for the changes in arterial oxygenation and ventilation efficiency among these different type of surgeries. However, oxygenation and dead space behaviour were similar and hemodynamic and metabolic conditions were constant along the study period. For these reasons, it is assumed that the changes in gas exchange and dead space observed in the study were related to the therapeutic effect of the recruitment maneuver.

Epidural anesthesia used in open thoracotomies can cause hemodynamic and metabolic changes that could influence gas exchange. However, these conditions were stable and no

differences in PaO_2 between open thoracotomies and thoracoscopies, without epidural anesthesia, were seen.

Empirical values of 40 cmH_2O of PIP were used as opening
5 pressure and 8 cmH_2O of PEEP to keep the lung open, since individual levels of these pressures for each patient are difficult to determine at the bedside.

Due to a mediastinal displacement, the surgeon's
10 manipulation and the chest fixation opening and closing pressures in the dependent lung could be higher during thoracic surgery as compared to the other types of surgeries. In addition, PIP pressure may not represent true alveolar pressure when using a narrow DLT. For these
15 reasons, it is possible that true opening and closing pressures were not reached in each patient which could have resulted in the absence of the maximal impact of the ARS on oxygenation and lung efficiency.

20 Lung recruitment improves gas exchange and ventilation efficiency during OLV anesthesia. The results suggest that one simple recruitment maneuver during OLV is enough to increase PaO_2 to safer levels thereby eliminating the need for any additional therapeutic intervention.

25

In the following, a second study concerning the effect of PEEP on dead space, with and without a lung recruitment maneuver, is discussed.

30 Sixteen patients were studied prospectively undergoing open lower abdominal surgery. The enrolled patients were patients ASA II-III, without smoking history or cardiopulmonary uncompensated diseases.

Anesthesia induction was performed with fentanyl 4 $\mu\text{g kg}^{-1}$,
35 thiopental 3 mg kg^{-1} and vecuronium 0,08 mg kg^{-1} and

maintained with Isofluorane and bupivacaine 0,5% through an epidural catheter inserted at L2-3.

After tracheal intubation with a cuffed endotracheal tube,
5 the lungs were ventilated with a Siemens 900 C ventilator (Siemens-Elema, Solna, Sweden). Air leaks from around the endotracheal tube were detected by comparing inspired-expired tidal volume (VT) measured proximally in the airway. A volume controlled mode was used with a VT of 8 ml
10 kg^{-1} , respiratory rate (RR) between 10 -15 bpm, FIO_2 of 0,5, inspiratory time of 0,3 without pause and initially, without positive end-expiratory pressure (ZEEP). Alveolar ventilation was increased or decreased by adjusting RR to reach an end-tidal CO_2 value of 34 mmHg while maintaining
15 VT constant.

Static respiratory compliance was measured dividing VT by the pressure differences between plateau and total PEEP. End-expiratory lung volume (EELV) was measured pushing the
20 expiratory pause button of the Servo 900C for 6 seconds during the inspiratory pause while releasing PEEP from 5 cmH_2O to ZEEP. Thus, a volume of gas is expelled until FRC at ambient pressure is reached. The EELV was then determined by subtracting the average value of the latest
25 three normal expiratory tidal volumes before the maneuver from the volume of gas measured. This volume was recorded continuously in a computer and analyzed it off-line. The return of the expiratory flow curve to baseline at the end of the EELV-maneuver was used for checking air trapping.

30

Carbon dioxide elimination (VCO_2) was calculated by multiplying alveolar ventilation and mean alveolar fraction of CO_2 . Oxygen consumption (VO_2) was calculated as the product of alveolar ventilation and inspiratory-expiratory
35 O_2 difference. The respiratory quotient (RQ) was calculated

dividing VCO_2 by VO_2 . The CO_2 single breath test and its tracing values are explained according to Fig. 3 and Fig. 6 above.

- 5 The ventilatory, hemodynamic and metabolic states were maintained constant during the study. In each patient 3 periods were studied sequentially:
1. ZEEP: ventilation with zero of PEEP.
 2. PEEP: ventilation with 5 cmH_2O of PEEP.
 - 10 3. ARS: Between point 2 and 3, the lungs were ventilated for 20 minutes without PEEP to reach baseline conditions once again.

The alveolar recruitment strategy is a maneuver assigned to
15 treat pulmonary collapse by reaching the alveolar opening pressure for ten breaths and keeping the lung open with a PEEP level above the lung's closing pressure. In the patients studied it is assumed that the lung opening pressure was 40 cmH_2O of peak inspiratory pressure (PIP)
20 and the closing pressure lower than 5 cmH_2O . The maneuver was performed according to Fig. 2 with the following settings:

- Ventilatory frequency was set to 15 breaths per minute.
- 25 - Inspiration/expiration ratio was set at 1:1.
- Delta pressure or the pressure difference between PIP and PEEP (PIP/PEEP) was maintained at 20 cmH_2O .
- Airway pressures were increased in steps: 25/5 to 30/10 and then to 35/15 cmH_2O . Each step of pressure was
30 maintained for 5 breaths.
- A final PIP/PEEP step of 40/20 cmH_2O was reached and maintained for 10 breaths.
- After the 10 breaths, airway pressures were gradually decreased returning to the previous setting at 5 cmH_2O
35 of PEEP reassuming a volume controlled ventilation

mode.

At the end of each period (30 minutes), the CO₂ single breath test curves were recorded and blood samples taken
5 for dead space analysis. Blood specimens were processed and corrected for body temperature within 5 minutes of extraction by a gas analyzer ABL 510. Body temperature was measured with an esophageal thermometer.

10 Comparison of tracing values (variables) among periods was carried out using analysis of variance. If the variance F-statistic was significant the Student-Newman-Keuls post-test detected significant differences. EELV between PEEP and ARS was evaluated by the Student t test. Values are
15 reported as mean $\pm$ SD and a $p < 0,05$ was considered significant.

Nine females and seven males, aged 65-80 years ($71,2 \pm 4,5$), with body mass indices between 24-30 ($26,8 \pm 2,1$)
20 undergoing hysterectomies ($n = 3$) and hemicolectomies ($n = 13$) were studied. The following table shows the detected tracing values (variables) with regard to the three different ventilation modes ZEEP, PEEP and ARS, where:

25 VD/VT = physiologic dead space to tidal volume
VDAW = airway dead space (ml)
VDALV = alveolar dead space (ml)
VDPHYS = physiologic dead space (ml)
VDAW / VTALV = alveolar dead space to tidal volume
30 VDAW/VT = airway dead space to tidal volume
VTCO_{2,br} = CO₂ elimination per breath (ml)
VTALV = alveolar tidal volume (ml)
Vol I/VT = volume of phase I to tidal volume
Vol II/VT = volume of phase II to tidal volume
35 Vol III/VT = volume of phase III to tidal volume

slope II = phase II slope

slope III/N = normalized phase II slope divided by the mean alveolar concentration of CO₂

angle II/III = angle formed between phase II and III slopes
5 (°).

* PEEP against ZEEP, $p < 0,05$

† ARS against ZEEP, $p < 0,05$

‡ ARS against PEEP, $p < 0,05$.

Values are presented as mean $\pm$ SD. A p value lower than
10 0,05 was considered significant.

Variable	ZEEP	PEEP	ARS
V _D /V _T	0,50 $\pm$ 0,07	0,51 $\pm$ 0,06	0,45 $\pm$ 0,01 *†
V _{D AW} (ml)	160 $\pm$ 48	161 $\pm$ 38	137 $\pm$ 32
V _{D ALV} (ml)	110 $\pm$ 35	113 $\pm$ 30	108 $\pm$ 32
V _{D PHYS} (ml)	270 $\pm$ 54	274 $\pm$ 56	246 $\pm$ 50
V _{D ALV} /V _{TALV}	0,29 $\pm$ 0,05	0,28 $\pm$ 0,06	0,26 $\pm$ 0,04
V _{D AW} /V _T	0,30 $\pm$ 0,08	0,29 $\pm$ 0,04	0,25 $\pm$ 0,04 ‡†
V _{T CO2,br} (ml)	23 $\pm$ 2,6	25 $\pm$ 3,3 *	27 $\pm$ 3,2 ‡†
V _{T ALV} (ml)	340 $\pm$ 72	355 $\pm$ 71	373 $\pm$ 68 ‡†
Vol I / V _T	0,22 $\pm$ 0,09	0,21 $\pm$ 0,06	0,18 $\pm$ 0,06
Vol II / V _T	0,35 $\pm$ 0,05	0,28 $\pm$ 0,05 *	0,26 $\pm$ 0,05 †
Vol III / V _T	0,45 $\pm$ 0,08	0,51 $\pm$ 0,1 *	0,57 $\pm$ 0,09 ‡†
Slope II (%/L)	46 $\pm$ 7,7	56 $\pm$ 10 *	63 $\pm$ 11 ‡†
Slope III/N (L ⁻¹)	0,21 $\pm$ 0,11	0,18 $\pm$ 0,10 *	0,13 $\pm$ 0,07 ‡†
Angle II / III (°)	127 $\pm$ 2,1	125 $\pm$ 7,7	113 $\pm$ 4 ‡†

Lung recruitment increased tracing values related to lung efficiency and decreased tracing values related to inefficiency. PEEP did not have same effect on dead space. Phase II slopes showed a significant increase with PEEP and ARS although lung recruitment showed the highest values. These steeper slopes were associated with a corresponding decrease in Vol II/VT.

Normalized phase III slope decreased with PEEP ventilation and showed an additional diminution after ARS. Volume of phase III increased with ARS and PEEP compared with ZEEP. The angle between II-III showed significant differences only after the recruitment maneuver.

The following table shows partial pressures of CO₂ and the alveolar ventilation at constant minute ventilation.

Variable	ZEEP	PEEP	ARS
PaCO ₂ (kPa)	5,1 ± 0,4	5,2 ± 0,6	4,9 ± 0,5
etCO ₂ (kPa)	4,0 ± 0,3	4,0 ± 0,4	3,9 ± 0,2
Pa-etCO ₂ (kPa)	1,1 ± 0,5	1,2 ± 0,5	0,9 ± 0,5 *†
VA (l/min)	3,3 ± 0,8	3,4 ± 0,6	3,6 ± 0,8 *†

PaCO₂ = arterial partial pressure of CO₂ (kPa)
 etCO₂ = end-tidal partial pressure of CO₂ (kPa)
 Pa-etCO₂ = arterial to end-tidal differences of CO₂ (kPa)
 VA = alveolar minute ventilation (l/min).

* ARS against ZEEP, p < 0,05

† ARS against PEEP, p < 0,05.

Pa-etCO₂ was significantly lower and alveolar ventilation larger after ARS compared with ZEEP and PEEP.

