CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF BIOMEDICAL ENGINEERING

Department of Biomedical Technology

Comparison of neonatal high frequency ventilators for neonates

Porovnání vysokofrekvenčních oscilačních ventilátorů pro novorozence

Bachelor thesis

Study program: Biomedical and clinical technology

Study branch: Biomedical technician

Author of the thesis: Yanina Kuzminich

Supervisor of the project: Ing. Petr Kudrna, Ph.D.

Kladno, May 2017

Czech Technical University in Prague, Faculty of Biomedical Engineering

Department of Biomedical Technology | Academic year: 2016/2017

Bachelor thesis assignment

Student: **Yanina Kuzminich**

Study branch: Biomedical Technician

Title: **Comparison of neonatal high frequency ventilators for neonates**

Title in Czech: Porovnání vysokofrekvenčních oscilačních ventilátorů pro novorozence

Instructions for processing:

Design a pilot experiment to compare high frequency oscillatory ventilators for neonates - HFOV ventilator 3100 (Sensormedics, California) and Babylog VN 500 (Dräger, Germany). Use the available models of neonatal respiratory system - single and multi compartment model. Focus on efficiency of CO2 elimination and distributing pressure effects in the model at a comparable parameter settings. Document the results and evaluate it properly.

References:

[1] Tricia L. Gomella, Neonatology: management, procedures, on-call problems, diseases and drugs, ed. Sixth Edition, McGraw Hill Professional, 2009, ISBN 78-0-07-154431-3

[2] John G. Webster, Encyclopedia of Medical Devices and Instrumentation, ed. 6, Wiley, 2006, ISBN 978-0-471-26358-6

[3] Roubík, K., Krejzl, J., Zábrodský, V, Real Time Monitoring and Evaluation System for High Frequency Ventilation, ed. 1, Proceedings of the 8th International IMEKO Conference on Measurement in Clinical Medicine, 1998, 19-22 s., ISBN 953-6037-26-2

Validity of assignment until date: 11.09.2018

Supervisor of bachelor thesis: Ing. Petr Kudrna, Ph.D.

.... Head of Department

.... Dean

In Kladno, 20.02.2017

České vysoké učení technické v Praze, Fakulta biomedicínského inženýrství

Katedra biomedicínské techniky Akademický rok: 2016/2017

Zadání bakalářské práce

Student: **Yanina Kuzminich**

Obor: Biomedicínský technik

Téma: **Porovnání vysokofrekven ních oscila ních ventilátor pro novorozence**

Téma anglicky: Comparison of neonatal high frequency ventilators for neonates

Zásady pro vypracování:

Navrhněte a proveďte experiment, při kterém budou porovnány vysokofrekvenční oscilační ventilátory pro novorozence, tj. HFOV ventilator 3100 (Sensormedics, California) a Babylog VN 500 (Dräger , Německo). Použijte dostupné jedno a více kompartmentové modely respirační soustavy novorozenců. Zaměřte se na účinnost eliminace CO2 a distribuci tlakových účinků v modelu při nastavení srovnatelných parametrů. Dokumentujte a vyhodnoťte dosažené výsledky.

Seznam odborné literatury:

[1] Tricia L. Gomella, Neonatology: management, procedures, on-call problems, diseases and drugs, ed. Sixth Edition, McGraw Hill Professional, 2009, ISBN 78-0-07-154431-3

[2] John G. Webster, Encyclopedia of Medical Devices and Instrumentation, ed. 6, Wiley, 2006, ISBN 978-0-471-26358-6

[3] Roubík, K., Krejzl, J., Zábrodský, V, Real Time Monitoring and Evaluation System for High Frequency Ventilation, ed. 1, Proceedings of the 8th International IMEKO Conference on Measurement in Clinical Medicine, 1998, 19-22 s., ISBN 953-6037-26-2

Zadání platné do: 11.09.2018

Vedoucí: Ing. Petr Kudrna, Ph.D.

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V Kladně dne 20.02.2017

Declaration

I hereby declare that I have completed this thesis with the topic "Comparison of neonatal high frequency ventilators for neonates" independently and I have included a full list of used references.

I do not have a compelling reason against the use of the thesis within the meaning of Section 60 of the Act No 121/2000 Coll., on copyright, rights related to copyright and amending some laws (Copyright Act).

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Bachelor's thesis title

Comparison of neonatal high frequency ventilators for neonates

ABSTRACT

Nowadays in clinical practice various HFOV ventilators are used. They create oscillations by various methods and for safety of the patients it is important to know, if the same settings provide the same ventilation on different devices. Also, it is necessary to know if the new features and technologies used in modern HFOV machines affect the work of the device and its functions in comparison with older ventilators. Suggested experiment allows to conduct the measurements for different types of high-frequency oscillatory ventilators and to draw a conclusion regarding the effectiveness of the devices in delivered tidal volume, pressure and CO_2 elimination. Delivered pressure in the newer HFOV ventilators has been recorded to be lower than in the SensorMedics 3100A, the CO_2 elimination depends on the used patient circuit as well as on the settings.

Key words

HFOV, High-frequency ventilation, CO_2 elimination, pressure measurements, tidal volume

Nazev práce

Porovnání vysokofrekvenčních oscilačních ventilátorů pro novorozence

ABSTRAKT

V současné klinické praxi se používá několik typů HFOV ventilátorů. Tato zařízení, fungující na rozdílných principech, generují oscilace, kdy pro bezpečí pacientů je nutné provést porovnání dostupných zařízení za účelem zjištění, zdali stejná nastavení generují stejnou ventilaci plic. Dalším kritériem zkoumaným v této práce je vliv nových technologií použitých v moderních HFOV přístrojích a porovnání těchto zařízení s těmi, která danými technologiemi nedisponují. Experiment, jehož výsledky jsou shrnuty v této práci, představuje měření na rozdílných typech vysokofrekvenčních oscilačních ventilátorů, kde celkový závěr o každém zařízení je sestaven z dílčích závěrů hodnocených kategorií. Těmito kategoriemi jsou efektivita daného zařízení v objemu dodávaného kyslíku do plic, tlaku a eliminace CO_2. U novějších přístrojů jsme zaznamenali nižší velikost tlaku v porovnání se starším HFOV ventilátorem SensorMedics 3100A. V případě eliminace CO_2 záleží jak na použitém dýchacím okruhu pacienta, tak na zvoleném nastavení.

