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A New Control Solution for Independent Synchronous Ventilation of Lungs

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A new control solution for independent, synchronous ventilation of lungs has been developed and a controller to perform it with use of only one respirator and a bilumen intubation tube has been built. The controller enables division of the inspiratory tidal volume between the lungs in desired ratio, and setting of the positive end-expiratory pressure (PEEP) separately for each lung. The model tests have shown that the characteristics of the flow meters used, however not linear, is good enough to achieve clinically accepted accuracy of volume division. The tests have shown that the volume division is independent from the total tidal volume and PEEP. Maximal errors of the tidal volume division was less than 10%. The case study of patient after lung injury has shown significant improvement of the X-ray image and respiratory parameters (blood oxygenation, ventilatory pressures) during the independent ventilation of lungs with the use of the new device. The clinical study of 60 patients has shown that differences between actually realized volume division and the adjusted values are practically negligible.

K e y w o r d s: independent ventilation of lungs, respiratory system, respirator

1. Introduction

In most of clinical situations artificial ventilation of lungs is performed with the use of one respirator and only total ventilation of lungs is controlled. However, there are

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some clinical cases, like lung pathology with unilateral prevalence, pneumotorax, or monolateral atelectasis, when mechanical properties of each lung of a patient differ so much, that it is necessary to ventilate them separately to control ventilation of each lung. Otherwise, ventilation of the lungs would be extremely uneven, producing ventilation/perfusion mismatch. Other cases when the separate ventilation would be advisable are: ventilation of only one lung during cardiothoracic surgery or reventilation of collapsed lung after cardiothoracic surgery. Also when patient is in lateral position, the “upper” lung is normally better ventilated than the “lower” one, while the perfusion of the lower lung is better.

In a standard set-up differential ventilation is performed by the connection of each lung to one respirator, by means of a double-lumen endotracheal tube, and two synchronized respirators are required then [1, 2]. There have been some attempts to use variable resistance valves [3 ÷ 7] to divide the ventilation from one ventilator between two lungs. However, ventilation of both lungs with a variable resistance valve cannot be easily and automatically controlled when lungs’ mechanical properties change. Our concept of differential ventilation system with one respirator only was to built a controlled divider of flow delivered to each lung [8]. In this solution the respirator is connected to the lungs by parallel two tubes for inspiration and two tubes for expiration of gases. A controller (divider) of inspiratory volumes is placed between the respirator and a double-lumen endotracheal tube (Fig. 1a). The device for independent ventilation connected with respirator and test lungs is shown in Fig. 1b. To achieve different positive end expiratory pressure (PEEP) for each lung, two PEEP valves are used.

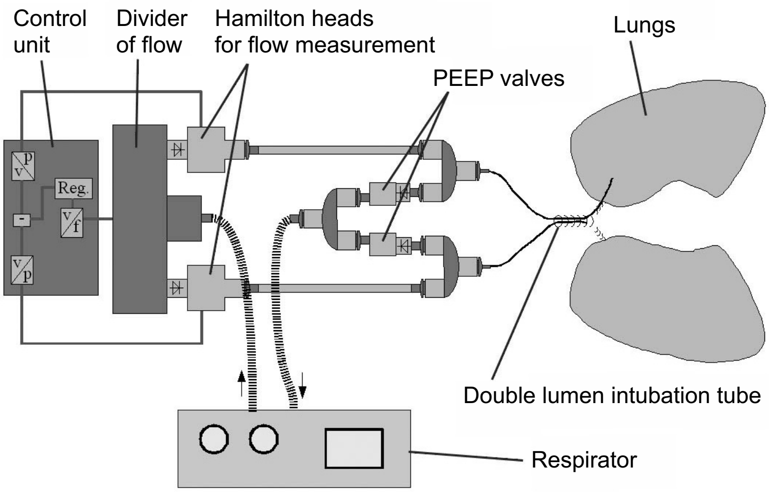

Fig. 1a. Scheme of the flow divider

Fig. 1b. Device for independent ventilation connected with respirator and test lungs