Fig. 11 shows measurements of the end-expiratory lung
5 volume (EELV), the partial paO₂ pressure and the compliance
at three different ventilation modes. Arterial oxygenation,
EELV and respiratory compliance showed a significant
increase after lung recruitment compared with ZEEP and
PEEP. PEEP without lung recruitment showed compliance
10 values significantly higher than ZEEP but without changes
in PaO₂.

When compared with ZEEP or PEEP, lung recruitment decreased
those tracing values of the CO₂ single breath test
15 which are related to pulmonary inefficiency and increased
the ones related to efficiency. The increased efficiency of
ventilation was associated with an increase in arterial
oxygenation, expiratory lung volume and respiratory
compliance, all parameters commonly used as markers of an
20 open lung condition.

PEEP without recruitment showed an intermediate effect
between ZEEP and ARS in all tracing values studied. In
anaesthetized patients low levels of PEEP have a
25 contradictory effect on arterial oxygenation and
atelectasis. Study results agree in that the recruitment of
collapsed airways is the main effect of PEEP without a
recruitment maneuver. Atelectasis treatment requires higher
airway pressures than the amount of PEEP commonly used
30 during anesthesia to pop open collapsed alveoli due to the
incomplete lung recruitment observed with the use of PEEP
alone.

In contrast to PEEP alone, lung recruitment maneuver
35 increase both, the cross-sectional area of small airways

and the alveolar-capillary area, by reversing airway and acinar collapse respectively. This total recruitment or open lung condition improves the diffusive CO_2 transport at the acinar level and could explain the changes observed in the CO_2 single breath test. Increasing CO_2 diffusion after the ARS moves the interface between convective-diffusive transport mouthward, thus decreasing the VDAW measured by Fowler's method.

10 Lung recruitment was also associated with an improved efficiency in CO_2 elimination as expressed by a larger $\text{VTCO}_{2,\text{br}}$ and a lower Pa-etCO_2 at constant VCO_2 and ventilator settings. These results indicate that the area of gas exchange increased and V/Q improved.

15 Differences between PEEP and ARS in the distribution of gas volumes within the lung may have an impact on gas exchange and respiratory compliance. Analyzing EELV and the volumes of phase I-II-III, it was observed that the recruitment maneuver re-distributed the VT away from phase I-II towards the volume of phase III (alveolar gas). Compared with ZEEP, PEEP without a recruitment maneuver increased volume of phase III but at the same time, retained some volume within the inefficient parts of the VT (phase I and II).

25 Changes in the slope of phase II and III at ZEEP could be explained by the co-existence of acini with different time constants due to aging and partial collapse.

30 Total lung recruitment has a positive effect on CO_2 diffusion as reflected by the changes observed in volumes and slopes of phase II-III after ARS. On the one hand it is assumed that an increase in the cross-sectional area caused by airway recruitment could improve the CO_2 diffusive transport from alveoli to bronchioli. On the other hand, an

35

increase in the area of gas exchange due to a recruitment of atelectasis improved the diffusive transport from the capillaries to the alveoli.

5 In summary, the alveolar recruitment strategy improved the efficiency of ventilation in anesthetized patients. Differences observed in the CO₂ single breath test between PEEP with and without an lung recruitment maneuver can be explained by the effectiveness of the treatment of
10 pulmonary collapse.

Fig. 12 shows an apparatus according to the invention connected in series with the ventilator to the patient. The apparatus comprises a carbon dioxide sensor for measuring
15 the expired CO₂ concentration, a pneumotachograph for measuring airway flow, a pressure sensor for measuring airway pressures, and a data processor which determines during a change of the airway pressure from the resulting course of at least one tracing value the airway
20 pressure level at which alveolar opening or lung overdistension or lung open condition or alveolar closing occurs. As indicated in Fig. 12, a feedback line can be included connecting the apparatus with the ventilator thus creating effectively a closed loop system. This allows to
25 directly control the ventilator, once the optimal values for PIP and PEEP have been identified.

As an example, with regard to the above-mentioned tracing values the following logic can be implemented in
30 the data processor:

Detection of lung recruitment

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the slope of phase III reaches a maximal decrease.

- 5 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the intercept of the slope of phase III reaches a maximal increase.

- 10 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the slope of phase II reaches a maximal increase.

- 15 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the intercept of slope of phase II reaches a maximal decrease.

- 20 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the angle II-III reaches a maximal decrease.

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase I reaches a maximal increase.

- 25 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase II reaches a maximal increase.

- 30 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase III reaches a maximal decrease.

- 35 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the $VT_{CO_2,br}$ reaches a maximal increase.

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the VCO_2 reaches a maximal increase.

5

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the VD_{bohr} reaches a maximal decrease.

- 10 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the negative gradient of the resulting course of the measured $etCO_2$ minus the mean alveolar partial pressure of CO_2 ($P_{et}-AECO_2$) reaches the maximal decrease.

15

Detection of lung overdistension

- The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the VD_{aw} reaches a
20 maximal increase, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

- 25 The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the VD_{aw}/V_T reaches a maximal increase, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal
30 peak inspiratory pressure defined by the user.

- The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the $VT_{CO_2,br}$ results in a decrease of about 10% from its previous value,
35 provided the maximal peak inspiratory pressure is below a

preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

- 5 The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the VCO₂ results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a
10 preset minimal peak inspiratory pressure defined by the user.

The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the PAECO₂ results in
15 a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

20

The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the angle II-III results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a
25 preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

The peak inspiratory pressure is increased continuously and
30 a lung overdistension is detected, if the phase II slope results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure
35 defined by the user.

Detection of open-lung condition

The positive end expiratory pressure is decreased
5 continuously and an open-lung condition is detected, if the
VDaw resulting in a minimal value observed before the
closing pressure is detected.

The positive end expiratory pressure is decreased
10 continuously and an open-lung condition is detected, if the
VDaw/VT resulting in a minimal value observed before the
closing pressure is detected.

The positive end expiratory pressure is decreased
15 continuously and an open-lung condition is detected, if the
VTCO₂,br resulting in a maximal value observed before the
closing pressure is detected.

The positive end expiratory pressure is decreased
20 continuously and an open-lung condition is detected, if the
angle II-III resulting in a minimal value observed before
the closing pressure is detected.

The positive end expiratory pressure is decreased
25 continuously and an open-lung condition is detected, if the
phase II slope resulting in a maximal value observed before
the closing pressure is detected.

The positive end expiratory pressure is decreased
30 continuously and an open-lung condition is detected, if the
Volume of phase II resulting in a minimal value observed
before the closing pressure is detected.

The positive end expiratory pressure is decreased
35 continuously and an open-lung condition is detected, if the

Volume of phase III resulting in a maximal value observed before the closing pressure is detected.

The positive end expiratory pressure is decreased
5 continuously and an open-lung condition is detected, if the intercept of phase II slope resulting in a maximal value observed before the closing pressure is detected.

Detection of lung re-collapse

10

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the VDaw shows a permanent gradient change after the point
15 corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

20

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the VTCO_{2,br} shows a permanent gradient change after the point
25 corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

30

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the VCO₂ shows a permanent gradient change after the point
35 corresponding to the open-lung condition values, provided

the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

5

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the volume of phase II shows a permanent gradient change after the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

15

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the volume of phase III shows a permanent gradient change after the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

25

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the angle II-III shows a permanent gradient change after the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

35

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the tracing values of the intercept of phase II slope shows a permanent gradient
5 change after the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

10

Re-opening procedure

The peak inspiratory pressure is set 2 - 5 cmH₂O above the value identified during the detection of the open-lung
15 condition, provided this value is below a preset maximum peak inspiratory pressure defined by the user and above a preset minimum peak inspiratory pressure defined by the user.

20 The positive end expiratory pressure is set 2 - 3 cmH₂O above the value identified during the detection of the lung re-collapse condition, provided this value is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory
25 pressure defined by the user.

The peak inspiratory pressure is set to a value to achieve the desired tidal volume, provided this value is below a preset maximum peak inspiratory pressure defined by the
30 user and above a preset minimum peak inspiratory pressure defined by the user.

Fig. 13 shows a plot of the O₂ single breath test depicting the O₂ gas concentration during the patient exhale cycle.
35 Plotted is the expiratory oxygen fraction in percentage

against time and a volume rate measurement against time. This plot corresponds to the O_2 single breath test. The plotted exhale cycle can be subdivided into two stages, one representing the airway dead space and the other one
5 representing the alveolar tidal volume. The expiratory oxygen fraction does not decrease considerably within the first stage, since the gas expired represents gas from the airway conduction structures where gas exchange does not occur. On the other side, the expiratory oxygen fraction is
10 considerably lower in the second stage, when unmixed gas from regions of the lung which normally are in active exchange with the alveolar tissue is expired. Within Fig. 13 paO_2 is the partial pressure of oxygen and etO_2 is the endtidal oxygen concentration of a single breath.

15

The plot according to Fig. 13 is formed by the exhaled partial pressure of O_2 against the expiratory tidal volume. Its analysis can be performed, e.g., using a fast side-stream or main-stream oxygen sensor. Furthermore, a
20 computer is provided to record and analyze data.

The side-stream O_2 signal has a time delay with respect to the flow signal. A corresponding software can correct the O_2 delays automatically using mathematical algorithms. The
25 $VTO_{2,br}$ or area under the curve can be computed by integrating expired flow and O_2 in each breath. Analysis of dead space can be done on-line and/or off-line using Fowler's analysis and adding arterial PO_2 values to the O_2 curve of the single breath test.

30

Fig. 14 shows a plot comparing the CO_2 gas concentration during a CO_2 single breath test with the O_2 gas concentration during an O_2 single breath test during the patient exhale cycle. As can be clearly seen, the curve of
35 the O_2 single breath test looks like a mirror image of the

curve of the CO₂ single breath test. Whereas, in this example simultaneous measurements of the CO₂ gas concentration and the O₂ gas concentration during a single breath test were performed, usually it is sufficient to perform measurements of only one gas concentration to determine the status of the lung according to the invention.

Fig. 15 shows some possible tracing values within a plot of an O₂ single breath test. As already mentioned, principally any gas concentration can be used within the method and apparatus according to the invention, provided this gas concentration allows to determine the status of the lung in accordance with the invention. In addition to the example given so far, namely to utilize the CO₂ concentration, Fig. 15 demonstrates that the O₂ concentration can be used equally well.

In order to determine the required tracing values, the curve shown in Fig. 15 is divided into three phases. Phase I represents CO₂ free gas expired from the airway conduction structures where gas exchange does not occur. Hence, the O₂ concentration is highest and remains comparatively constant. Phase II is characterized by an counter-S-shaped downswing and represents the transition from airway to alveolar gas. Phase III reflects the exhalation of unmixed gas from regions of the lung which normally are in active exchange with the alveolar tissue and thus closely resembles at least in healthy patients gas properties associated with arterial blood in contact with the lung for gas exchange, i.e. CO₂ release and O₂ absorption. In normal lungs, Phase III is characterized by a horizontal level since ventilated and perfused alveolar regions are closely matched. In a diseased lung, Phase III

may not appear horizontal due to a mismatch in ventilation and perfusion of this lung region.

