Computerised decision support for differential lung ventilation

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Differential lung ventilation treatment is a mechanical ventilation strategy used for unilateral lung disease or injury. This treatment can be provided to patients who fail to respond to conventional mechanical ventilation to both lungs and is technically challenging to medical personnel. An effective computerised decision support system (CDSS) can be used as a support system to intensivists in providing this treatment to their patients. In this study, a CDSS for differential lung ventilation is presented. By using this system, the mode of ventilation to each lung can be pressure controlled or volume controlled and all ventilation parameters including the peak inspiratory pressure (P_{insp}), tidal volume (V_t), positive end-expiratory pressure, fraction of inspired oxygen (F_{IO_2}), and the respiratory rate (f) can be assigned individually to each lung. The proposed CDSS has the potential to be used as a support system to clinicians in providing differential lung ventilation treatments to patients.

1. Introduction: Mechanical ventilation is a life-saving technology that is used during and after major surgical operations and to treat patients who due to different illnesses are not capable of breathing on their own [1]. Positive pressure conventional mechanical ventilation is the most commonly used ventilation technology in which the patient's lungs are inflated by applying positive pressure to his airways. In this technology which can be applied by using many different modalities [2, 3], the same treatment is given to both lungs by using the same ventilatory parameters. However, in many cases, patients fail to respond to conventional mechanical ventilation. Differential lung ventilation treatment is a ventilation technique provided to patients whose lungs' characteristics are significantly different. Independent lung ventilation (ILV) is a mechanical ventilation treatment used in intensive care (ICU) settings to provide therapy for differential lung disease. This technically demanding treatment is considered as a rescue method when conventional mechanical ventilation to both lungs fails or is not considered appropriate. The first cases of ILV use in the ICU settings were reported in the mid-1970s [4, 5].

Depending on the difference in lung disease, various methods of ILV are used by the intensivists. In general, ILV can be divided to two types of techniques: (i) anatomical lung separation in which one lung is separated from the other (ii) physiological lung separation when different treatment strategies are used for each lung.

Anatomical lung separation is normally a short-term rescue treatment strategy in conditions such as massive hemoptysis and inter-bronchial aspiration of secretions [6]. Physiological lung separation, however, is applied when the lungs have different characteristics such as in unilateral lung disease or injury [6–8], bronchopleural fistulas [9], or after single lung transplant operations [6, 10].

In ILV by using physiological lung separation, different treatment strategies can be applied to each lung. In synchronous treatments, the frequency of respiration is the same for both lungs while the other ventilatory parameters such as tidal volume, inspiratory pressure, positive end-expiratory pressure (PEEP), and the fraction of inspired oxygen (F_{IO2}) can be individually set for each lung [9, 11]. In asynchronous treatments, the ventilation mode and all ventilatory parameters including respiratory rate can be different for each lung [5, 6, 12, 13]. A discussion of medical indications for these techniques and their possible complications is not within the scope of this Letter and can be found in the medical literature on this subject [e.g. 5–8].

Application of ILV which can be an effective life-saving treatment for some respiratory diseases and conditions is a demanding technique for the medical personnel. In addition to the technical challenges involved, choosing the right mode of ventilation for each lung and appropriate ventilatory parameters can be a difficult task for the medical personnel in an ICU setting. Application of intelligent computerised decision support systems (CDSSs) to provide optimal mechanical ventilation to patients has been the focus of significant research for many years [14–16]. In the case of ILV, an effective CDSS can be a valuable aide to the clinician to predict the results of various ventilation strategies to each lung. The CDSS described in this Letter is presented towards this objective and is the first system for use in differential lung ventilation.

2. Methods: The model of the respiratory system's plant used in the CDSS is based on modifications of physiological models of adult and infant respiratory systems [17–19] that have been used extensively for research and teaching [20] by many researchers. The CDSS has two lung compartments that can be ventilated independently. A block diagram of the system is shown in Fig. 1.

As shown in Fig. 1, Lung 1 and Lung 2 represent two separate lung compartments. These two compartments have different characteristics and can be ventilated by two separate ventilators. The ventilation parameters for each lung are assigned independently based on the characteristics of the lung. The inspiratory gas provided by the ventilators comes into contact with the bloodstream perfusing each compartment. Then the oxygenated blood leaves the two compartments and is distributed to the body tissue and the brain. The cardiac output control adjusts the rate of blood perfusion to the body and the brain based on the chemical composition of the arterial blood. The arterial transport delay represents the transportation delay caused by the arteries from the heart to the brain. The circulating arterial blood perfuses the body tissue and the brain tissue. The venous blood from these compartments mix before entering the lung compartments and the cycle is repeated.