2. Materials and Methods

A control device for independent ventilation of lungs by only one respirator has to fulfill the following assumptions: the relation between lungs ventilation must be easily adjusted in a wide range (e.g. ratio between the tidal volumes of 1/5–5/1), PEEP should be adjusted independently for each lung; synchronization of inspiratory and expiratory phases for each lung should be realized without delay, which may cause undesired shifts of blood from around one lung to another. This last requirement is automatically fulfilled by a sequentially working regime of inspiratory and expiratory valves in each modern respirator, with time-cycled, volume control mode of artificial ventilation. The differential lung ventilation with one respirator as a gas source is based on an automatic division and stabilization of tidal volume of each lung, according to the settings made by a physician. A feedback controlled circuit, precisely keeps tidal volume division on a constant value, independently of the respiratory system compliance, airways resistance or ventilatory parameters (tidal volume, PEEP, frequency) changes. In order to meet the mentioned above requirements, a feedback control unit of adjustable inspiratory flow division was designed. The idea based on measurement of flows is realized by means of Bird flow meters together with Honeywell differential pressure transducers. The flow meters were chosen because of their certificate to use on contact with respiratory gases and single use in contact with patient. The flow meter characteristic measured by authors is shown in Fig. 2. This characteristic, however not linear, is repeatable and good enough to

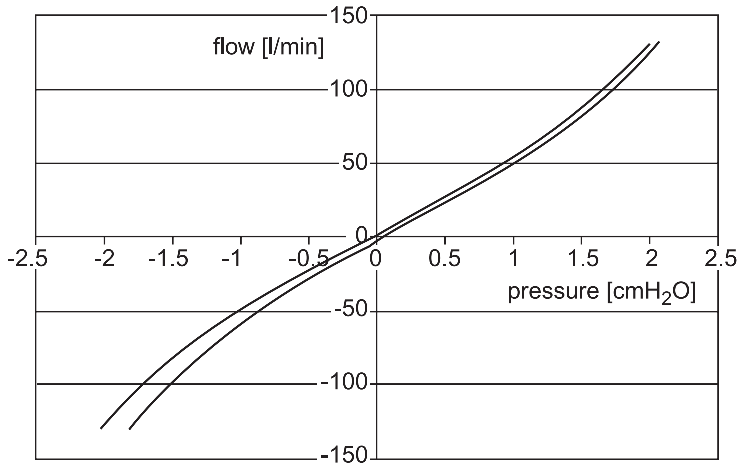

Fig. 2. Generated flow dependent from differential pressure

achieve clinically accepted accuracy of volume division. The developed control system was tested on a physical model of the respiratory system, which consisted of two parallel branches of pneumatic elements of resistance and compliance, one for each lung. Two standard test lungs (Siemens – Elema, type 190) were used for modeling of respiratory system mechanics. During the model studies only one of ventilation parameters (frequency, tidal volume, inspiratory/expiratory time ratio or selective PEEP) was changed at a time. The alternative way of testing the developed control system would be to use more advanced model of lungs developed recently in the Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences (IBBE PAS) [9]. The lungs model was ventilated by a servoventilator (Siemens – Elema) in the mode of volume controlled ventilation. i.e. total volume was kept constant in each of simulation series. Airway pressures, flows and volumes were simultaneously measured in the lungs model.

3. Results of Model Tests

The results of model tests are shown in Fig. 3–5. As can be easily observed from these figures, the inspiratory volume ratio in both lungs was constant when PEEP was changed in one lung selectively from 0 to 20 cmH_2O, for respiratory frequency 10, 15 and 25 breaths per minute (Fig. 3 and 4). The tidal volume ratio delivered to each lung did not change when the total tidal volume changed (compare Fig. 3 and 4). The maximal errors of tidal volume division was less than 10%. The measured tidal volume ratio followed its adjustment when different values of PEEP from 0 to 20 cmH_2O for one lung are set (Fig. 5).