Fig. 15 shows only two possible tracing values within
5 a plot of the O₂ single breath test, which are

slope II or steepest mean slope	determined by the steepest mean slope (either over time or over volume) of the O ₂ concentration in the expired gas in vicinity of the point of inflection, and
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slope III or endtidal mean slope	determined by the mean slope (either over time or over volume) of the O ₂ concentration in the expired gas towards the final stage of a single breath.
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However, the same types of tracing values as obtained
from a CO₂ single breath test can be determined from Fig.
10 15. The two presented tracing values can be obtained ned
in the same way as described for the CO₂ single breath test
with reference to Fig. 6.

It should be noted with reference to Fig. 14, that certain
15 tracing values will have opposite signs when
performing an O₂ single breath test compared to
corresponding values obtained from a CO₂ single breath
test.

20 According to the invention, a gas concentration can be used
to determine the status of the lung, i.e. the O₂ gas
concentration or the CO₂ gas concentration. However, the
results of the evaluation of an O₂ single breath test
according to Fig. 15 could be combined with the results of
25 an evaluation of a CO₂ single breath test. This would
increase the accuracy of the diagnostic method
considerably.

ABBREVIATIONS

	ARS	alveolar recruitment strategy
5	BTPS	ambient pressure and water vapor saturation
	DLT	double lumen tube
	EELV	end-expiratory lung volume
	etCO ₂	endtidal CO ₂ concentration
	FaeCO ₂	mean expired alveolar fraction of CO ₂
10	FiO ₂	inspired oxygen fraction
	FIR	finite impulse response
	OLV	one-lung ventilation
	paCO ₂	partial pressure of CO ₂
	paeCO ₂	mean alveolar fraction of CO ₂
15	paO ₂	partial pressures of oxygen
	PEEP	positive end-expiratory pressure
	PIP	peak inspiratory pressure
	RQ	respiratory quotient
	RR	respiratory rate
20	slope II	steepest mean slope
	slope III	endtidal mean slope
	SO ₂	hemoglobin oxygen saturation
	TLV	intermittent ventilation
	V/Q	ventilation/perfusion relationship
25	VCO ₂	carbon dioxide elimination
	VD ^{alv}	alveolar dead space
	VD ^{aw}	airway dead space
	VD ^{phy}	physiological dead space
	VO ₂	oxygen consumption
30	VT	tidal volume
	VT ^{alv}	alveolar tidal volume
	VTCO _{2,br}	expired volume of CO ₂ per breath
	VTe	expired tidal volume
	ZEEP	positive end-expiratory pressure

5 **CLAIMS**

- 1 Apparatus for providing ventilator settings with regard to airway pressure levels of an artificial ventilator, said artificial ventilator comprising:
- 10 a patient interfacing means for providing an interface with a patient and a connection to a lung of the patient;
- a sensor for measuring data samples of gas concentration in an expired gas during a single breath in a time domain;
- a means for assessing a volumetric rate of the expired gas;
- 15 a means for converting the obtained data samples from the time domain to a volumetric domain;
- means for selecting a plurality of data samples from said obtained data samples, said means serving to exclude data samples representing airway gas only;
- means for calculating a tracing value being sensitive to changes of alveolar dead space on the basis of said selected data samples; and
- 20 a data processor which detects during a change of at least one airway pressure level of the artificial ventilator from the resulting course of a plurality of calculated tracing values the airway pressure level at which alveolar opening or lung overdistension or lung open condition or alveolar closing occurs.
- 25 2. Apparatus according to claim 1, wherein the gas concentration represents the CO₂ concentration.
- 30 3. Apparatus according to claim 1, wherein a first ventilator setting corresponds to the peak inspiratory pressure and wherein a second ventilatory setting corresponds to the positive end expiratory pressure.

- 5 4. Apparatus according to claim 3, wherein a first tracing value is represented by the endtidal mean slope of the CO₂ concentration in the expired gas during a single breath.
- 10 5. Apparatus according to claim 4, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined first tracing values reaches a minimum.
- 15 6. Apparatus according to any one of the claims 4-5, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined first tracing values reaches a maximum.
- 20 7. Apparatus according to any one of the claims 4-6, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of the plurality of determined first tracing values reaches a minimum.
- 25 8. Apparatus according to any one of the claims 4-7, wherein starting from an open lung condition the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined first tracing values reaches a maximum.
- 30 9. Apparatus according to any one of the claims 3-8, wherein a second tracing value is represented by the steepest slope of the CO₂ concentration in the expired gas during a single breath.
- 35 10. Apparatus according to claim 9, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by

- 5 breath and wherein an alveolar opening of the lung is detected, if the resulting
course of the plurality of determined second tracing values reaches a maximum.
11. Apparatus according to any one of the claims 9-10, wherein starting from
alveolar opening the peak inspiratory pressure of the artificial ventilator is
10 increased stepwise breath by breath and wherein a lung overdistension is
detected, if the negative gradient of the resulting course of the plurality of
determined second tracing values reaches a minimum.
12. Apparatus according to any one of the claims 9-11, wherein starting from lung
15 overdistension the positive end expiratory pressure of the artificial ventilator is
decreased stepwise breath by breath and wherein an open lung condition is
detected, if the resulting course of the plurality of determined second tracing
values reaches a maximum.
- 20 13. Apparatus according to any one of the claims 9-12, wherein starting from an
open lung condition the positive end expiratory pressure of the artificial ventilator
is decreased stepwise breath by breath and wherein an alveolar closing is
detected, if the negative gradient of the resulting course of the plurality of
determined second tracing values reaches a minimum.
- 25 14. Apparatus according to any one of the claims 3-13, wherein a third tracing value
is represented by the angle between the endtidal mean slope and the steepest
mean slope of the CO₂ concentration in the expired gas during a single breath.
- 30 15. Apparatus according to claim 14, wherein starting from alveolar closing the peak
inspiratory pressure of the artificial ventilator is increased stepwise breath by
breath and wherein an alveolar opening of the lung is detected, if the resulting
course of the plurality of determined third tracing values reaches a minimum.
- 35 16. Apparatus according to any one of the claims 14-15, wherein starting from
alveolar opening the peak inspiratory pressure of the artificial ventilator is
increased stepwise breath by breath and wherein a lung overdistension is

- 5 detected, if the positive gradient of the resulting course of the plurality of
determined third tracing values reaches a maximum.
17. Apparatus according to any one of the claims 14-16, wherein starting from lung
overdistension the positive end expiratory pressure of the artificial ventilator is
10 decreased stepwise breath by breath and wherein an open lung condition is
detected, if the resulting course of the plurality of determined third tracing values
reaches a minimum.
18. Apparatus according to any one of the claims 14-17, wherein starting from an
15 open lung condition the positive end expiratory pressure of the artificial ventilator
is decreased stepwise breath by breath and wherein an alveolar closing is
detected, if the positive gradient of the resulting course of the plurality of
determined third tracing values reaches a maximum.
- 20 19. Apparatus according to any one of the claims 3-18, wherein a plurality of
different types of tracing values are calculated in parallel and wherein from the
resulting course of the plurality of different types of tracing values the peak
inspiratory pressure at which alveolar opening or lung overdistension and/or the
positive end expiratory pressure at which lung open condition or alveolar closing
25 occurs are detected.
20. Apparatus according to any one of the claims 3-19, wherein during a recruitment
maneuver of the lung the peak inspiratory pressure is set above the peak
inspiratory pressure at which alveolar opening has been detected and the
30 positive end-expiratory pressure is set above the positive end expiratory
pressure at which alveolar closing has been detected.
21. Apparatus according to claim 1, wherein said data processor is designed to
detect the airway pressure level at which alveolar opening or lung overdistension
35 or lung open condition or alveolar closing occurs where said resulting course of
the plurality of determined tracing values reaches minima or maxima.