2.1. Equations of the plant: A list of the symbols used in the equations of the system is provided in the Appendix. The equations that are provided are those that are particularly modified for this CDSS.
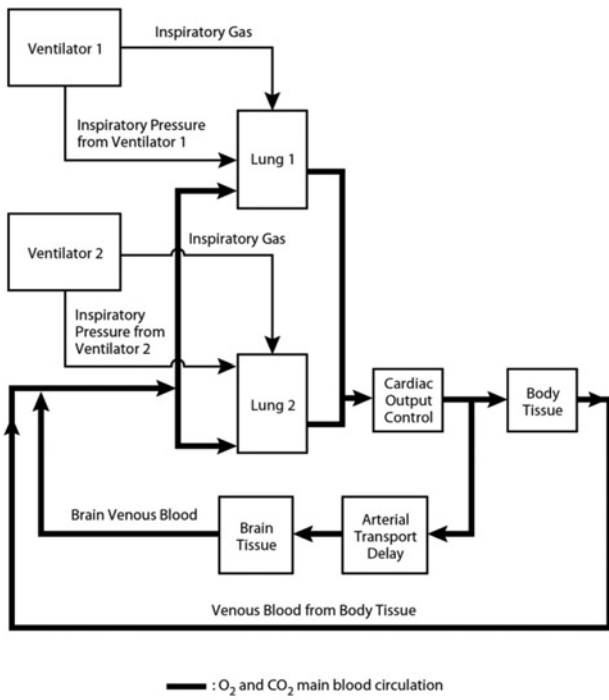
Fig. 1 *Block diagram of the system*

The mass balance equations for the lung compartments are as follows:

For the alveolar space in lung 1

For CO_2

$$(C_{VTCO_2} - C_{a1CO_2})Q_T + (C_{VBCO_2} - C_{a1CO_2})Q_B$$
$$= \left[\frac{v_1}{(P_b - 47)}\right]\frac{dP_{A1CO_2}}{dt} + FACT11 \tag{1}$$

For O_2

$$(C_{a1O_2} - C_{VTO_2})Q_T + (C_{a1O_2} - C_{VBO_2})Q_B$$
$$= \left[\frac{-v_1}{(P_b - 47)}\right]\frac{dP_{A1O_2}}{dt} + FACT12 \tag{2}$$

where in inspiration that $dv_1/dt \geq 0$

$$FACT11 = \left[\frac{(P_{A1CO_2} - P_{I1CO_2})}{(P_b - 47)}\right]\frac{dv_1}{dt}$$

and

$$FACT12 = \left[\frac{(P_{I1O_2} - P_{A1O_2})}{(P_b - 47)}\right]\frac{dv_1}{dt}$$

and during expiration that $dv_1/dt < 0$: $FACT11 = FACT12 = 0$.

For the alveolar space in lung 2

For CO_2

$$(C_{VTCO_2} - C_{a2CO_2})Q_T + (C_{VBCO_2} - C_{a2CO_2})Q_B$$
$$= \left[\frac{v_2}{(P_b - 47)}\right]\frac{dP_{A2CO_2}}{dt} + FACT21 \tag{3}$$

For O_2:

$$(C_{a2O_2} - C_{VTO_2})Q_T + (C_{a2O_2} - C_{VBO_2})Q_B$$
$$= \left[\frac{-v_2}{(P_b - 47)}\right]\frac{dP_{A2O_2}}{dt} + FACT22 \tag{4}$$

where in inspiration that $dv_2/dt \geq 0$

$$FACT21 = \left[\frac{(P_{A2CO_2} - P_{I2CO_2})}{(P_b - 47)}\right]\frac{dv_2}{dt}$$

and:

$$FACT22 = \left[\frac{(P_{I2O_2} - P_{A2O_2})}{(P_b - 47)}\right]\frac{dv_2}{dt}$$

and during expiration that $dv_2/dt < 0$: $FACT21 = FACT22 = 0$.

In the above alveolar space equations, it is assumed that the alveolar and arterial partial pressures of CO_2 are equal

$$P_{A1CO_2} = P_{a1CO_2} \tag{5}$$

$$P_{A2CO_2} = P_{a2CO_2} \tag{6}$$

and for oxygen:

$$P_{A1O_2} = P_{a1O_2} + K_1 \tag{7}$$

$$P_{A2O_2} = P_{a2O_2} + K_2 \tag{8}$$

where K_1 and K_2 are the alveolar–arterial oxygen differences in lung 1 and lung 2, respectively.

