LUNG VENTILATORS PARAMETERS DETERMINATION

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Se dezvolta un sistem de testare unitar cu ajutorul caruia se determina automat parametrii ventilatori furnizati de echipamentul de ventilatie pulmonara. Pentru determinarea automata a parametrilor ventilatori se utilizeaza diversi senzori montati prin intermediul unei placi de achizitie de date la un calculator pe care are instalat software-ul LabView. Cu ajutorul software-ului Labview se dezvolta un program care poate extrage automat parametrii ventilatori.

An integrated test unit that can automatically determine the ventilators parameters provided by pulmonary ventilation equipment is being developed. Several sensors mounted to a computer via a data acquisition card are used for automatic determination of the parameters. A program that can automatically extract the ventilator's parameters is developed using the LabView software.

Keywords: Ventilation parameters, Test system.

1. Introduction

The ventilators automated testing system should automatically extract the ventilation parameters values. For this it must determine the pressure values of (p_{max}- maximum pressure, $p_{plateau}$ - plateau pressure, PEEP - Positive End-Exhale Pressure, VT_i - inhale tidal volume, VT_e - exhale tidal volume, f - respiratory rate, t_{insp} – inhale time, t_{exp} - exhale time, t_1 – the part of inhale time in which gas is introduced into the lung, t_2 - the part of inhale time in witch the lung volume remains constant (do not enter gas), F_iO_2 - inhale O_2 concentration etc.) For this purpose a program is developed in LabView to process the electric signal collected from the sensors [3] through a data acquisition card and display the pressure and flow diagrams and, also, the values of the ventilation parameters.

For testing purpose the system should extract ventilating parameters for different ventilation modes.

2. Ventilation parameters values determination

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The variation diagrams of pressure, flow and oxygen concentration versus the electric power voltage supplied by the sensor were determined.

The characteristic equations of these parameters are:

$$p = 15.54 + 34.54 \cdot U \tag{1}$$

$$\dot{V} = -18.23 + 32.63 \cdot U \tag{2}$$

for $\dot{V} > 0, U > 0.56$

$$\dot{V} = -26.35 + 47.06 \cdot U \tag{3}$$

for $\dot{V} < 0, U < 0.56$

$$FiO_2 = 1.25 + 1316.67 \cdot U \tag{4}$$

where p is the pressure,
U - the electrical voltage,
$\dot{V}$ - the gas flow,
FiO_2 – the oxygen concentration.

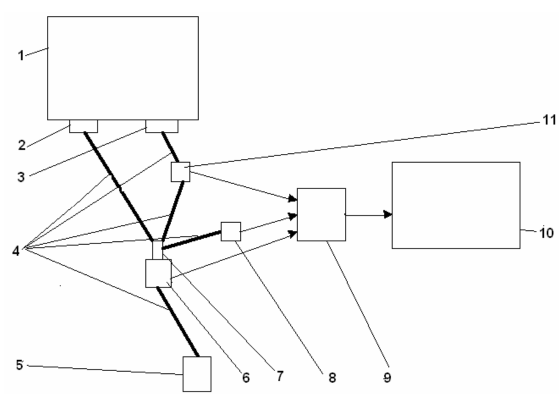

Fig. 1. Test system diagram. 1. ventilator, 2. exhale block, 3. inhale block, 4. connecting hoses, 5. lung simulator, 6. flow sensor, 7. Y piece, 8. pressure sensor, 9. data acquisition card, 10. computer, 11. oxygen concentration sensor.

Using the LabView software [5], a computer program has been developed to extract data from pressure, flow and oxygen concentration sensors using data acquisition card USB 6009 produced by National Instruments. For sampling, the rate was settled at 1000 Hz. This value was chosen because this system can test the ventilation equipment used in neonate area, where respiratory frequencies are high (30-100 breaths / minute).

3. Determining airway pressure

Fig. 2 illustrates the standard pressure variation in automatic ventilation when the patient is sedated. [1]

Pressure variations in the system versus time can have the shape shown in Fig. 3.

In Fig. 3 area 1 represents pressure limited ventilation, the trigger is in zone 2, zone 3 shows the ventilation with peak and plateau pressure (IPPV classic), 4 is the spontaneous breath exhale while 7 is spontaneous breathing in inhale phase. Zone 5 is the ASB (Assisted Spontaneous Breathing), or inhale pressure with "autoflow" option, or pressure limited. Zone 6 represents exhale pressure in classical IPPV.