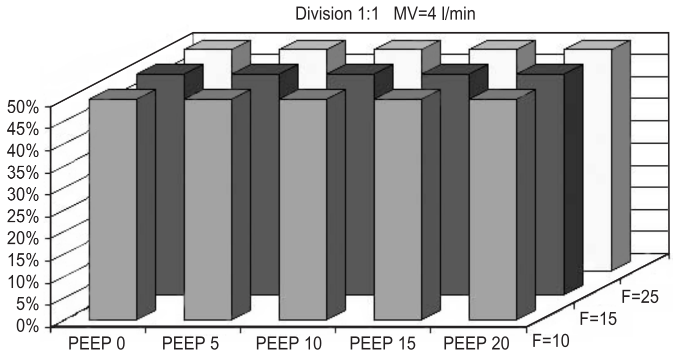

Fig. 3. Influence of selective PEEP on tidal volume in both lung models registered for unchanged adjustment of tidal volume division 1:1 for different respiratory rates (*F* = 10, 15, 25 br/min) and constant minute volume = 4 l/min

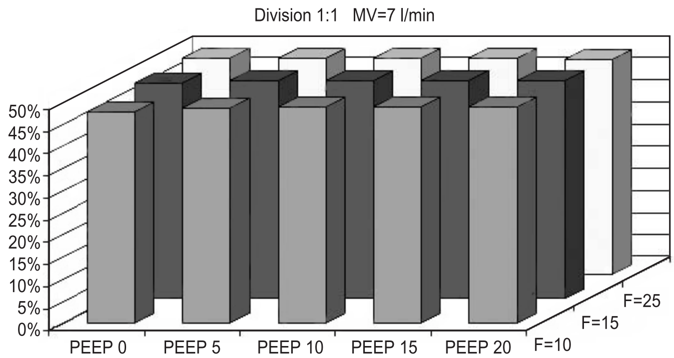

Fig. 4. Influence of selective PEEP on tidal volume in both lung models registered for unchanged adjustment of tidal volume division 1:1 for different respiratory rates (*F* = 10, 15, 25 br/min) and constant minute volume = 7 l/min

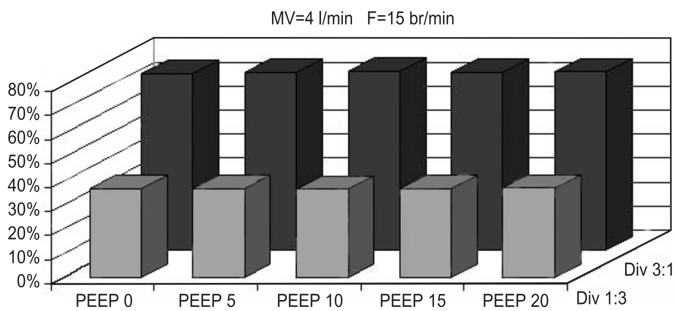

Fig. 5. Influence of selective PEEP on tidal volume in both lung models registered for unchanged adjustment of tidal volume division 1:3 and 3:1, respiratory rate = 15 br/min and minute volume = 4 l/min