To relate the O_2 and CO_2 gas concentrations to blood gas pressures, the following equations are used in the system:

$$C_{O_2} = K_3(1 - \exp(-K_4 P_{O_2}))^2 \tag{9}$$

$$C_{CO_2} = K_5 P_{CO_2} \tag{10}$$

Assuming homogeneous mixing of arterial blood from the two lungs

$$C_{aCO_2} = (C_{a1CO_2} + C_{a2CO_2})/2 \tag{11}$$

$$C_{aO_2} = (C_{a1O_2} + C_{a2O_2})/2 \tag{12}$$

and the arterial oxygen saturation S_{aO_2}, is related to the arterial partial pressure of oxygen P_{aO_2}, and C_{aO_2} as: $S_{aO_2} = C_{aO_2}/K_3$.

For the lumped body tissue and the brain compartments, the equations used are the same as those in [17] and are not repeated here for brevity. Also, Q_T and Q_B that represent the blood flow rates in the lumped body tissue and the brain tissue, respectively, are functions of the arterial partial pressure of carbon dioxide (P_{aCO_2}) and the arterial partial pressure of oxygen (P_{aO_2}). The equations for the blood flow rates as functions of arterial O_2 and CO_2 pressures and their dynamics are derived and described in detail elsewhere [17, 18] and are not repeated here because they are too long.

2.2. Application of ILV: In order to apply ILV, separate ventilators can be used for the lungs. The lungs' volumes are affected by the PEEP levels applied

$$\Delta FRC1 = C_{dyn1}PEEP1 \tag{13}$$

$$\Delta FRC2 = C_{dyn2}PEEP2 \tag{14}$$

The fraction of inspired oxygen in lung 1 ($F_{IO_2}(1)$) and lung 2 ($F_{IO_2}(2)$) are:

$$F_{IO_2}(1) = P_{I1O_2}/(P_b - 47) \qquad (15)$$

$$F_{IO_2}(2) = P_{I2O_2}/(P_b - 47) \qquad (16)$$

By using the CDSS, different modes of mechanical ventilation can be applied to each lung. If the mode applied to the lung is volume controlled, any waveform (e.g. square wave, exponential etc.) can be applied. Regardless of the particular waveform applied, a sinusoidal airflow can be considered as a generic pattern that represents the main harmonic of any other airflow pattern. The sinusoidal airflow can be given as:

$$dv/dt = \pi V_A^{\bullet} Sin(2\pi ft) \qquad (17)$$

where $V_A^{\bullet}$ is the alveolar ventilation in that lung in lit/sec and found as:

$$V_A^{\bullet} = f\,(V_t - V_D) \qquad (18)$$

where f is respiration frequency in breaths/s, V_t is the tidal volume, and V_D is the dead space in that lung, respectively. The dead space volume in normal adults in both lungs can be estimated from the ideal body weight (Weight) as:

$$V_{D\,(in\,both\,lungs)} = 0.0026(Weight) \qquad (19)$$

In normal lungs, this value of V_D can be used to find an approximate value of the dead space in each lung. However, in a diseased lung, its value can be increased based on the lung's conditions.

In the pressure-controlled mode of ventilation, the following equations are used for the lungs:

$$\Delta P_1 = K_1' v_1' + K_1'' dv_1/dt \qquad (20)$$

$$\Delta P_2 = K_2' v_2' + K_2'' dv_2/dt \qquad (21)$$

3. Application of the system: An example of the application of this system is described as follows.

The details and results of an asynchronous ILV treatment to a 69-year-old patient with chronic obstructive pulmonary disease and air leak in the right lung posted in [21] are shown in Table 1.

Table 1 Ventilator settings and the results of an ILV treatment for a patient [21]