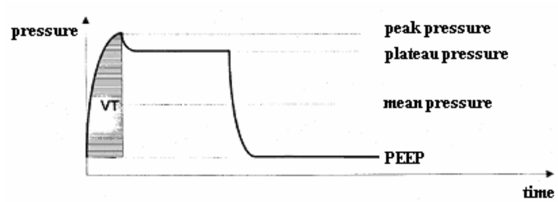

Fig. 2. Airway pressure diagram

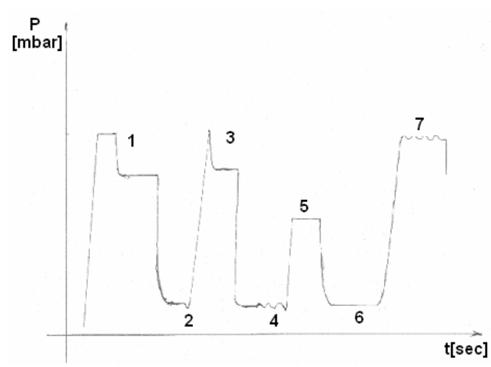

Fig. 3. Possible airway pressure variation

With the pressure sensor and the LabView [5] software the maximum pressure during the respiratory cycle is measured, and is considered as p_{max}.

Plateau pressure is calculated as the average pressure from it's beginning to its end (starts at the end of t_1 and last t_2). If maximum and minimum pressures in this period t_2 varies significantly from plateau pressure (more than 2 mbar), it means that the patient has spontaneous inhale breathing. Maximum and minimum plateau pressure represents the spontaneous inhale breathing.

PEEP pressure is calculated as the average pressure from the exhale period when flow is zero.

Spontaneous exhale breathing is considered when the maximum / minimum pressure varies by more than 2 mbar pressure from PEEP.

Minimum pressure in the system during a cycle is compared with PEEP. If values are significantly different (>2 mbar) then the minimum pressure will be considered the trigger pressure.

4. Determining the frequency and inhale and exhale time

The quasi-constant gas flow in the patient's system is determined with the flow sensor and the LabView software. Knowing the gas flow one can determine respiratory volumes and times.

The inhale time beginning is considered when the positive flow appears. The inhale time end stage with inserting flow in the lungs is considered when the zero flow appears (no flow). At this point the plateau stage begins. In real human breathing between inhale and exhale (and vice versa) there are break times that allow the muscles to relax and nervous system to change commands. In ventilation the resting stage is known as the plateau phase. The plateau phase ends with the appearance of the negative flow (reverse flow). At this point the exhale time begins which ends at the appearance of the positive flow [4].

t_1 – starts at the positive flow and ends to zero flow

t_2 – starts at zero flow (after positive flow) and ends to the negative flow appearance.

$$t_{inhale} = t_1 + t_2 \tag{5}$$

t_{exhale} – begins at the negative flow appearance and ends at the positive flow appearance

$$t_{respiratory} = t_{inhale} + t_{exhale} \tag{6}$$

All times are expressed in seconds.

$$f = \frac{60}{t_{respiratory}} \tag{7}$$

f – the respiratory rate expressed in breaths per minute.

The inhale: exhale time ratio $(I:E)$ represent, among other parameters, an important parameter for all lung ventilators, usually adjustable.

$$I:E = \frac{t_{inhale}}{t_{exhale}} \tag{8}$$

Some uncommon cases when the end of the examined t_2 is previous of the t_1 end, so the t_2 is negative, can be encountered. To eliminate these anomalies (negative time) some queries that check the time sequence are inserted. Calculation of t_1 is chosen so is depending on the beginning time of the inhale before t_1. The t_2 value, where his end is before the t_1 end, is calculated according to a beginning inhale time before the end of the t_2 and the t_1 value.

$$t_2 = t_{end\_t_2} - t_1 - t_{begin\_inhale\_before\_t_2} \tag{9}$$

Tidal volumes are determined using the following relationship:

$$VT_i = \sum \left(rate \cdot \dot{V}_{pos} \right) \tag{10}$$

$$VT_e = \sum \left(rate \cdot \dot{V}_{neg} \right) \tag{11}$$

Where $rate$ is the sampling rate,

VT_i – the inhale tidal volume,

$\dot{V}_{pos}$ – the positive flow,

VT_e – the exhale tidal volume,

$\dot{V}_{neg}$ – the negative flow.