4. Case Study of Independent Ventilation of Lungs on a Patient After Injury

A 42 years old patient was admitted to the Intensive Care Unit of Emergency and Trauma Centre, Medical University of Warsaw, because of serious multiorgan injury caused by a communication accident. This accident resulted in serious injuries of the left side of the body and secondary injuries of the right side. The following body injuries were certified: brain contusion, sub-arachnoid bleeding, fracture of the cranium base, contusion of the chest, lungs and heart, fracture of the right collarbone, fracture of the chest vertebral body, fracture of the left thigh bone and the left shank, hypovolemic shock. The patient was intubated and mechanically ventilated immediately after arrival of the ambulance to the place of the accident. Besides, an immediate liquid resuscitation was started. A massive blood and blood preparates transfusion was performed, in order to supplement a big loss of blood and to control the hypovolemic shock. Before the patient was delivered to the intensive care unit, diagnostic examinations were carried out, on the basis of which a preservative post-traumatic treatment in the region of central nervous system was decided. The broken leg was surgically prepared for later treatment. After two days of treatment, an exacerbation of the respiratory function occurred; the patient demanded gradually higher oxygen concentrations in the respiratory mixture and higher positive end expiratory pressures (PEEP). The radiological image of the lungs became decidedly worse, there was a blood-pus mucus in the airways, demanding intensive respiratory physiotherapy and bronchial tree lavation. The cause of the respiratory insufficiency was complex: the contusion of the lung, the transfusion syndrome, pneumonia of the mechanically ventilated lungs (Ventilator Associated Pneumonia). The pathological changes in both lungs were different in the radiological image, as well as in the computer tomographic image. The symptoms of the respiratory insufficiency were intensified by iatrogenic fistulas (pneumothorax), which arose in the consecutive days of treatment, and were a result of different mechanics of the left and right lung. At this stage, independent ventilation of the lungs (approved by Ethical Committee) by means of the control device developed in the Institute of Biocybernetics and Biomedical Engineering of Polish Academy of Sciences (IBBE PAS) started. The procedure lasted twenty hours, and allowed consecutive reduction of the oxygen concentration in the respiratory mixture. During the independent ventilation of lungs, the parameters of the arterial and the peripheral blood oxygenation of the patient were monitored. The blood gas samples were taken in time intervals of 30, 60, 90, 150, 300, 600, 900 and 1200 minutes, and the saturation of the peripheral blood was monitored continuously. Also pressures and ventilation and the radiological image of lungs were monitored. The aim of the therapy was achieving the partial pressures of oxygen equal or higher than 80 [mmHg], saturation of the peripheral blood 96–99%, decrease of the pressures in the airways, and improvement of the transparency of the lung tissue in the X-ray image. The procedure was stopped after stabilizing of the respiratory parameters on a constant satisfactory level, when it was necessary to transport the patient to a remote laboratory for diagnostic examination, for the patient's safety during transport.

The effect of the independent ventilation was following: The use of the control device for the independent ventilation of the lungs improved the blood oxygenation (Fig. 6) and allowed to decrease the ventilatory pressures (Fig. 7). There was an improvement in the radiological image of the lungs – Fig. 8a) and Fig. 8b) represent the X-ray of the chest before and after the procedure of independent ventilation of the lungs. The device was used rather late in the course of disease; earlier use of the apparatus could possibly protect the patient from complications (iatrogenic pneumothorax, and the ventilatory overload of the less damaged lung).

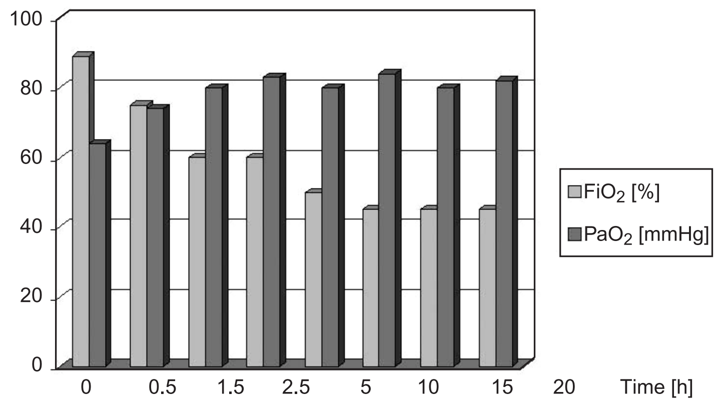

Fig. 6. The change in oxygen demand in the respiratory mixture (FiO_2) of the patient and the partial pressure of oxygen (PaO_2) in arterial blood during 20 hours of the independent ventilation of lungs