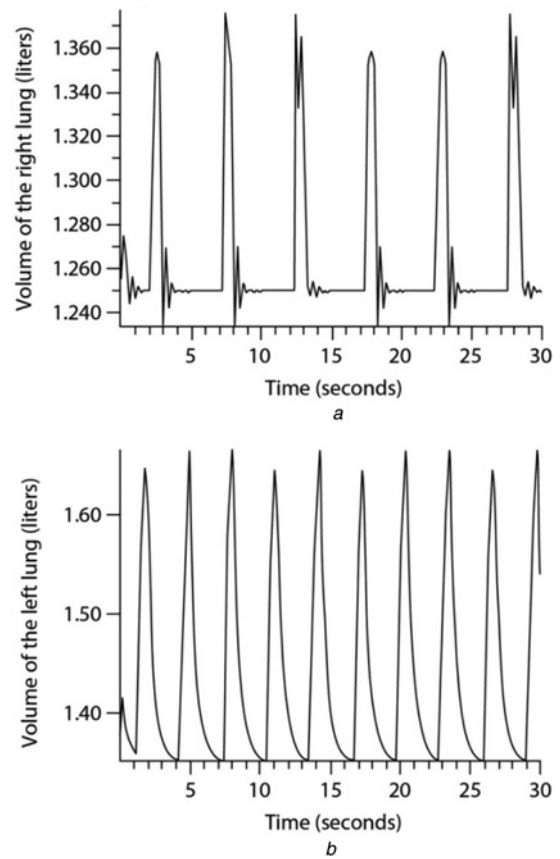| |
| --- |
| *Right lung mode of ventilation: pressure controlled* |
| $F_{IO_2} = 0.8$ |
| PEEP = 0 |
| peak pressure = 32 cmH$_2$O |
| respiratory rate = 12 breaths/min |
| $V_t = 100$ ml |
| I/E = 1:6.2 |
| *Left lung mode of ventilation: pressure controlled* |
| $F_{IO_2} = 0.8$ |
| PEEP = 5 cmH$_2$O |
| peak pressure = 23 cmH$_2$O |
| respiratory rate = 20 breaths/min |
| $V_t = 300$ ml |
| I/E = 1:3.5 |
| *The blood gas results after the ILV treatment* |
| $P_{aCO_2} = 34.3$ mmHg |
| $S_{aO_2} = 100\%$. |

Fig. 2 *CDSS predictions of lung volume for a patient treated with ILV*
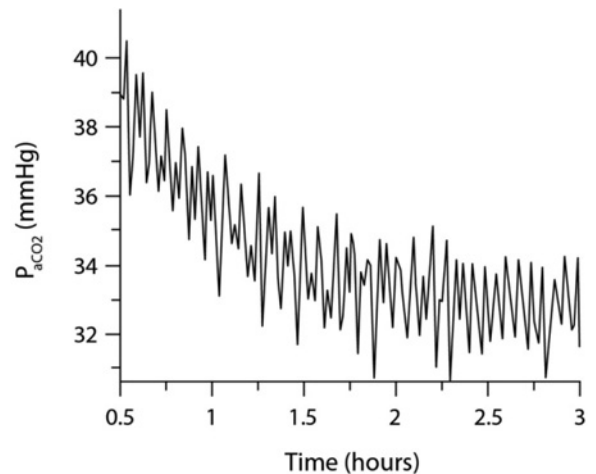*a* Volume of right lung
b Volume of left lung

Fig. 3 *CDSS predictions of arterial partial pressure of CO$_2$ (P_{aCO_2}) for a patient treated with ILV*

Fig. 2 shows the simulation lung volume results of the CDSS. Fig. 2a shows the volume of the right lung that increases by about 110 ml above FRC1 in each breathing cycle. Fig. 2b shows the volume of the left lung that rises by about 300 ml above FRC2 in each breath. According to the CDSS predictions, S_{aO_2} reaches 100% early on during the treatment and Fig. 3 shows the arterial partial pressure of CO$_2$ results (P_{aCO_2}) of the CDSS that reaches to about 33 mmHg after 3 h of treatment.

4. Discussion: As shown in Fig. 2a in the above example, the CDSS shows that the volume of the right lung increases by about

110 ml above FRC1 in every breathing cycle. This is in response to the application of the prescribed pressure-controlled mechanical ventilation to the right lung. In comparison, the tidal volume in the right lung was measured to be 100 ml for this patient. In response to the pressure-controlled mechanical ventilation to the left lung, The CDSS shows in Fig. 2b that the volume of the left lung increases by about 300 ml above FRC2 in every breath as compared to the measured tidal volume of 300 ml in the left lung of the patient.

The CDSS predicts that the patient's arterial oxygen saturation (S_{aO_2}) reaches 100%. According to the CDSS, the arterial partial pressure of CO_2 (P_{aCO_2}) reaches to about 33 mmHg after 3 h of the prescribed ILV treatment as shown in Fig. 3. According to the clinical observations reported in [21], the measured S_{aO_2} and P_{aCO_2} values for this patient were 100% and 34.3 mmHg, respectively.

The predicted results by the CDSS are seen to be in close agreement with clinical observations.

The CDSS described above is designed to simulate ILV treatments in both synchronous and asynchronous types of ventilations. Different modes of ventilation can be applied to each lung and ventilatory parameters including respiratory rate, tidal volume, F_{IO2}, PEEP, and the inspiratory pressure can be specified independently for each lung.