5. The software development

The developed software purpose is to extract the major parameters of the patient's ventilation system provided by the ventilator (maximum pressure, PEEP, plateau pressure, VT, inhale and exhale times, respiratory rate, oxygen concentration in inhaled gas).

The software is structured as follows:

a) Data acquisition is performed using a data acquisition card.

The data collected from the tester's sensors for the ventilators are retrieved with a certain sampling frequency (1000Hz in this case). This sampling frequency was chosen because the ventilators to be tested work with a respiratory frequency of one hundred breaths / minute, and a respiratory cycle consist of several different times (t_1, t_2, t_{exhale}).

To increase the time period in witch the ventilator parameters are analyzed (at least one respiratory cycle) the sensors measurements must be saved. To achieve this, data acquisition was introduced in a "while" loop.

Because ventilator parameters can instantly change, the analysis is done on a complete respiratory cycle. It thus sets the samples number for a complete ventilation cycle to be included in a test.

b) The pressure, flow and oxygen concentration sensors electrical voltage values obtained through the data acquisition card are converted into pressure, flow and oxygen concentration values. The formula obtained at the sensors calibration, (1), (2), (3) and (4) are used to achieve this purpose.

c) Determining the ventilation cycle.

The positive flow appearance is considered the inhale phase start point, and the negative flow appearance exhale phase start point. The positive and negative flow means flow towards the patient and from the patient to sensor. A complete cycle is considered to be the time period between two successive inhale phases.

d) Determining VT_i and VT_e

During a respiratory cycle the positive and the negative flows, the tidal volumes, with the equations (10) and (11), are determined.

The amount of negative volumes, VT, is determined. If the analyzed cycle is not a complete one, there is the risk that the VT calculated value to be less than the real one. To eliminate this case the maximum VT is extracted from the analyzed period, so a complete VT is determined, even if it is considered at a later time than the ventilation cycle beginning. The same procedure is assumed for VT_i.

e) Determining the ventilation's pressures

The maximum pressure during the respiratory cycle is determined and it is considered to be $p_{\max}$. The plateau pressure is calculated as the average pressure from the beginning to the end of the plateau. If maximum and minimum pressures in this time period, t_2 fluctuate with significant values from the plateau pressure (with more than 2 mbar) it means that the spontaneous inhale breathing is produced. Plateau phase maximum and minimum pressure values are the spontaneous inhale breathing. PEEP pressure is calculated as the average pressure in the exhale period when flow is zero.

Spontaneous exhale breathing is considered when the maximum / minimum pressure varies by more than 2 mbar from the PEEP pressure. The smallest pressure of the system during a cycle is compared to the PEEP pressure. If values are significantly different (>2 mbar) then the minimum pressure will be considered the trigger pressure.

f) Determining the ventilation's characteristic times (t_{inhale}, t_1, t_2, t_{exhale}, f, $I:E$ - inhale : exhale time ratio)

The inhale time beginning is considered to be the positive flow appearance. The inhale time ending, with no gas flow in the lung, is considered to be the zero flow (absence of the flow). At this point the plateau phase begins. The plateau phase ends at the negative flow appearance (reverse flow). In this point the exhale time begins, and ends at the appearance of the positive flow. The (5), (6), (7), (8) and (9) equations are used to determinate the numerical values.

g) The values obtained with this program are exported into an spreadsheet file format to be easily used in various forms, reports or further analysis.

6. Obtaining the ventilation's parameters

To determine the main ventilation parameters the test system is coupled to the ventilator as shown in Fig. 1.

The sensors are coupled with the data acquisition card and this one to the computer. The application starts and the data are recorded. After processing, the ventilation parameters are displayed on the computer display as shown in Fig. 4.