PRIOR ART

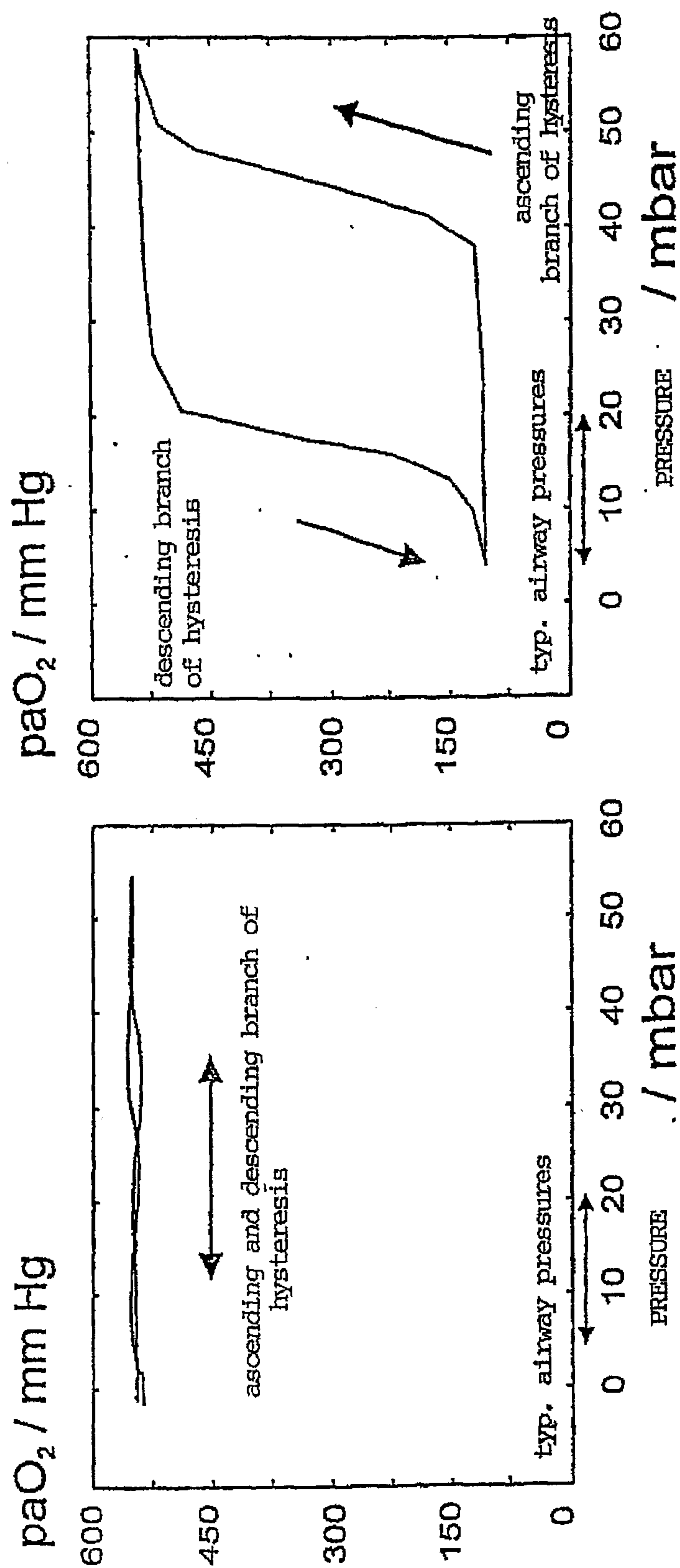


Fig. 1

PRIOR ART

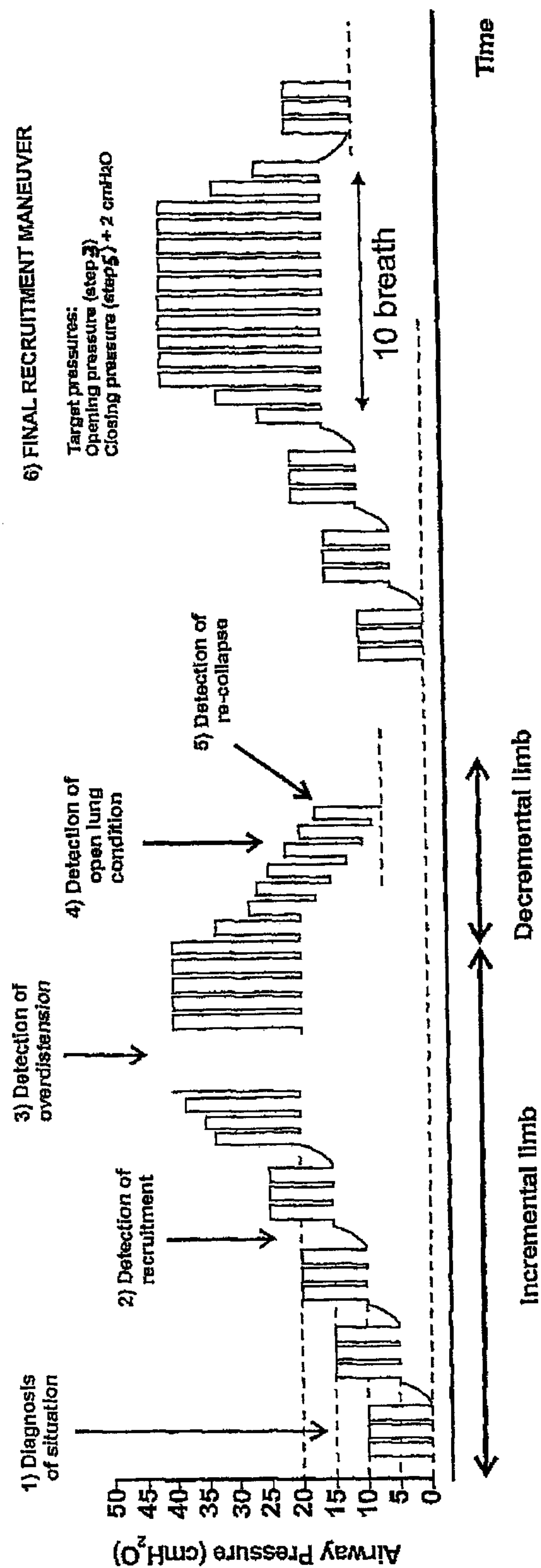


Fig. 2

PRIOR ART

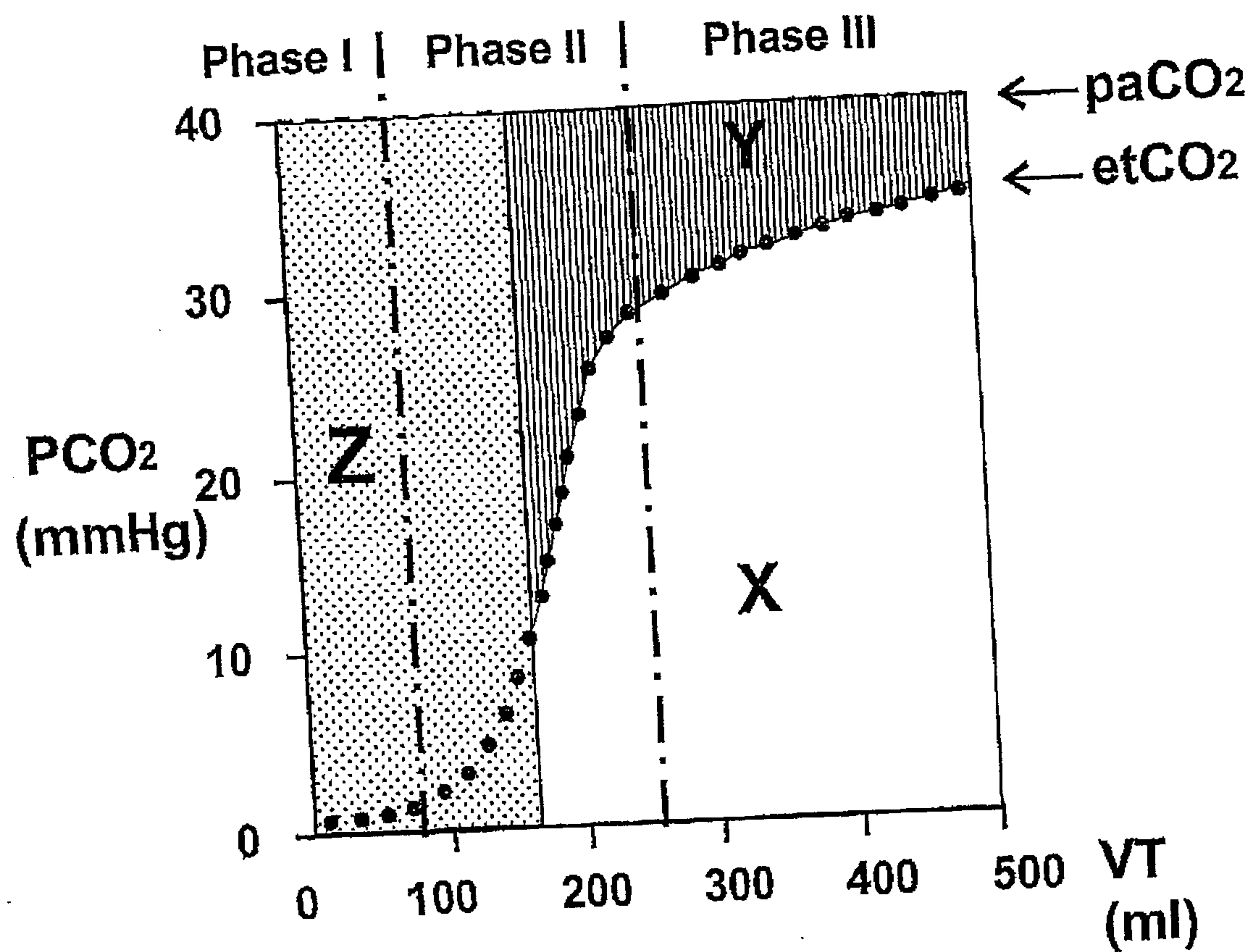


Fig. 3