Klíčová slova

HFOV, High-frequency ventilation, CO_2 eliminace, měření tlaku, tidal volume

Content

List of symbols and abbreviations

Abbreviation	Meaning
BPM	Breaths Per Minute
CDP	Constant Distending Pressure
CMV	Conventional Mechanical Ventilation
ETT	Endotracheal tube
HFOV	High-Frequency Oscillatory Ventilation
HH	Heat Humidifier
I:E	Inspiratory/expiratory ratio
MAP	Mean Airway Pressure
MV	Expiratory Minute Volume
PIP	Peak Inspiratory Pressure
RR	Respiratory rate

Symbol	Meaning
CO_2	Carbon dioxide
c	Concentration
c_f	Maximum achieved concentration of CO_2
f_s	Sampling frequency
N	Count
$\overline{P_{AW}}$	Proximal Mean Airway Pressure
P_{ETT}	Pressure at the Distal End of the Endotracheal Tube
ΔP	Amplitude
P_{AW}	Proximal Airway Pressure
t	Time
τ	Time constant
V_T	Tidal Volume
V_{Te}	Expiratory Tidal Volume

1 Introduction

High-frequency oscillatory ventilation (HFOV) is a type of mechanical ventilation, which was introduced in 1970's to treat lung decease of prematurity. Nowadays it is used for all age groups of patients with acute hypoxemic respiratory failure. [1] For pre-term infants HFOV is widely deployed in clinical practice as well as conventional mechanical ventilation (CMV). There is no significant difference between HFOV and conventional mechanical ventilation in mortality, adverse neurological outcomes or bronchopulmonary dysplasia. [2,3] However, another researches suggest, that use of HFOV facilitates the decrease of incidence of chronic lung disease. [4] In addition to that, there are types of patients that can significantly benefit from HFOV.

For instance, premature infants have functional and structural predisposed lungs to hypoxia. Neonates in critical states tend to have low lung volumes as well as increased intrapulmonary shunt due to the poor compliance. HFOV is of high importance for those patients: this technology provides lower inspired concentration of oxygen and PIP (peak inspiratory pressure). [5] Also HFOV uses constant MAP (mean airway pressure), while pressure changes at high rates (due to oscillations) around this MAP value. This approach allows to provide small tidal volume and besides that, it avoids rapid and large change of pressure and prevents lungs from collapsing. [6] It is also important to note that HFOV provides both active inspiration and expiration, in a contrast with other modes of high-frequency ventilations (active inspiration and passive expiration).

Currently on the market there is a variety of high frequency oscillatory ventilators for neonates, New devices as well as older ones are used in clinical practice. For instance, ventilator 3100A (SensorMedics, Yorba Linda, CA) is being used since 90s, while Babylog VN500 (Dräger Medical, Germany) was launched in 2009, and Fabian HFOi (Acutronic Medical System, Switzerland) was presented in 2015. There are also the other new devices on the market: the SLE5000 (SLE, United Kingdom), the Leoni Plus (Heinen+Löwenstein, Germany). An overview of several HFOV machines, that are used in clinical practice, is presented in Table 1.1.

New products provide CMV and HFOV modes of ventilation. Babylog VN500, Fabian HFO, and Leoni Plus present the concept of tidal volume-targeting while working in HFOV mode. On the other side, SensorMedics 3100A is without any monitoring of flow or tidal volumes. However, we know little about V_T (tidal volume) stability during volume-targeted ventilation and volume delivery accuracy in those ventilators, that provide the choice between CMV and HFOV modes. [7]

Oscillations may be formed by membrane oscillation, opposing flow at the expiratory manifold or Venturi expiratory system. Pressure amplitude setting range changes from 1 to 90 cmH_2O in 3100A and VN500, Fabian HFO has interval of 5-80 cmH_2O, Leoni Plus provides 0-100 cmH_2O, while SLE5000 provides from 4 up to 180 cmH_2O. Common frequency range for all ventilators is 5-15 Hz, since SensorMedics provides smaller frequency range in comparison with new ventilators. Inspiratory/expiratory ratios (I:E) for majority of the devices is from 1:1 to 1:3. However, SensorMedics 3100A allows 1:1 and 1:2 I:E ratios, while SLE 5000 presents 1:1 only. The newer generations of high frequency oscillatory ventilators provide significantly smaller flow range in comparison with SensorMedics3100A. [7]

Table 1.1. Comparison of technical principles and available settings for SensorMedics 3100A, Babylog VN500, Fabian HFO, Leoni Plus, SLE 5000 (taken from [4])

	SensorMedics 3100A	Babylog VN500	Fabian HFO	Leoni Plus	SLE 5000
Manufacturer	CareFusion	Dräger	Acutronic	Heinen+Löwenstein	SLE
Technical principles	Oscillations generated by a large loudspeaker	Servo valve controlled pulsed inspiratory flow Expiratory valve oscillation	Membrane oscillation	Membrane oscillation	Opposing flow at the expiratory manifold
Mode	HFOV	Conventional mechanical ventilation and HFOV	Conventional mechanical ventilation and HFOV	Conventional mechanical ventilation and HFOV	Conventional mechanical ventilation and HFOV
Volume-targeted mode	No volume-targeted mode	Volume-targeted mode in HFOV	Volume-targeted mode in HFOV	Volume-targeted mode in HFOV	No volume-targeted mode in HFOV
V_T monitoring	No V_T monitoring	Hot-wire anemometer	Hot-wire anemometer	Hot-wire anemometer	Hot-wire anemometer
Flow	0–40 L/min	2–30 L/min	1–20 L/min	7 L/min	8 L/min
Pressure amplitude setting range	1–90 cm H_2O	1–90 cm H_2O	5–80 cm H_2O	0–100 cm H_2O	4–180 cm H_2O
Mean pressure setting range	3–45 cm H_2O	5–50 cm H_2O	5–50 cm H_2O	0–40 cm H_2O	0–35 cm H_2O
Frequency setting range	3–15 Hz	5–20 Hz	5–20 Hz	5–20 Hz	3–20 Hz
Inspiratory/expiratory ratios	1:1 and 1:2	1:1 to 1:3	1:1 to 1:3	1:1 to 1:3	1:1