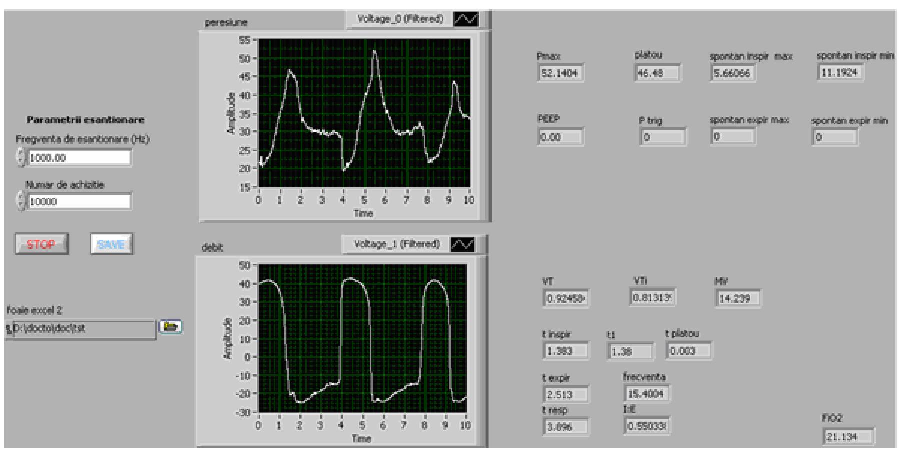

Fig. 4. User display for viewing ventilation parameters

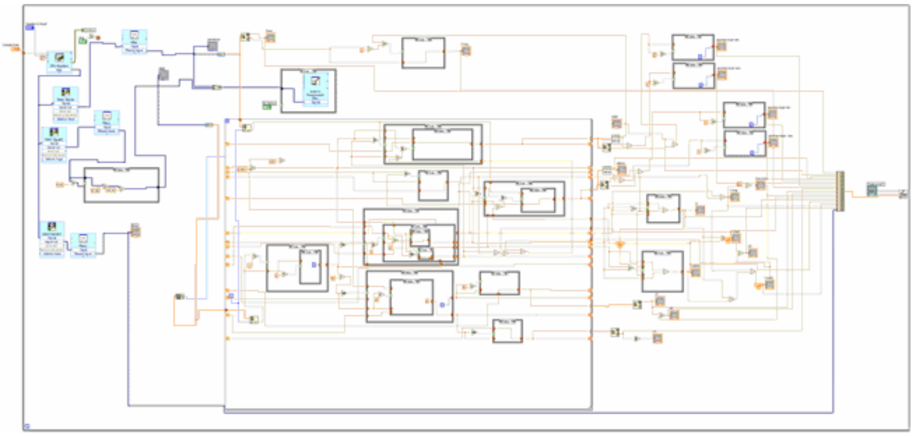

Fig. 5. Software in LabView for viewing ventilation parameters

The pressure and flow diagram are visualized. Check whether the shapes of these diagrams are similar to the classic ones for the chosen ventilation mode.

The ventilation parameter's values are read and compared with the values preset for the test equipment.

Data gathered by the system presented in this paper are saved in a spreadsheet file format where it can be easily printed or processed.

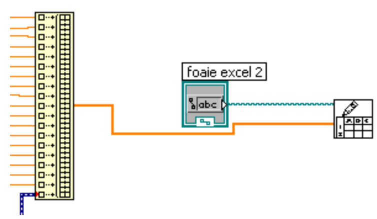

Fig. 6. Copy data in spreadsheet file format

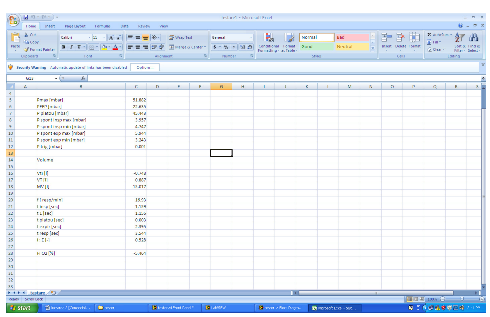

Fig. 7. Data in spreadsheet file format

7. Testing the lung ventilator unit system for different ventilation modes

a) Intermittent Positive Pressure Ventilation (IPPV)

In IPPV ventilation mode, the ventilator provides to the patient a predetermined gas volume (VT) at a pressure that cannot exceed the maximum pressure set by the doctor. Exhale occurs at PEEP pressure. This ventilation mode does not allow spontaneous breathing and it is used for the sedated patients.