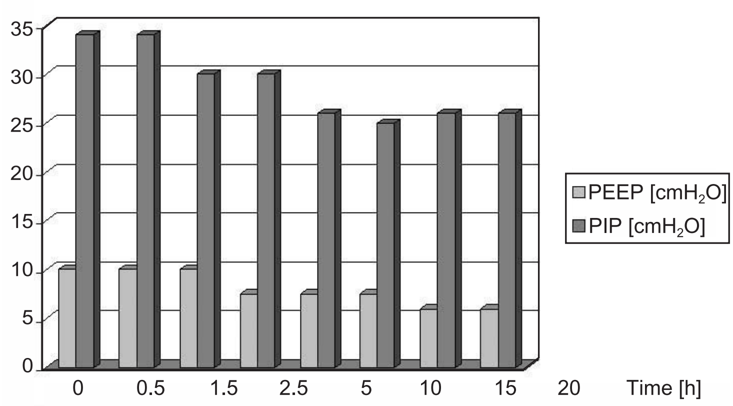

Fig. 7. The change of the peak inspiratory pressure (PIP) and the positive end expiratory pressure (PEEP) during 20 hours of the independent ventilation of lungs

a) b)

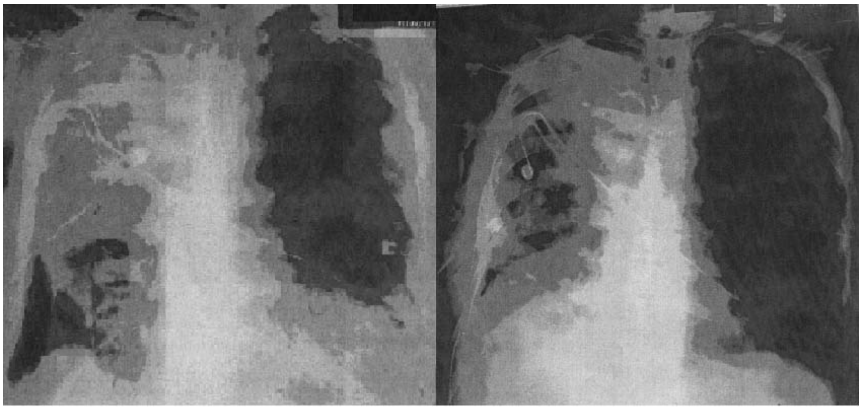

Fig. 8. a) The radiological image of the patient's lungs before starting of the independent ventilation of lungs. There is a massive lung contusion requiring chest drainage. Gas exchange parameters are borderline. The patient requires high oxygen supply, b) There is a better aeration in right upper lobe. It corresponds to changes in oxygen requirement and reduction in inspiratory pressures in clinical tests

5. Clinical Studies

The clinical studies were aimed at testing of the efficiency of the control device for independent ventilation of lungs, built in IBBE PAS. The studies were conducted in the Clinics of Anaesthesiology and Intensive Therapy of the Medical University of Lublin. The treatment was approved by the Ethical Committee. The tests were made during routine, planned procedures of the general, composite anaesthesia, for the lung parenchyma surgery. The patients were classified as ASA I-II. The patients were intubated with bilumen tubes, which position was monitored with the use of fiberoscope. During the anaesthesia, the SAP (systolic arterial pressure), DAP (diastolic arterial pressure), HR (heart rate), SPO_2, (pulseoximetric blood saturation) $EtCO_2$, (end tidal CO2 concentration) and the tidal volumes for both lungs were monitored. The data logging was made with free division of the respiratory mixture between the two lungs, and then with controlled division 1:1, 1:2, and 1:5.

The data were registered with the CosmoPlus and Florian monitors of the lung functions.

There were 60 examined patients, aged 19–78 years. In the first stage of investigation, when conventional ventilation was applied and the gas mixture was freely divided between two lungs, the difference between tidal volumes of both lungs was 72.4 ± 74.7 [ml]. In the next stage, the IBBE PAS flow divider was set for 1:1 proportion; the difference between tidal volumes of both lungs was 15.88 ± 14.94 [ml] ($p < 0.0001$). The result of the comparative test of the tidal volumes set in the divider (the tidal volume of both lungs divided by proportion set in the divider), and the tidal volumes actually realized is as an example presented in Fig. 9.