V_T = tidal volume
HFOV = high frequency oscillatory ventilation

1.1 Steady state and aim of the thesis

In recent research, it was found that the newer HFOV devices could provide adequate oscillation V_T of 1 mL/kg, while some of them were not able to deliver this value of 4 mL/kg. Also, there was observed oscillatory flow limitations for Babylog VN500. There was recorded lower delivered tidal volume for newer devices, while there were same settings of the pressure amplitudes on the ventilators. In that research the bias flow was set to the different values for most of the devices and CO_2 elimination was not one of the main interests of the study. [7]

Mentioned above research became an inspiration for the current project.

1.2 The aim of the thesis

The aim of this bachelor thesis is to design an experiment for comparison of several HFOV ventilators. This examination evaluates the performance of the devices with the same settings. It also allows to find out if there are differences in functioning between newer and older ventilators and how significant they are. Parameters for comparison are delivered tidal volume and CO_2 elimination.

Hypothesis is that the same settings on the devices may lead to diverse delivered tidal volumes as well as different efficiencies in CO_2 elimination due to the various techniques for creation of oscillations in HFOV ventilators.

In Czech Republic SensorMedics 3100A, Babylog VN500 and Fabian HFO are the most commonly used devices. This is explained by the fact, that on the Czech market there are no distributors for Leoni Plus and SLE 5000. For that reason, the current paper is focused for those three available ventilators.

2 Methods

In this project were studied three neonatal HFOV: SensorMedics3100 A, Babylog VN 500, and Fabian HFOi (newer model of Fabian HFO).

To accomplish the goal of the thesis and create precise experiment it was important to find similar points in all ventilators, maintain same initial conditions and use the identical lungs models as well as measuring devices to avoid uncertainties or calibration errors.

In the following chapters is provided overview of the used ventilators and experimental set-up. The examination consisted out of two parts: evaluation of pressure distribution and CO_2 elimination. All measurements were completed dry air.

2.1 Devices used for the experiment

2.1.1 SensorMedics 3100A

SensorMedics 3100A is a high frequency oscillatory ventilator that is commonly used NICU (neonatal intensive care unit) and PICU (pediatric intensive care unit).

Figure 2.1. SensorMedics 3100A (taken from [8])

System of 3100A is composed from eight subsystems: six of them is a part of this ventilator, while two others should be supplied additionally by the user.

Two subsystems, that should be provided externally, are:

- An External Air/Oxygen Blender;
- An External Humidifier.

The subsystems included within the HFOV 3100A are:

- The pneumatic logic and control system;
- The patient circuit;

- The oscillator subsystem;
- The airway pressure monitoring system;
- Electronic controls and alarms;
- Electrical power supply.

Oxygen and air should be filling an Air/Oxygen Blender as a requirement for the work of 3100A. Since the device doesn't include the humidifier initially, it is necessary to add it to the patient circuit. [9] In clinical practice it is commonly used respiratory humidifier MR850 (Fisher Paykel, New Zealand) with chamber MR 340/370(Fisher Paykel, New Zealand). However, for this experiment will be used only dry air.

The pneumatic logic and control system gets pressurized gas from the Blender. This subsystem includes four pneumatic controls:

- Bias Flow Control—establishes the flow of mixed gas, that constantly moves past the patient airway.
- Mean Pressure Adjustment;
- Mean Pressure Limit Control—defines the limiting proximal Paw in the patient circuit;
- Patient Circuit Calibration Adjustment—screwdriver adjustment, that allows to set maximum MAP for certain conditions in patient circuit. [9]

The Patient Circuit is composed from the following elements, that are required for ventilation using HFOV:

- bias flow/pressure;
- pressure oscillations;
- pressure limiting. Patient circuit is presented on the Figure 2.1.

During operation, blended bias gas, from the external humidifier goes into the bias flow tube. Then it flows into the inspiratory limb, through the "Y" coupler and then into expiratory limb (Figure 2.2). The exchange of oxygen and carbon dioxide takes place at the ET tube, while the fresh gas is passing through the "Y" coupler. [9]

The oscillator is composed of electronic control circuit (square-wave driver), linear motor, and a piston assembly (Figure 2.3). In current configuration square-wave driver controls the linear motor, which runs a piston. Inspiration is created, when the electronic control circuit has positive polarity, so it moves the electrical coil together with the piston towards the patient. Therefore, expiration appears, when negative polarity causes the electrical coil to go in opposite direction. [9]

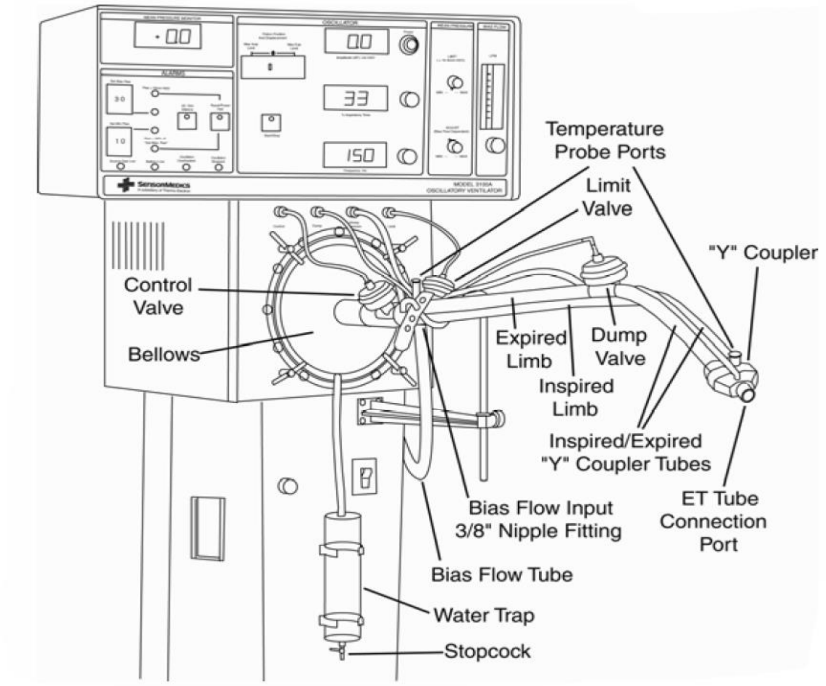

Figure 2.2. Details of Patient Circuit for SensorMedics 3100A (taken from [9])