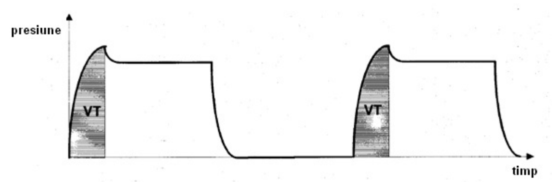

Fig. 8. IPPV - theoretical diagram [2]

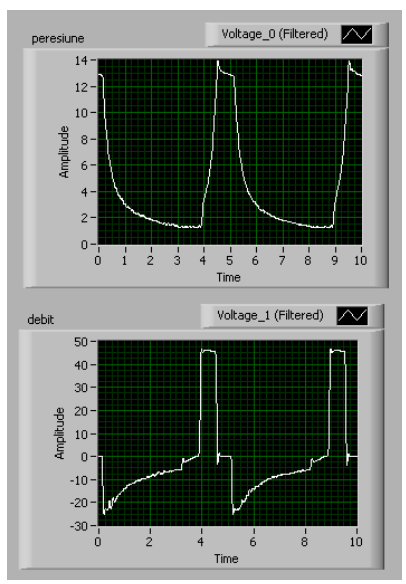

Fig. 9. IPPV - measured diagram

b) Synchronized Intermittent Positive Pressure Ventilation (SIPPV)

SIPPV ventilation mode is similar to IPPV mode excepting the fact that it allows spontaneous breathing at the exhales end. The time period at the exhales end, in which spontaneous breathing is possible and the machine delivers the patient's a normal inhale, is called the trigger window. When the patient tries to inhale in the trigger window the machine delivers a normal inhale.

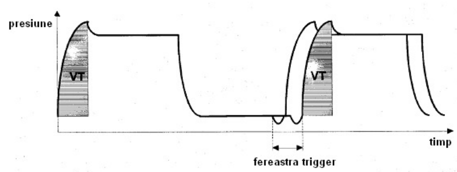

Fig. 10. SIPPV - theoretical diagram [2]

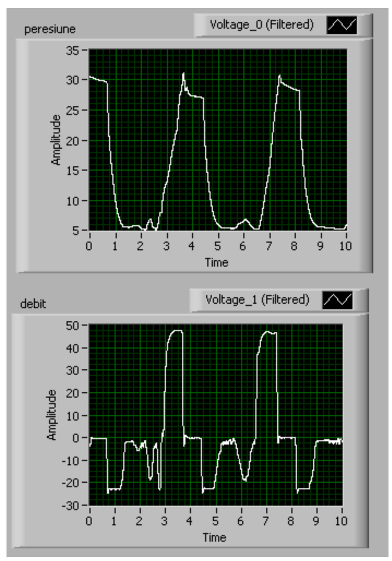

Fig. 11. SIPPV – measured diagram

c) Synchronized Intermittent Mandatory Ventilation (SIMV)

SIMV ventilation mode is similar to SIPPV ventilation mode. The difference between the two ventilation modes is that in SIMV allows the patient to breathe spontaneously at any time during the exhale. The patient adapts his breathing around the PEEP value. When the patient tries to breathe during the trigger window the ventilator delivers a normal inhale.

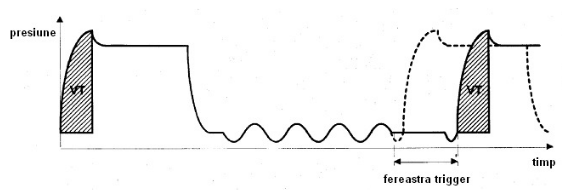

Fig. 12. SIMV - theoretical diagram [2]

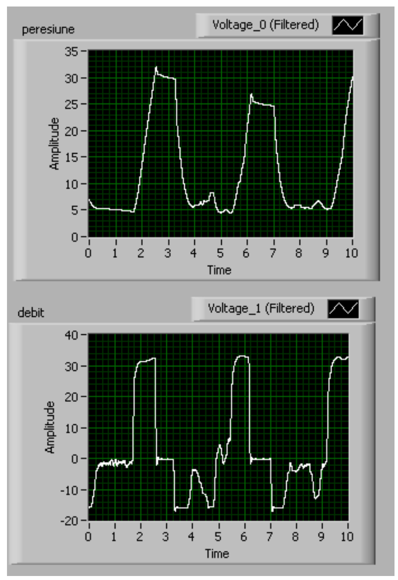

Fig. 13. SIMV – measured diagram

d) Biphasic Positive Airway Pressure (BIPAP). Ventilation mode for spontaneous breathing at continuous positive airway pressure with two different pressure levels

BIPAP ventilation mode is characterized by two pressure levels, one for inhale and one for exhale pressures. These pressures have similar values (5-10 mbar difference). In the inhale phase the machine delivered gas to the patient at an inhale pressure for an inhale time set by the doctor. In this ventilation mode the patient can breathe spontaneously both during the inhale and exhale phases.