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PRIOR ART

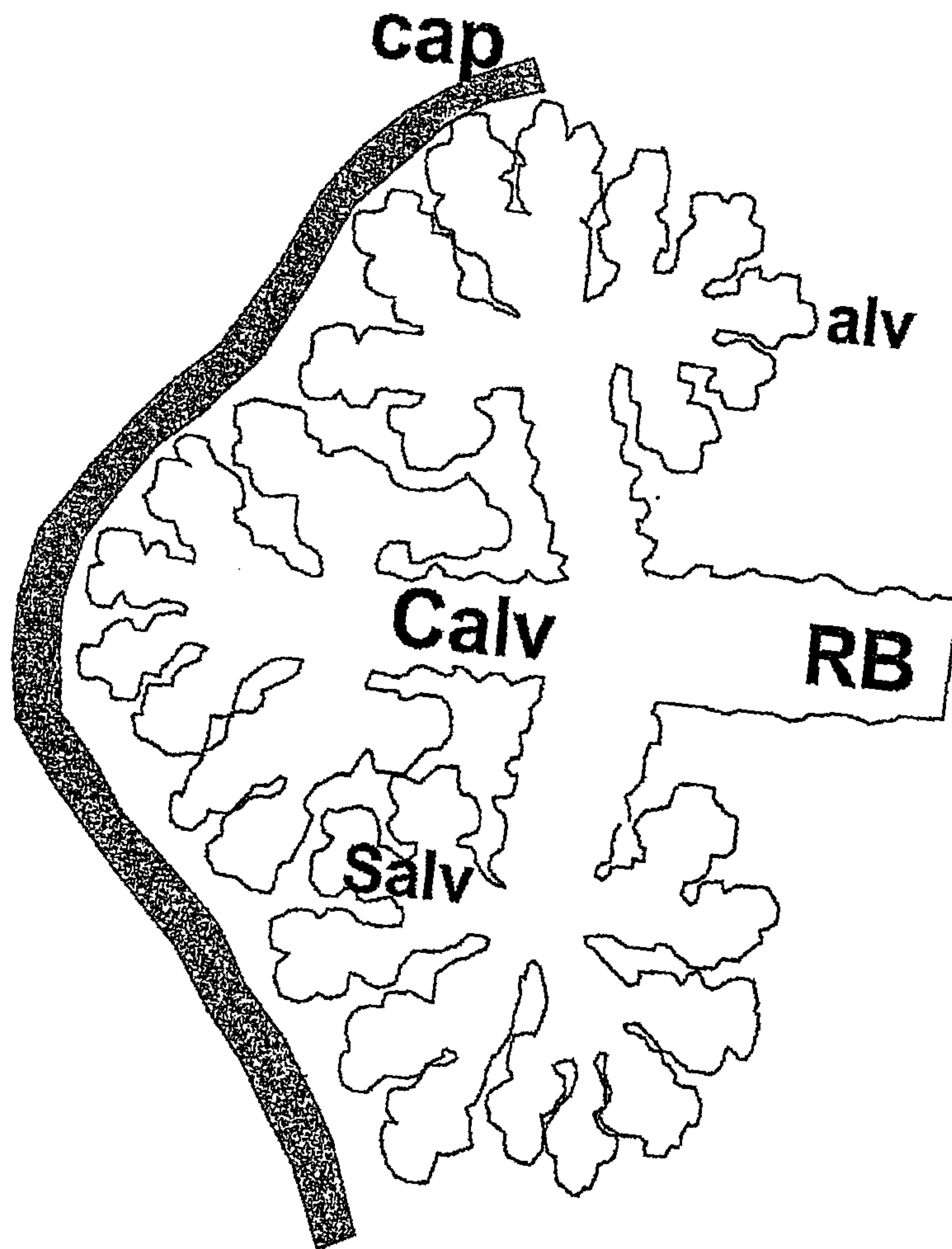


Fig. 4

PRIOR ART

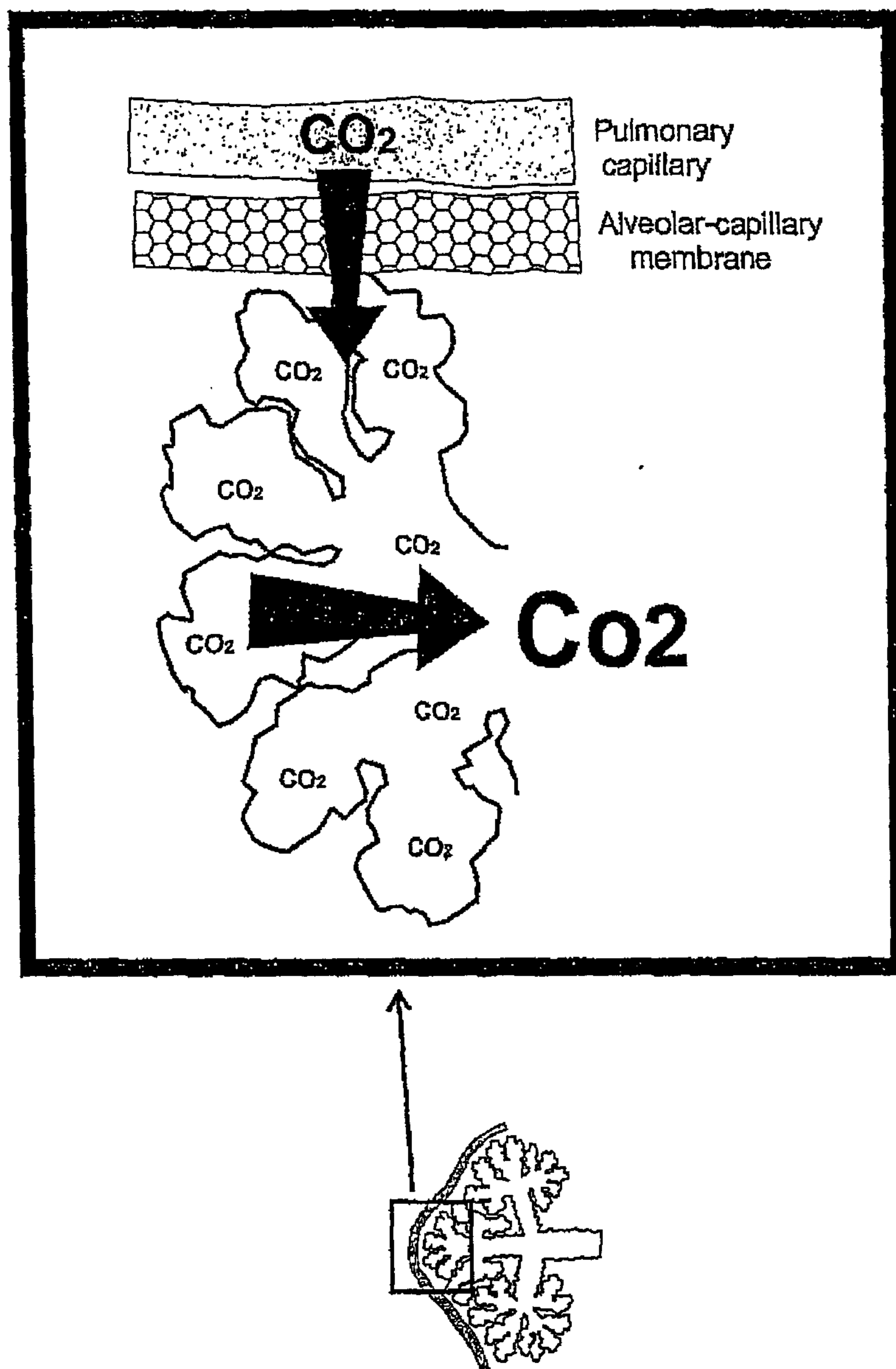


Fig. 5

PRIOR ART