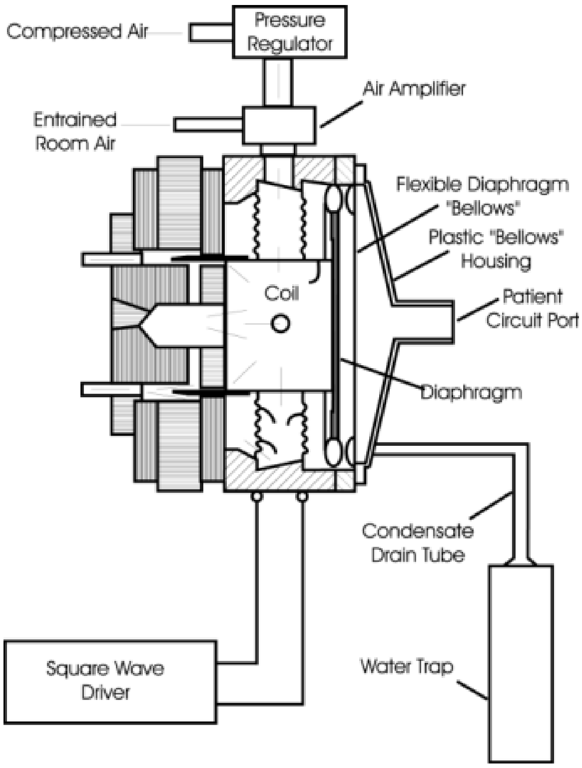

Figure 2.3. Details of Oscillator for SensorMedics 3100A (taken from [9])

2.1.2 Babylog VN500

The second device, which was used in the experiments, is a Babylog VN500. This HFOV was relatively recently introduced to the market. Babylog VN500 has a specific design that combines technical approach used in Babylog 8000 (Venturi multi-valve expiratory system) and a new pulsed inspiratory flow. This flow is arranged based on the frequency and the $\overline{\mathbf{P}_{\mathbf{AW}}}$ (mean airway pressure). Unlike in SensorMedics 3100A and Fabian HFO, the bias flow is set automatically. [7]

Figure 2.4. HFOV Babylog VN500 (taken from [10])

2.1.3 Fabian HFOi

The Fabian HFOi is an electronically, microprocessor controlled ventilator, that provides a wide range of the ventilation modes. It is equipped with integrated air/O_2 blender. Unlike in previous model of the ventilator (Fabian HFO), there is no need in additional tube (T-Piece adaptor) to connect an internal HFO module to the patient circuit. This solution allows usage of the same patient circuit for both CMV and HFOV modes, also more power is being transmitted to the patient in this setting. [11]

Figure 2.5. Fabian HFOi (taken from [11])

As in any HFOV device, during the HFOV mode active inspiration and expiration are created. Fabian HFOi also includes its own flow sensor and presents values on the user interface.

2.2 Experimental set-up

2.2.1 Pressure distribution evaluation

SensorMedics 3100 uses a large speaker to create oscillations, Babylog VN500 has pulsed inspiratory flow controlled by servo valve and expiratory valve oscillation, Fabian HFO creates oscillations with electronically controlled membrane. The way that devices provide oscillations do not affect the experiment. To compare the devices, we needed to choose the points for the measurements. They must correspond for all ventilators regardless their design. All measurements were completed on the patient's circuit and on identical lung models.

On Figures 2.6 and 2.7 are shown a simplified version of the patient circuits for 3100A, VN500 and Fabian HFOi. Mentioned below points A, B, C and D correspond between all three ventilators and the resulting measurements can be compared for those devices based on the proposed nodes.

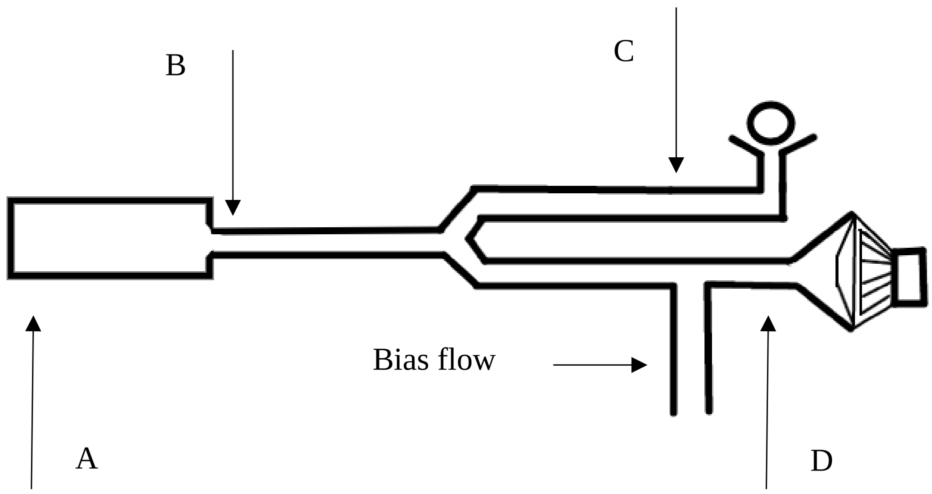

Figure 2.6. Principle scheme of breathing circuit for SensorMedics3100 (inspired by image from [12]); where A is a test lung/patient, B — endotracheal tube, C—expiratory limb, D— inspiratory limb, connected to the oscillator from the right and to the bias flow on the left.