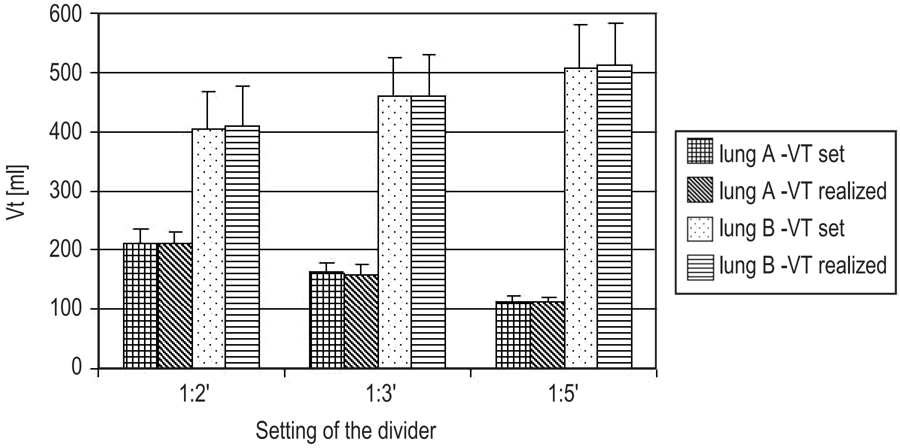

Fig. 9. The comparison of the tidal volumes set in the divider, and the tidal volumes actually realized for settings of the divider 1:2, 1:3 and 1:5. The differences between the set and the realized tidal volumes are negligible

6. Discussion

The results of model tests have shown that maximal errors of tidal volume division is less than 10%. Such an accuracy is acceptable in clinical practice. In the case study of a patient after serious lung and multiorgan injury, the therapy with use of the apparatus for independent ventilation improved the blood oxygenation, allowed decreasing of the ventilatory pressures and improvement in the radiological image of lungs. In opinion of the anaesthesiologist, the control device was used too late in the course of the disease; earlier use of the apparatus could protect the patient’s lungs from damage caused by mechanical ventilation (iatrogenic pneumothorax, and the ventilatory overload of the less damaged lung). The clinical study of 60 patients has shown that differences between actually realized volume division and the division set by the user are practically negligible. There is also another application of the developed control system. The need of multiplying ventilator capacity may occur in different places throughout the world as a result of massive accidents and natural disasters, or terrorist attack with gas poisoning. Hospitals equipped for peacetime operation have no adequate number of ventilators in reserve to handle these patients [10, 11]. To develop a convenient, reliable method of performing ventilation of two patients by only one respirator the new control system may be used. When placed between respirator and endotracheal tubes of two patients it divides total tidal volume between the patients and controls pressure at their airways. A special arrangement of valves in the control system enables to separate inspiratory and expiratory paths for each patient and adjust selectively their ventilation and positive and expiratory pressures. In this way cross-infection is avoided. The proposed technique fulfills the same functions as a conventional set up of two respirators but at a price about 2 times lower. Model studies performed according to ISO and ASTM standards on a mechanical test lung showed that the proposed control system enables to adjust ventilatory parameters at desired values when each lungs compliance or respiratory airway resistance differ [12, 13]. Further model tests will be performed on more complex lung models eg. [14–16]. Proposed one source artificial ventilation of the patients is a simple solution to deal with providing controlled automatic ventilation for patient numbers in excess of the number of ventilators that are available.

7. Conclusions

The control device for independent, synchronous lung ventilation can be used when connected to only one respirator instead of the conventional setup of two synchronized respirators. The described device could be a cost effective and room sparing solution for independent ventilation of lungs. It could also be used in emergency situations, when there are many patients to ventilate at a time, because it gives possibility to ventilate two patients with one respirator.

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