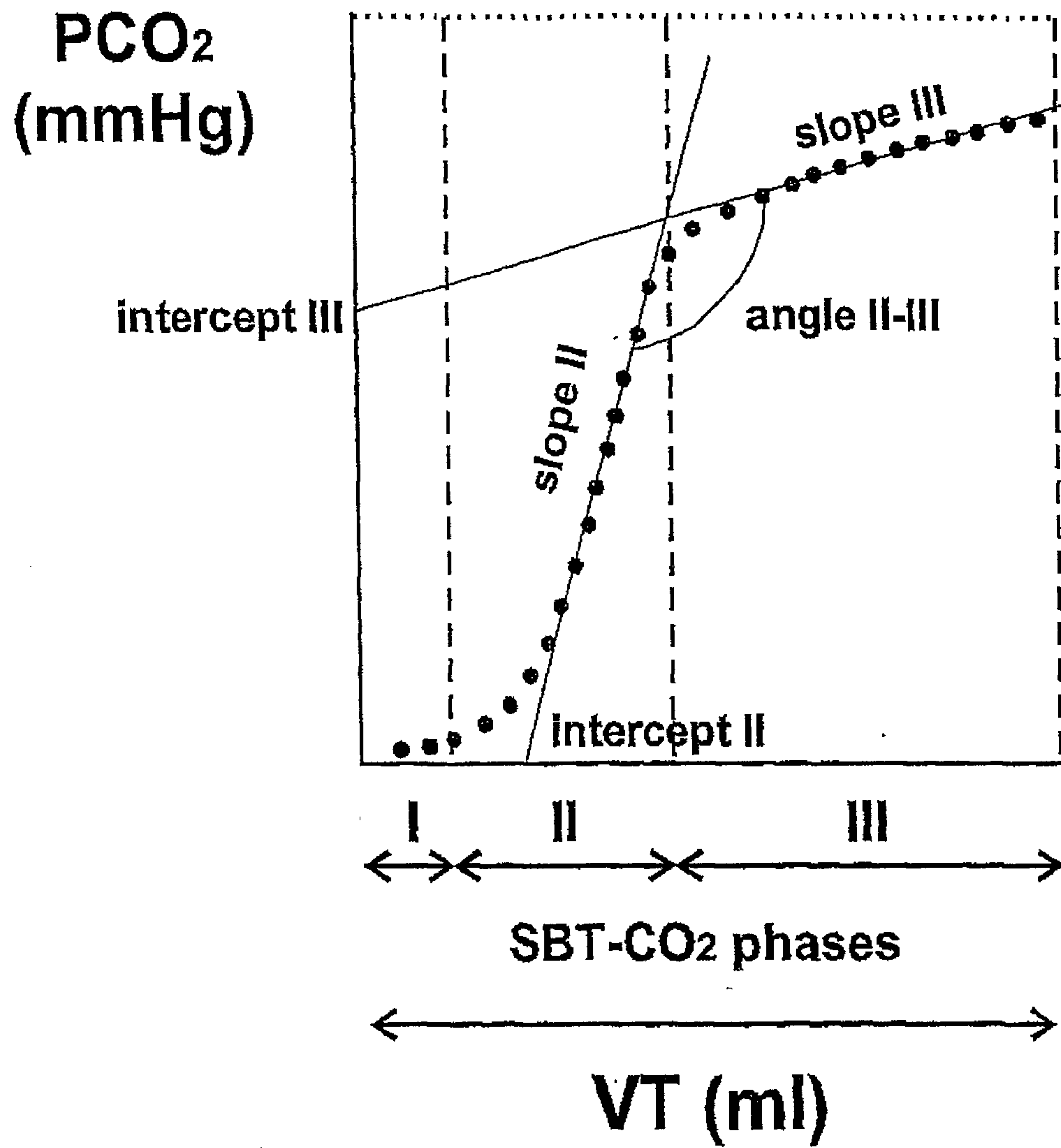


Fig. 6

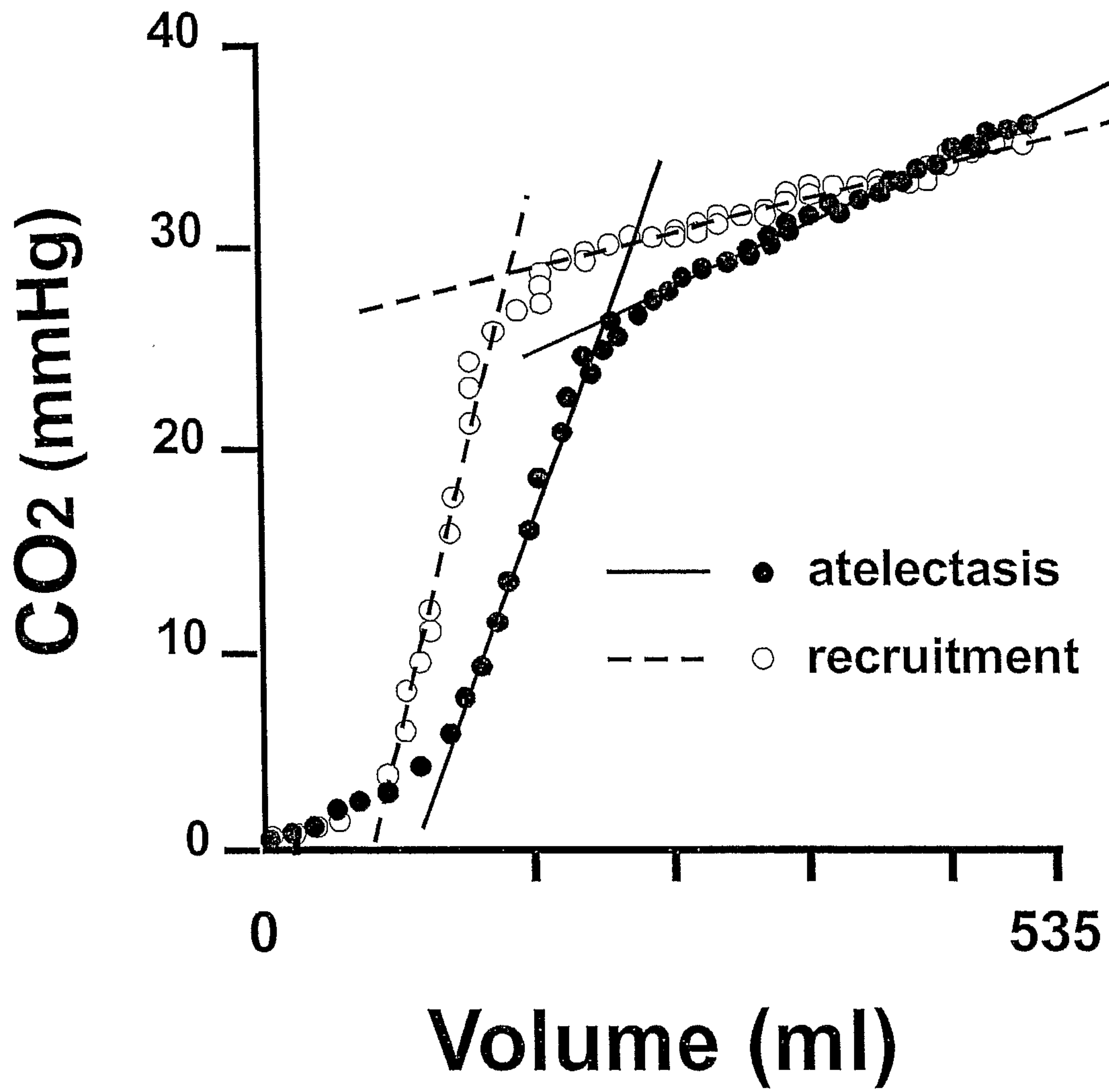


Fig. 7

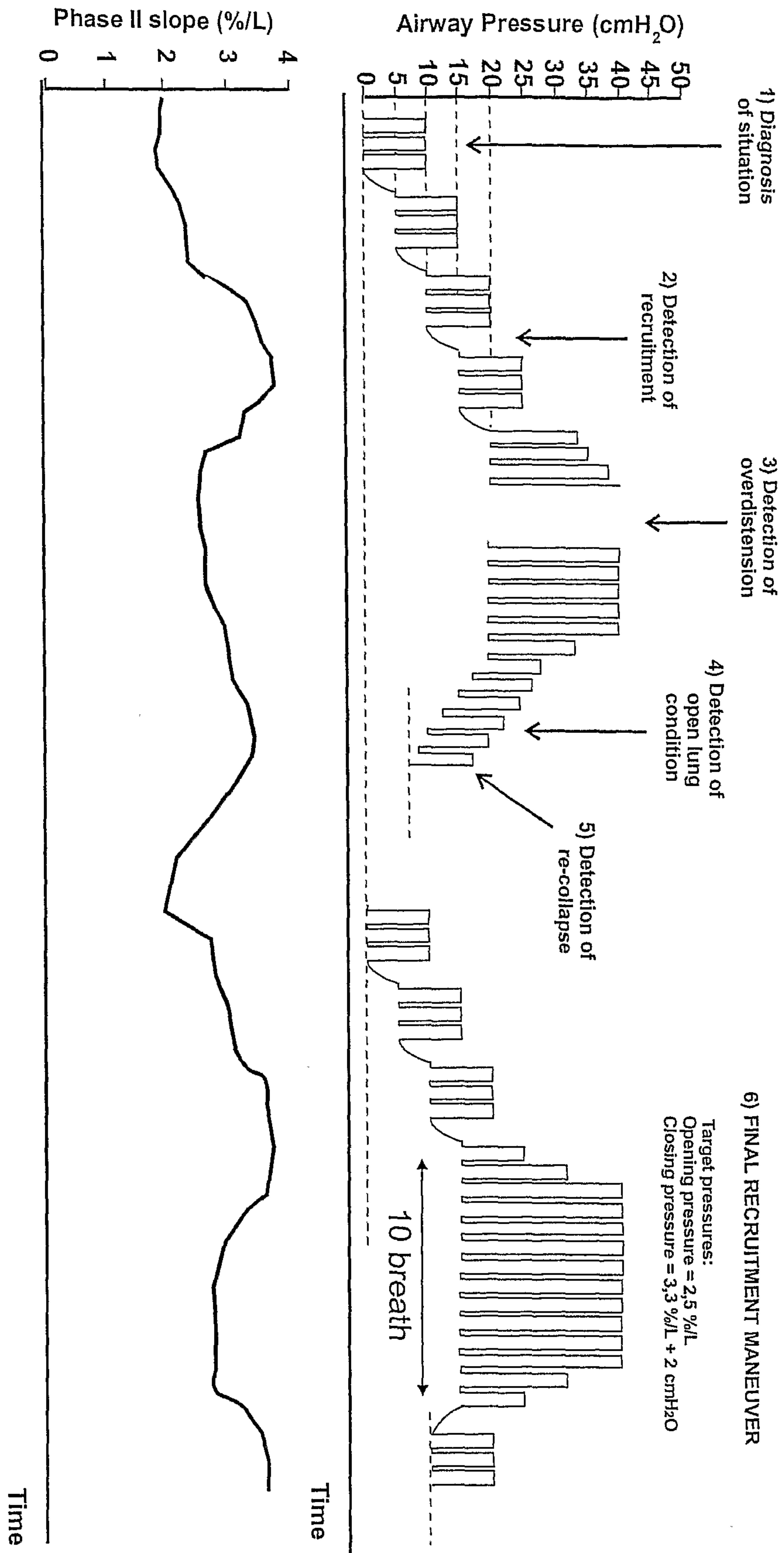


Fig. 8

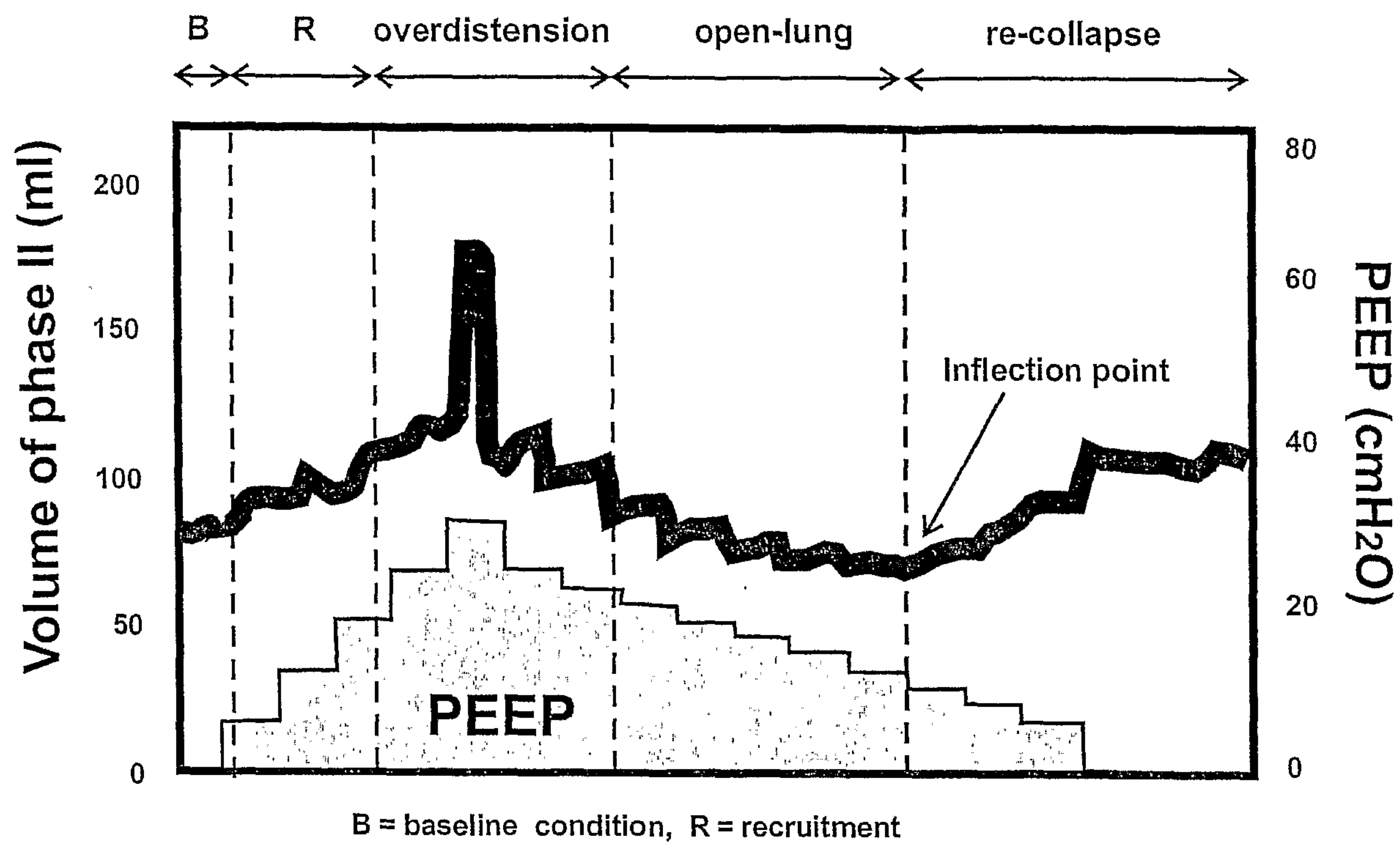