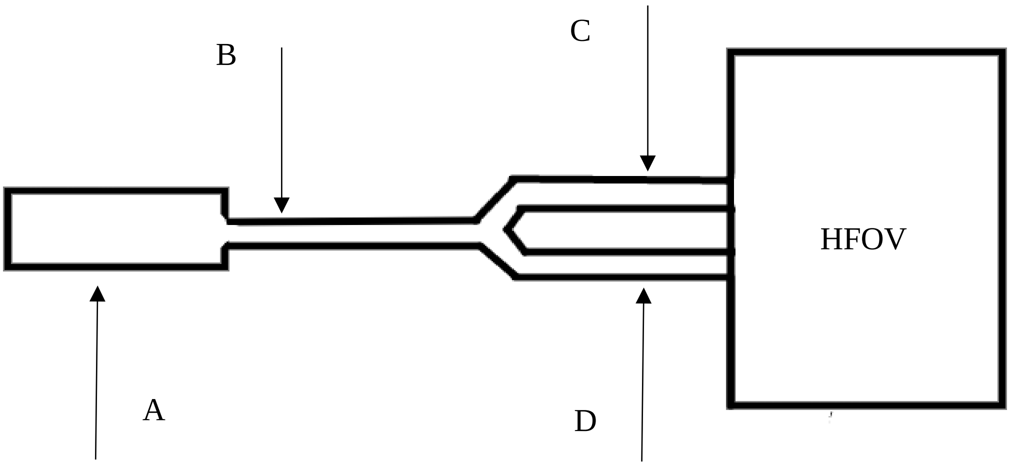

Figure 2.7. Principle scheme of breathing circuit for Babylog VN500 and for Fabian HFOi (inspired by image from [12]); where A is a test lung/patient, B — endotracheal tube, C— expiratory limb, D—inspiratory limb.

A pilot experiment was performed to measure the delivered tidal volume and the resultant pressure within the multi-compartment model of the lungs for healthy newborn (Figure 2.8.). On the Florian was measured the compliance of this model, which equals to 2.1 mL/cmH_2O and the resistance is 144 cmH_2O 144 cmH_2O/l/s.

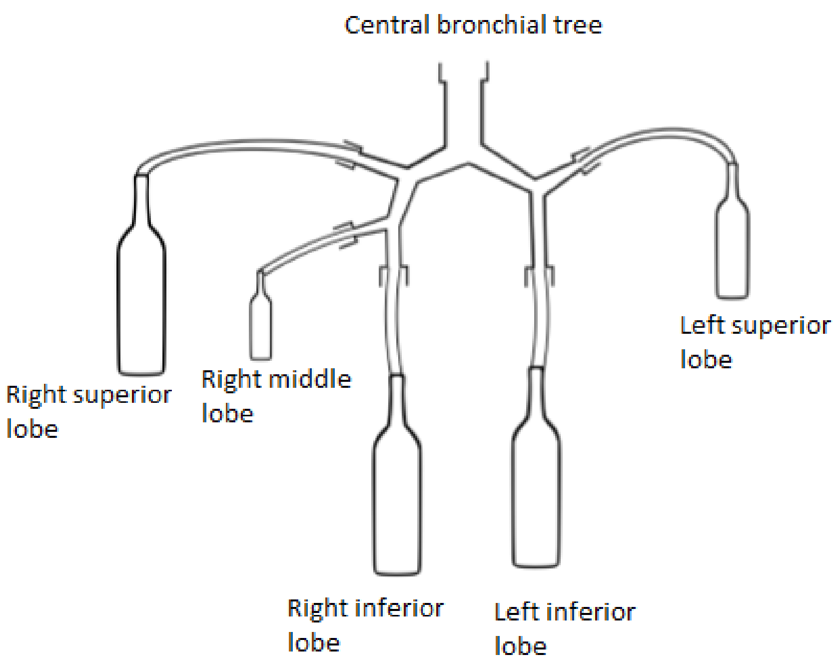

Figure 2.8. Schema of multi-compartment model of the neonatal lungs (taken and changed from [13])

Differently sized bottles and the 3D printed model of the central bronchial three presented the neonatal respiratory system. Connectors (tubes) for the pressure measurements were previously installed to each of the bottles, that represent some lobe of the lungs (Figure 2.8.).

Mentioned tubes were connected probes from the device called “Chobotnice”, which allows continuous real time monitoring and storing of the pressure values to *.txt files. Sampling frequency for Chobotnice is 2000 Hz. For the control of the V_T and MV was used the Florian Neonatal Respiratory Function Monitor (Acutronic Medical Systems AG, Zug, Switzerland).

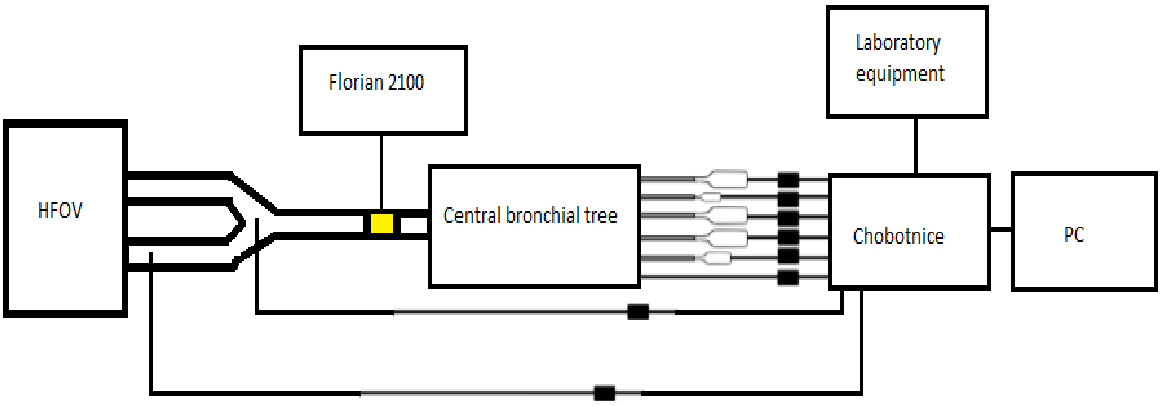

Figure 2.9. Generalized schema of the experiment for evaluation of pressure distribution (taken and changed from [13])

Based on the schema above, the measurements were performed with SensorMedics 3100A and Fabian HFOi. Left most probe, connected to the Chobotnice represents an expiratory part of the patient circuit. Second probe at the “Y” coupler or inspiratory limb (depending on the ventilator’s patient circuit), represents the input pressure to the model. Florian 2100 was connected to the endotracheal tube (ETT), which was followed by central bronchial tree. After that there was a setting of the multi-compartment model of the lungs (Figure 2.8). Each of the lobes was connected to the individual probe from Chobotinice. This device is running with the support of the laboratory equipment, such as voltage and current source. The measured data from Chobotnice was saved to the computer with aid of LabView. Complete overview of the connection can be found in the Table 2.1.