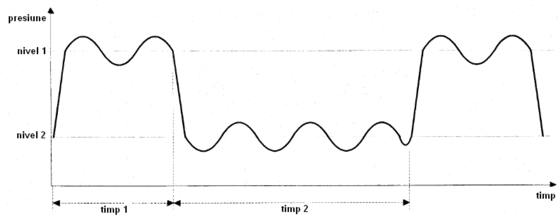

Fig. 14. BIPAP - theoretical diagram [2]

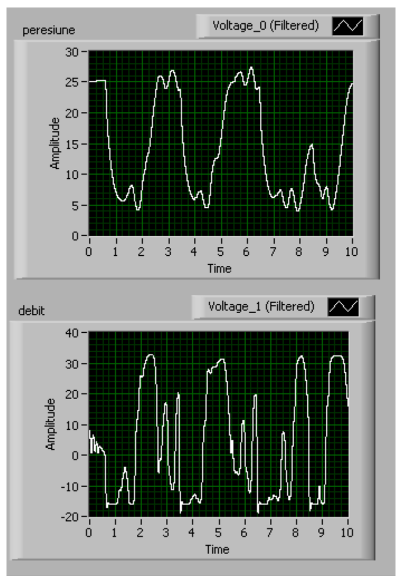

Fig. 15. BIPAP – measured diagram

e) Spontaneous breathing with positive airway pressure. Continuous Positive Pressure Ventilation (CPAP)

CPAP ventilation mode is more a breathing than a ventilation mode. CPAP mode differs from the classical breathing because the breathing is not made around atmospheric pressure value (considered zero) but around a positive pressure value CPAP (above the atmospheric pressure). The machine provides gas at CPAP pressure and the patient breathing is made around this pressure.

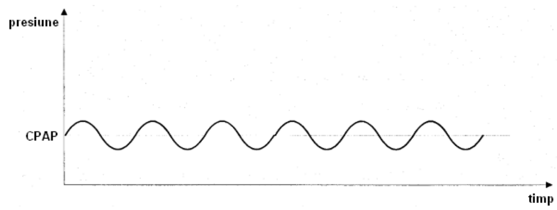

Fig. 16. CPAP - theoretical diagram [2]

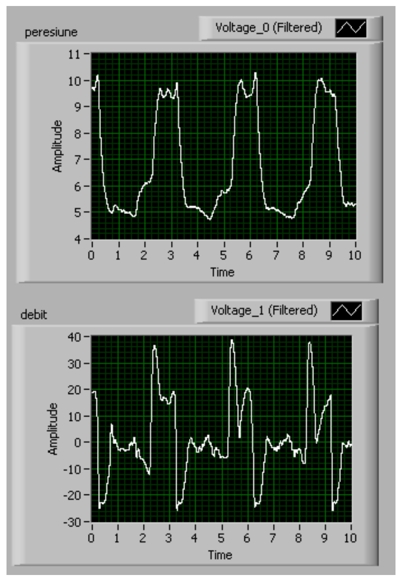

Fig. 17. CPAP – measured diagram

8. Conclusions

A great similarity between the theoretical and the measured diagrams from Fig. 8 and 9, 10 and 11, 12 and 13, 14 and 15, 16 and17, which confirms that the system developed and presented in this paper is working properly. The ventilator used in tests was prior adjusted and calibrated.

Table 1 shows the values set on ventilator and the measured values with this test system. It shows a very good accuracy. Deviation is less then 1 mbar for pressures and less then 25 ml for volumes. These differences may be due to ventilation equipment's tolerances.

Table 1

Summarizing the set and measure parameters

p_{max} set	p_{max} measured	PEEP set	PEEP measured	VT set	VT measured	f set	f measured	t_{insp} set	t_{insp} measured
15	14.2	0	1	400	375	12	11.95	1.8	1.83
32	32	5	5.4	400	378	12	11.94	1.8	1.85
32	32	5	4.5		376		14	1.8	1.78
25	25.3	5	5.2				18		
		7	7.43				20		

R E F E R E N C E S

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