Fig. 9

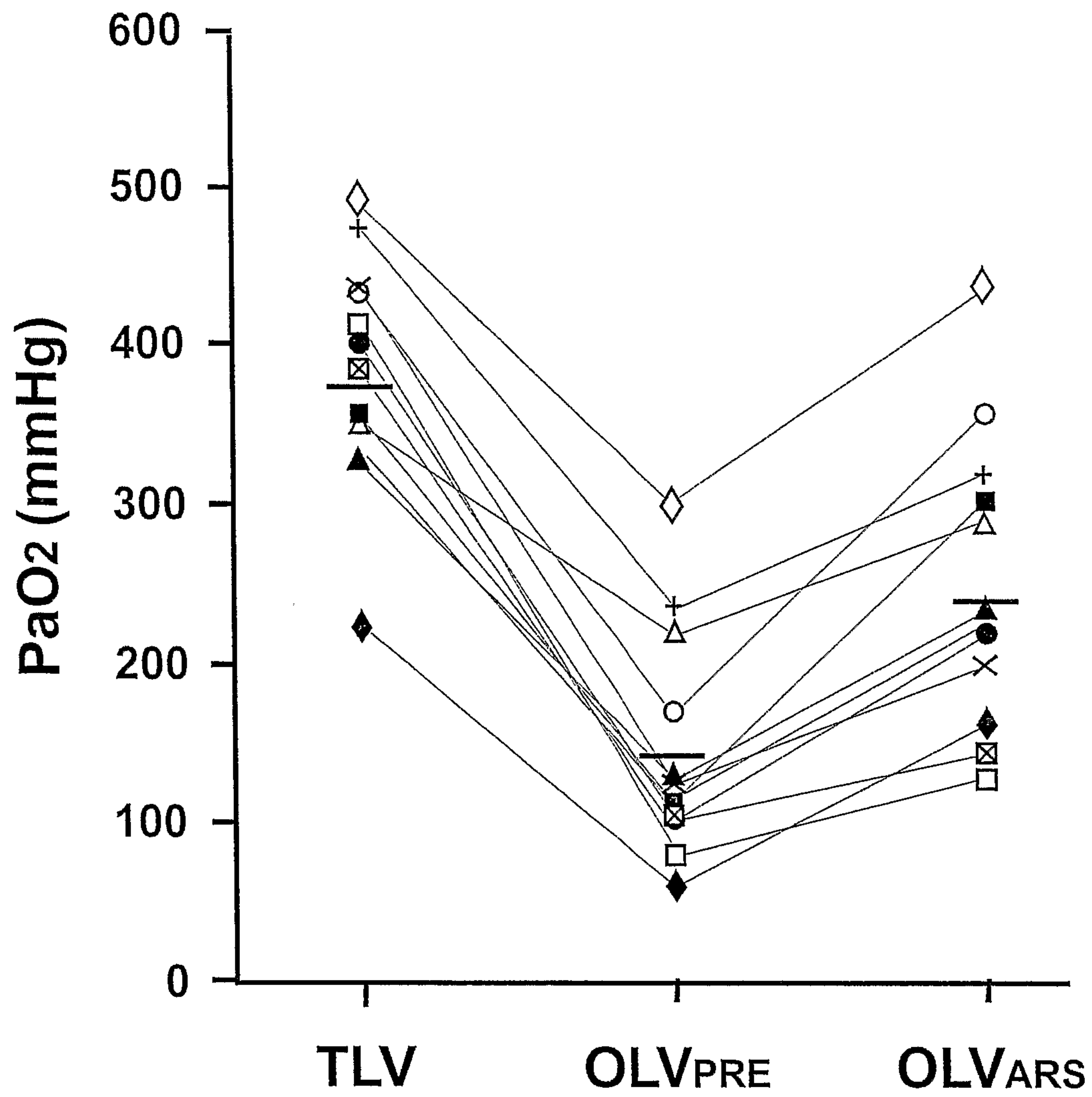


Fig. 10

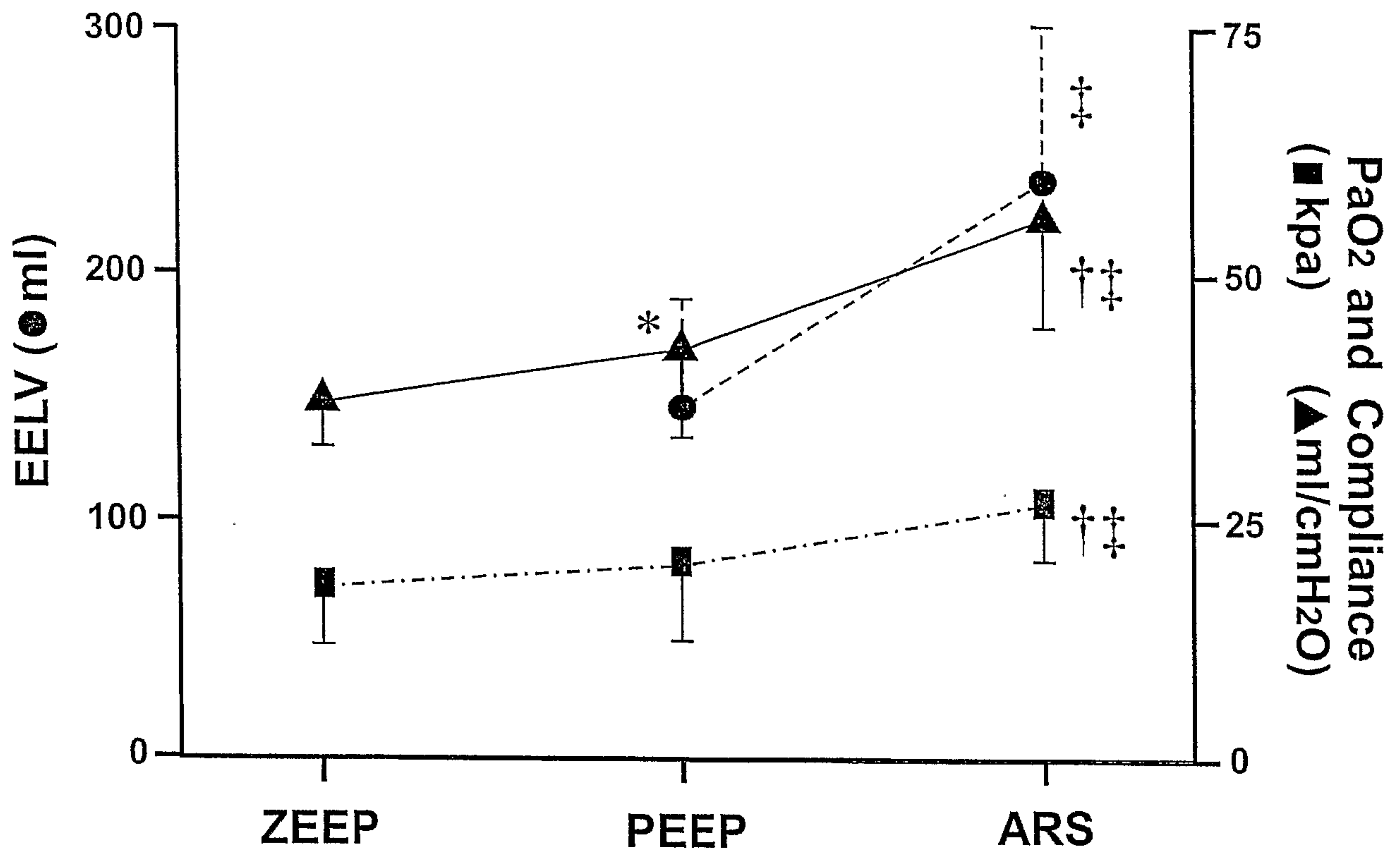


Fig. 11

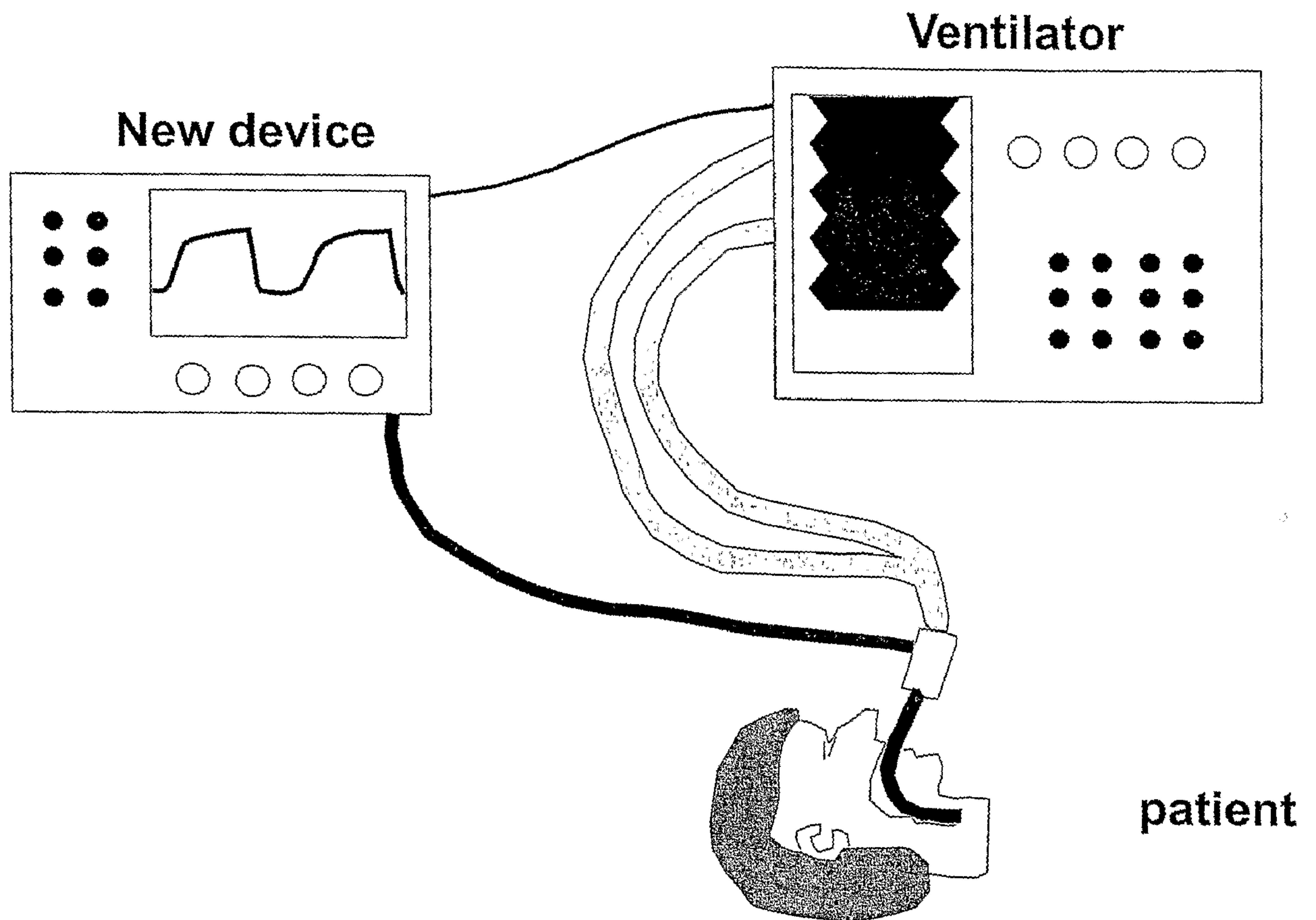


Fig. 12