Table 2.1. Connections of the patient circuit nodes and lungs model to the Chobotnice's probes

Number of the probe	Patient circuit or lungs model element
1	Expiratory limb (point C on Figure 2.6, 2.7)
2	Inspiratory limb or "Y" coupler (point D on Figure 2.6, 2.7)
3	Left superior lobe of the lungs
4	Left inferior lobe of the lungs
5	Right superior lobe of the lungs
6	Right middle lobe of the lungs
7	Right inferior lobe of the lungs

On all ventilators were set same default values, that are mentioned in the Table 2.2. For some parameters, there were assigned several values, which means that the measurements were conducted for all possible combinations. Those values were chosen as some of the most frequently used. Maximum amplitude was introduced to allow evaluation of truly available amplitude range in combination with other parameters at the same time.

Table 2.2. Default values for the measurement of the pressure distribution

Parameter	Values	Units
Bias flow	10, 20	L/min
Amplitude (ΔP)	30,45,60, maximum available value	cmH_2O
Inspiratory time (I:E)	33 (1:2)	% (-)
Frequency (RR)	5,10,15	Hz
MAP	15	cmH_2O

2.2.2 CO_2 elimination

Due to the turbulent gas exchange and absence of the expiratory plateau for the evaluation of the carbon dioxide at the end of the expiratory phase, it is impossible to measure exhaled CO_2 during the HFOV. However, the efficiency of CO_2 elimination may be also verified by the following experiment (Figure 2.10).

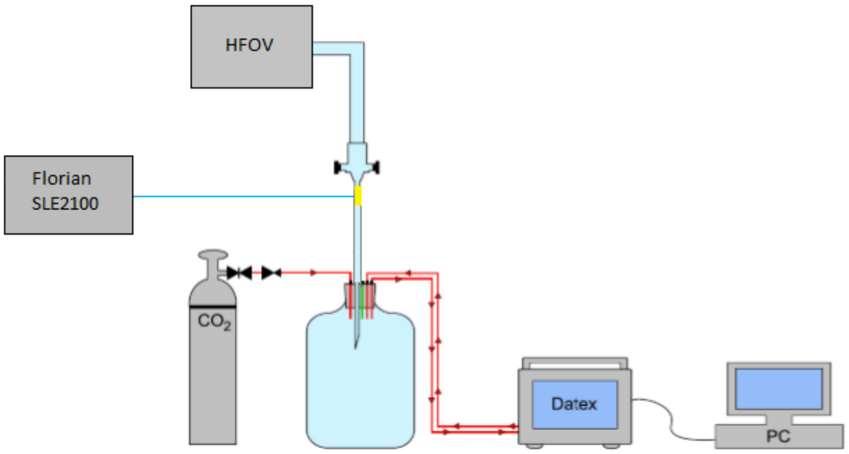

Figure 2.10. Setup of the CO_2 elimination experiment using high frequency oscillatory ventilation. (taken and changed from [14])

The test lung was continuously supplied with constant dose of the CO_2; the patient model was connected to the Datex (General Electrics Healthcare, USA), which provides automatic analyzing of the CO_2 concentration. In current examination was used single compartment model of neonatal respiratory system, since Datex has one input and one output for sampling of gas and returning it to the model. Florian 2100 monitor was connected to the patient's circuit for the measurement of the gas flow, tidal volume and minute ventilation. (Figure 2.10).

At the beginning of each measurement, pressure regulating valve on CO_2 cylinder was open to allow the flow of the gas 0.1 L/min until it saturated and would remain at constant value of the maximum concentration. After that the valve would be closed to ensure the complete reduction of the CO_2 from the test lung. The change in carbon dioxide concentration was recorded by Datex and was analyzed at the next stage of the project.

Ventilators were set to the bias flow of 10 and 15 L/min; frequencies 5,10,15 Hz; amplitude 30, 45 cm H_2O. Those settings were common for all devices. The only exception was Babylog VN500, that doesn't allow to preset the values of bias flow. This parameter was noted for each other combination of initial conditions.

In the measurements for the Babylog VN500 were used to type of patient circuits: HFV Babylog circuit from Dräger and CV circuit - RT 125 Fisher&Paykel (New Zealand). That was done to evaluate, if the usage of the tubes for the conventional ventilation instead of specified one would affect the elimination of the CO_2. Often in clinical practice medical staff keep using the CV circuit, while switching to the HFOV mode to save the time.

2.3 Methods for data analysis

Data from two parts of the experiment was saved automatically to the *.txt files. The files were cleared from the unnecessary values: for the pressure distribution files, it was first column and headers; for CO_2 elimination first two rows. The information was transferred to Excel files with the identical file names and loaded to the Matlab (The Mathworks, Nattick, USA). Codes for the data processing are in the Appendices A and B. Since "Chobotnice" has sampling frequency 2000 Hz and the Datex has 25 Hz, the following formula was used to derive the time scale:

$$t = \frac{N}{f_s}\,, \tag{2.1}$$

where t is time in seconds,

N— number of samples,

f_s— sampling frequency in Hz.