5. Conclusion: ILV is a demanding ventilation technique that can be used to save the lives of patients who cannot be successfully treated by conventional mechanical ventilation to both lungs. An effective CDSS can be used as an aide to assist the medical personnel in choosing the right ventilation modes and parameters for patients who need such treatment in the ICU settings. The CDSS presented in this Letter is the first system designed to predict the results of various modes of ventilation at different rates to each lung by using differential lung ventilation treatments. Further future applications of the CDSS by using data from a wide group of patients receiving the ILV treatment can enhance the understanding of the capabilities and any limitations of the proposed CDSS.

7 References

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Appendix: Glossary of Symbols

The main symbols represent the parameters or variables and the subscripts denote a chemical or location (where applicable, the parameter values are shown for adult patients) (Table 2).

Table 2 Glossary of Symbols

Variable/ Parameter	Definition and units	Value
C	volume concentration of gas in the blood (l(STPD)/l)	—
C_{dyn}	respiratory dynamic compliance (l/cmH$_2$O)	—
C_{dyn1}	respiratory dynamic compliance in the right lung (l/cmH$_2$O)	—
C_{dyn2}	respiratory dynamic compliance in the left lung (l/cmH$_2$O)	—
F	fractional composition of gas	—
f	respiratory frequency (breaths/s)	—
f_1	respiratory frequency in the right lung (breaths/s)	—
f_2	respiratory frequency in the left lung (breaths/s)	—
F_{IO_2}	fraction of inspired oxygen	—
$F_{IO_2}(1)$	fraction of inspired oxygen in the right lung	—
$F_{IO_2}(2)$	fraction of inspired oxygen in the left lung	—
FRC	functional residual capacity (l)	2.5
FRC1	functional residual capacity in the right lung (l)	—
FRC2	functional residual capacity in the left lung (l)	—
ΔFRC	change in the functional residual capacity (l)	—
ΔFRC1	change in the functional residual capacity of the right lung (l)	—
ΔFRC2	change in the functional residual capacity of the left lung (l)	—
K_1	alveolar–arterial oxygen difference in the right lung (mmHg)	—
K_2	alveolar–arterial oxygen difference in the left lung (mmHg)	—
K_3	blood gas constant for oxygen	0.2

Continued

TABLE 2 *Continued*

Variable/ Parameter	Definition and units	Value
K_4	blood gas dissociation constant for oxygen $(\text{mmHg})^{-1}$	0.046
K_5	blood gas dissociation constant for carbon dioxide $(\text{mmHg})^{-1}$	0.016
K'_1	respiratory elastance in the right lung ($\text{cmH}_2\text{O/l}$)	—
K'_2	respiratory elastance in the left lung ($\text{cmH}_2\text{O/l}$)	—
K''_1	respiratory airway resistance in the right lung ($\text{cmH}_2\text{O/l/s}$)	—
K''_2	respiratory airway resistance in the left lung ($\text{cmH}_2\text{O/l/s}$)	—
P	partial pressure or gas pressure (mmHg or cmH_2O)	—
ΔP_1	inspiratory pressure above PEEP in the right lung (cmH_2O)	—
ΔP_2	inspiratory pressure above positive end-expiratory pressure in the left lung (cmH_2O)	—
PEEP	PEEP (cmH_2O)	—
PEEP1	PEEP in the right lung (cmH_2O)	—
PEEP2	PEEP in the left lung (cmH_2O)	—
Q_T	blood flow rate in the body tissue (l/s)	0.07083 (basal value)
Q_B	blood flow rate in the brain (l/s)	0.0125 (basal value)
S_{aO_2}	arterial oxygen saturation	—
t	time (s)	—
V	gas volume (l)	—
v	lung volume (l)	—
v_1	alveolar space in the right lung (l)	—
v_2	alveolar space in the left lung (l)	—
v'_1	right lung volume above the functional residual capacity (l)	—
v'_2	left lung volume above the functional residual capacity (l)	—
$\dot{V}_\text{A}$	alveolar ventilation (l/s)	—
V_t	tidal volume (l)	—
V_D	dead space volume (l)	—
Weight	ideal (predicted) body weight (Kg)	—
subscript	definition	—
a	arterial blood	—
a1	arterial blood in the right lung	—
a2	arterial blood in the left lung	—
A	alveolar gas	—
A1	alveolar gas in the right lung	—
A2	alveolar gas in the left lung	—
b	barometric pressure	—
B	brain	—
CO_2	carbon dioxide	—
D	dead space	—
I	inspired gas	—
I1	inspired gas in the right lung	—
I2	inspired gas in the left lung	—
O_2	oxygen	—
T	body tissue	—
V	venous blood	—
VB	brain venous blood	—
VT	tissue venous blood	—