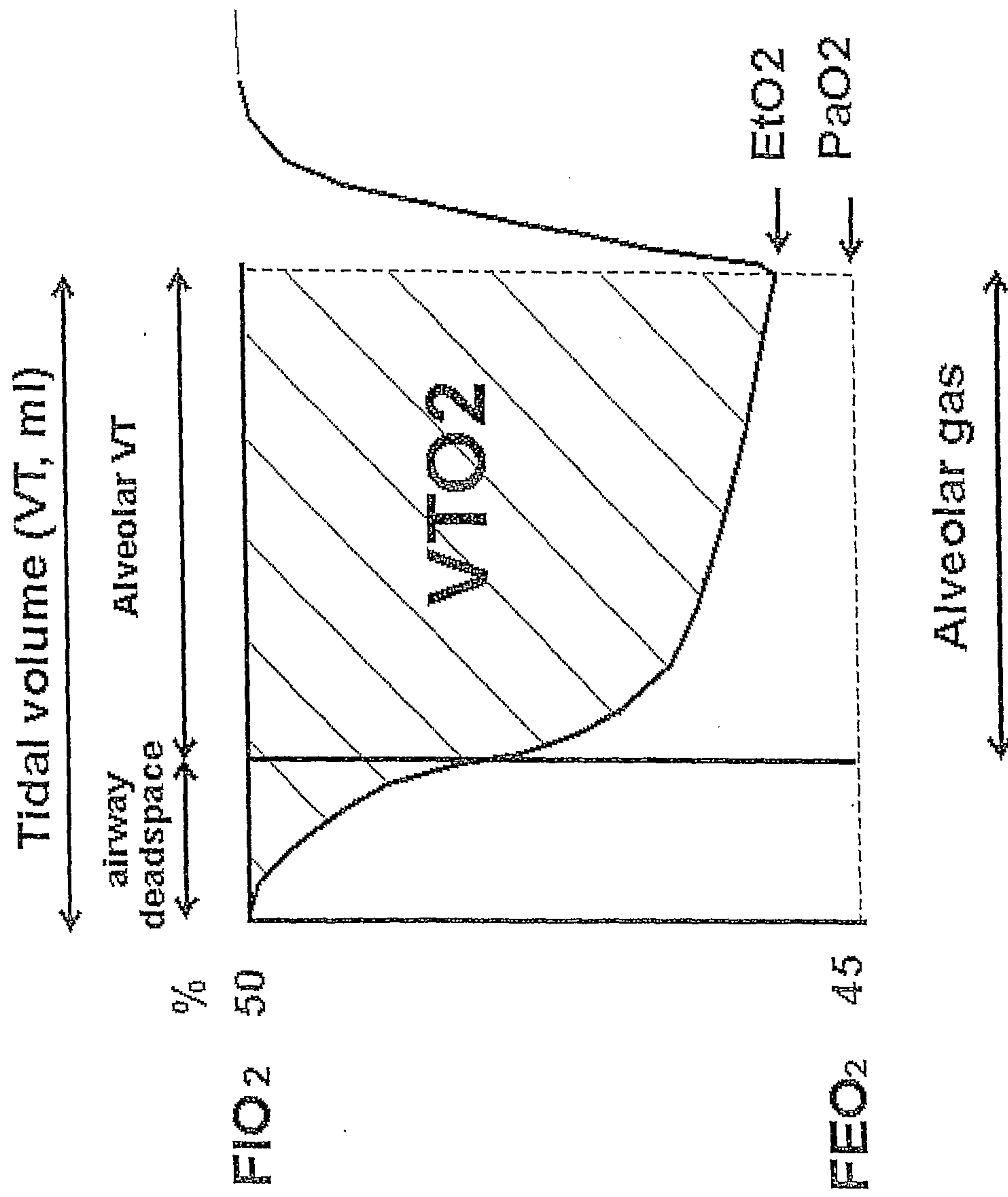
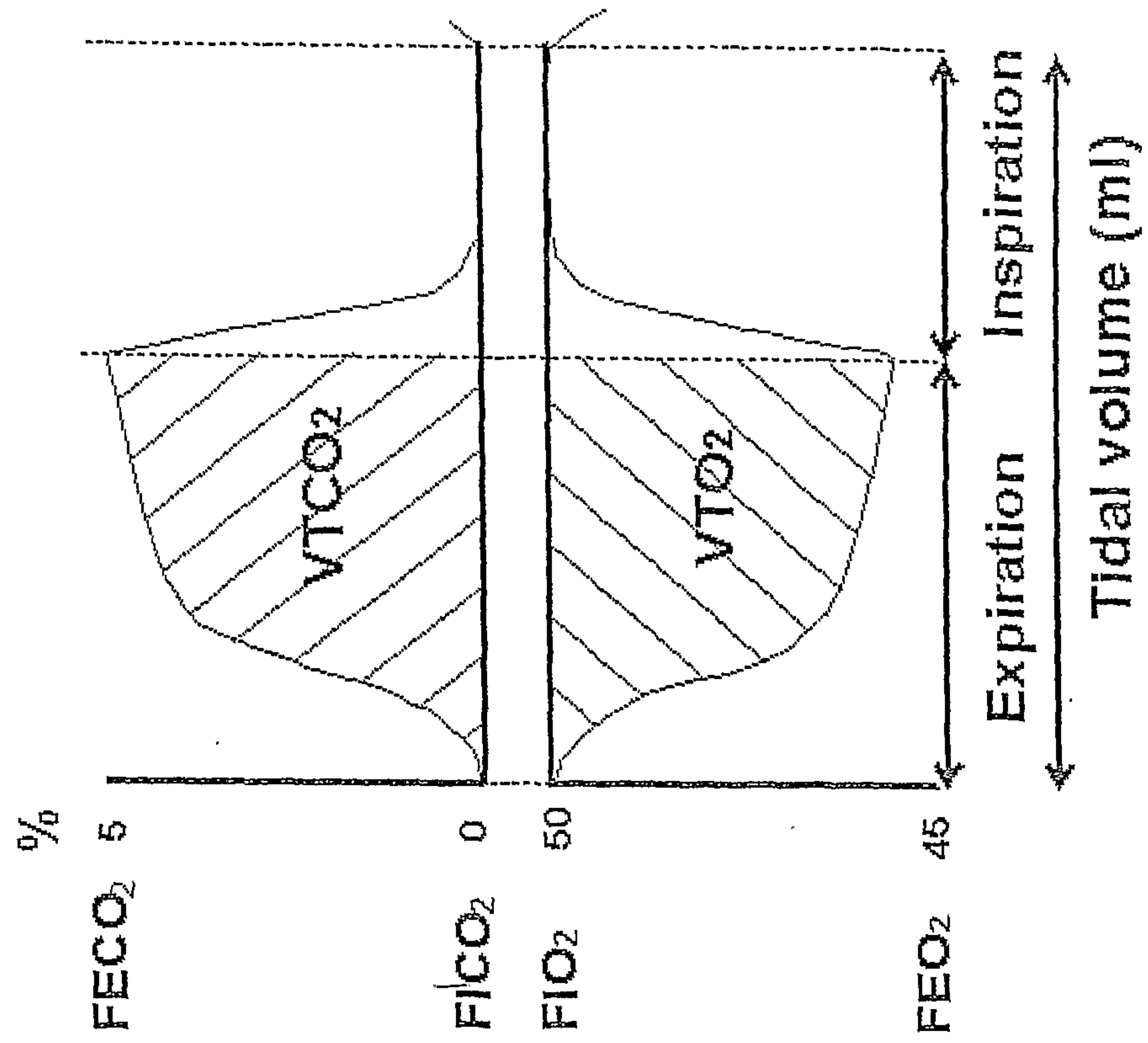


Fig. 13

VOLUMETRIC CAPNOGRAPHY AND OXYGRAPHY**Fig. 14**

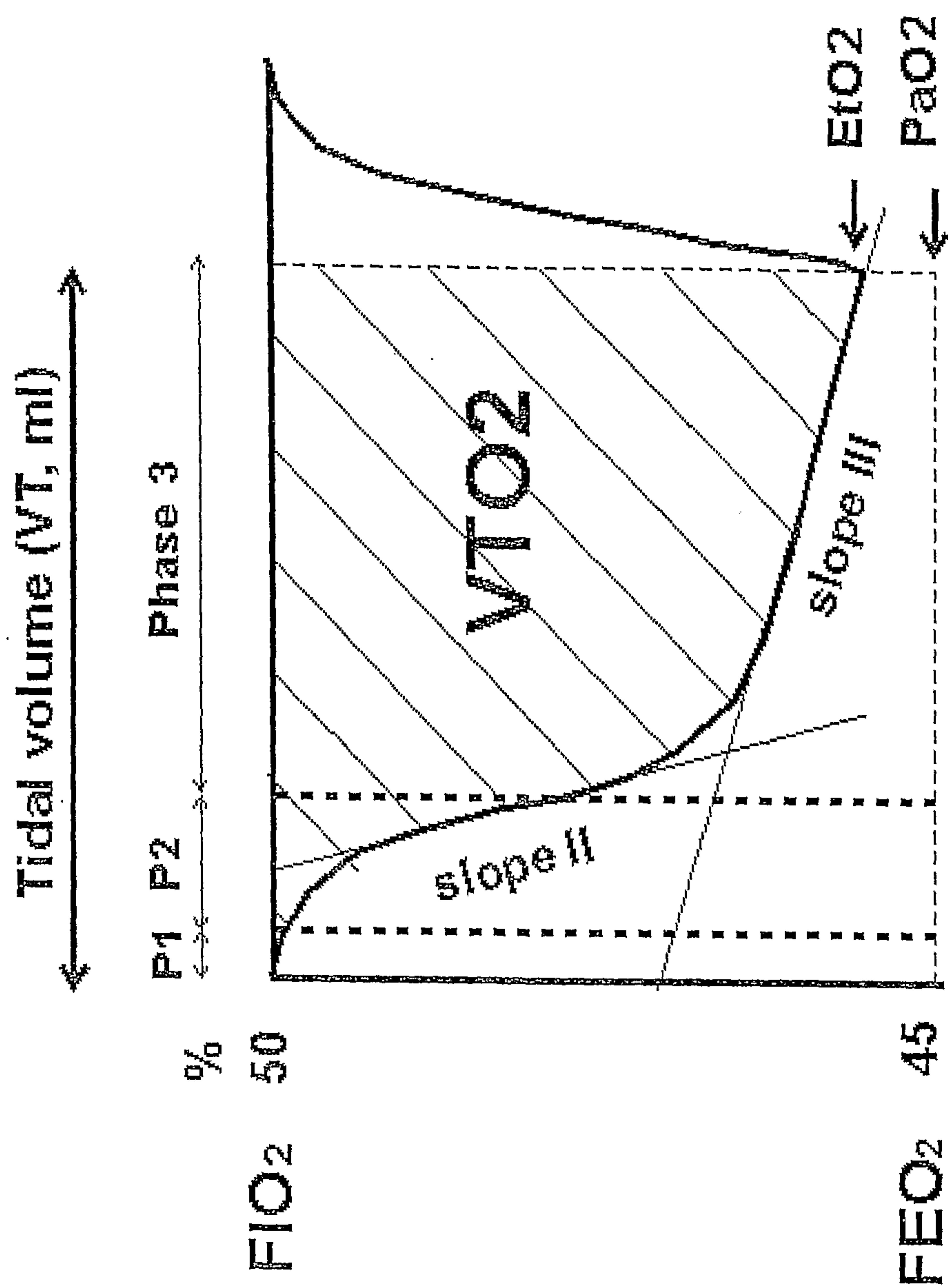


Fig. 15