Appendix A also contains supplementary functions, that allow to choose the time frame for the analysis of pressure distribution, create visualization for the selected period, calculate the maximum, minimum and average for the selected time frame as well as percentage of the delivered pressure. As there were used seven probes for the pressure distribution measurement the resultant values are stored in seven rows for the extremes and mean values, followed by the same number of rows with percentage ratios. Top rows are identical to the first probe's values, and the last rows are identical to the values from the seventh probe, respectively.

The percentages were calculated in the following manner: as it MAP was constant for the all experiment and it was equal to 15 cmH_2O, the variable, directly affecting the pressure was ΔP (Pressure amplitude). From that was concluded the maximum possible pressure delivered to the lung model can be evaluated with by the equation (2.2).

$$\max(\text{P delived}) = \text{MAP} + \frac{\Delta \text{P}}{2}, \tag{2.2}$$

Mean values of the delivered pressure are equal to MAP and lowest possible pressure values can be calculated by the next formula:

$$\min(\text{P delived}) = \text{MAP} - \frac{\Delta\text{P}}{2}, \tag{2.3}$$

To obtain percentages of delivered pressure relatively to the input values, previously calculated extremes values of the signal were divided by the results from the formulas 2.2 and 2.3, while mean values were divided by MAP.

Data measured by Datex was also loaded to the Matlab and with aid of curve fitting tool the time constants for the increasing and decreasing parts of the graphs were established. Since the process is similar to charging and discharging of the capacitor, analogous formula was used.

Increase in CO_2 concentration can be expressed as:

$$\text{c}(CO_2) = c_f(1 - e^{-\frac{t}{\tau}}), \tag{2.4}$$

where $\text{c}(CO_2)$— immediate concentration of the carbon dioxide,

c_f— parameter, that describes maximum achieved concentration of the gas,

τ— time constant.

Decrease in CO_2 concentration was evaluated with the next formula:

$$\text{c}(CO_2) = c_f(e^{-\frac{t}{\tau}}), \tag{2.5}$$

Matlab Curve Fitting was used to estimate the c_f and τ; as custom equations for estimation were used formulas 2.4 and 2.5.

3 Results

Results contain tables, graphs and bar charts with examples of final values.

Waveforms of pressure oscillation around the MAP value for SensorMedics 3100A and Babylog VN500 represented on Figures 3.1 and 3.2. Settings on both devices for those graphs were ΔP 30 cmH_2O, frequency 5 Hz, bias flow 10 L/min.

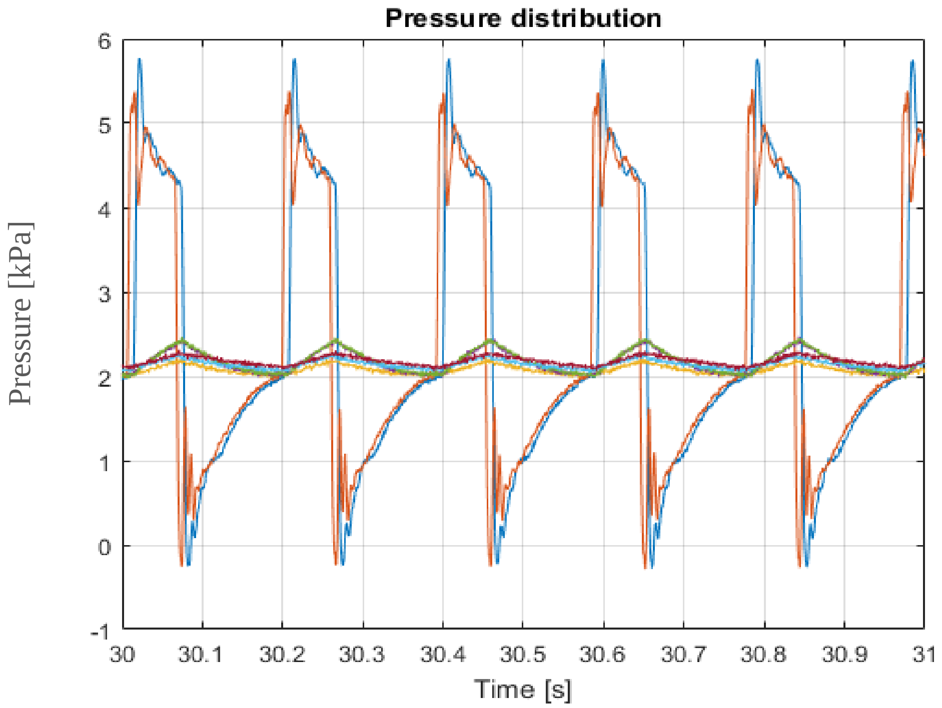

Figure 3.1. Waveforms of pressure distribution in different parts of the patient circuit for SensorMedics 3100A

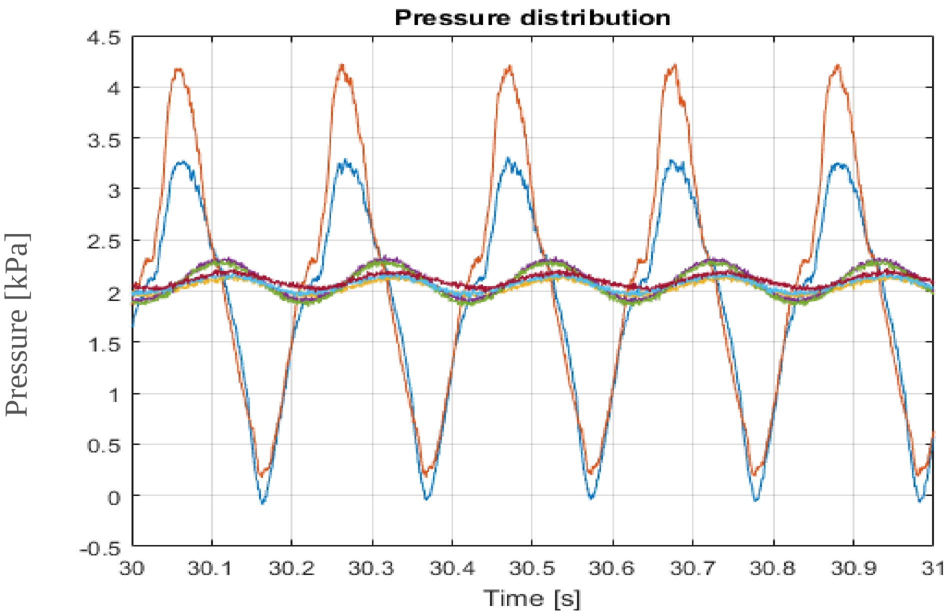

Figure 3.2. Waveforms of pressure distribution in different parts of the patient circuit for Fabian HFOi.

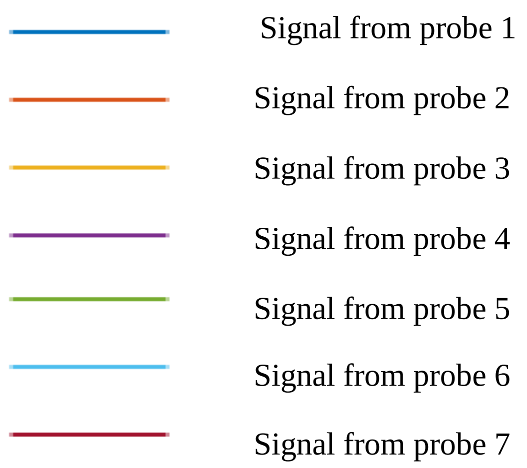

Figure 3.3. Color coding for the signals on Chobotnice from different probes. Detailed information on the meaning of the probe numbers presented in Table 2.1.

In the following tables (3.1-3.4) shown the results for measurements of tidal volume and minute ventilation during the pressure distribution evaluation on the multi compartment model. Column "Files with saved data" contains the file names, to which the data from Chobotnice was saved. Same name used for the Excel files with those values.

Table 3.1. Values of tidal volume and minute ventilation measured by Florian 2100 in front of ETT on SensorMedics 3100A for bias flow 10 L/min.

SensorMedics 3100A tidal volume and minute ventilation in multi comartment model for bias flow 10L/min					
Initial settings			Measured values		
Bias flow	f (Hz)	ΔP (cmH2O)	V_T (mL)	MV (L)	Files with saved data
10	5	30	9.60	3.05	29_04_2017_105809
		45	12.90	4.01	29_04_2017_110417
		60	16.00	4.94	29_04_2017_110559
		70	17.60	5.49	29_04_2017_110840
	10	30	4.80	2.92	29_04_2017_111318
		45	4.01	6.80	29_04_2017_111757
		57	8.10	4.76	29_04_2017_112555
	15	30	2.80	2.47	29_04_2017_113003
		45	4.00	3.50	29_04_2017_113327
		53	4.50	3.91	29_04_2017_113712

Table 3.2. Values of tidal volume and minute ventilation measured by Florian 2100 in front of ETT on SensorMedics 3100A for bias flow 15 L/min.

SensorMedics 3100A tidal volume and minute ventilation in multi comartment model for bias flow 15L/min					
Initial settings			Measured values		
Bias flow	f (Hz)	ΔP (cmH2O)	V_T (mL)	MV (L)	Files with saved data
15	5	30	8.80	2.76	29_04_2017_114252
		45	11.70	3.65	29_04_2017_114527
		60	14.70	4.60	29_04_2017_114731
		70	17.10	5.36	29_04_2017_115039
	10	30	4.60	2.79	29_04_2017_115322
		45	6.30	3.81	29_04_2017_115539
		57	7.80	4.62	29_04_2017_115915
	15	30	2.70	2.36	29_04_2017_120244
		45	3.90	3.42	29_04_2017_120451
		51	4.60	3.85	29_04_2017_120957

Table 3.3. Values of tidal volume and minute ventilation measured by Florian 2100 in front of ETT on Fabian HFOi for bias flow 10 L/min.

Fabian HFOi tidal volume and minute ventilation in multi comartment model for bias flow 10L/min					
Initial settings			Measured values		
Bias flow	f (Hz)	ΔP (cmH2O)	V_T (mL)	MV (L)	Files with saved data
10	5	30	7.80	2.30	11_04_2017_133104
		45	10.90	3.18	11_04_2017_133258
		60	13.70	4.04	11_04_2017_133443
		80	17.00	5.00	11_04_2017_134006
	10	30	3.50	2.10	11_04_2017_135448
		45	4.50	2.89	11_04_2017_135311
		60	5.90	3.48	11_04_2017_135140
		80	7.10	4.19	11_04_2017_134916
	15	30	2.00	1.78	11_04_2017_135626
		45	2.70	2.41	11_04_2017_135803
		60	3.50	3.12	11_04_2017_135940
		80	4.20	3.82	11_04_2017_140109

Table 3.4. Values of tidal volume and minute ventilation measured by Florian 2100 in front of ETT on Fabian HFOi for bias flow 15 L/min.

Fabian HFOi tidal volume and minute ventilation in multi comartment model for bias flow 15L/min					
Initial settings			Measured values		
Bias flow	f (Hz)	ΔP (cmH2O)	V_T (mL)	MV (L)	Files with saved data
15	5	30	8.40	2.47	11_04_2017_142056
		45	10.70	3.15	11_04_2017_141929
		60	13.50	3.94	11_04_2017_141753
		80	16.40	4.81	11_04_2017_141612
	10	30	3.30	2.00	11_04_2017_140923
		45	5.10	3.00	11_04_2017_141108
		60	6.30	3.73	11_04_2017_141244
		80	7.40	4.36	11_04_2017_141437
	15	30	2.00	1.80	11_04_2017_140747
		45	2.90	2.60	11_04_2017_140612
		60	3.50	3.20	11_04_2017_140429
		80	4.40	3.91	11_04_2017_140251

Pressure distribution in the graphs below represents the maximum, minimum and mean values for the selected period of signal. The preset values for those measurements where bias flow 10 L/min, frequency 5 Hz, pressure amplitudes 30, 45,60 cmH_2O.

It is an example of the pattern, that have been notices in the experiment. On the x-axis is numbering of the probes, for which the experiment was completed and the y-axis represents the pressure in kPa.

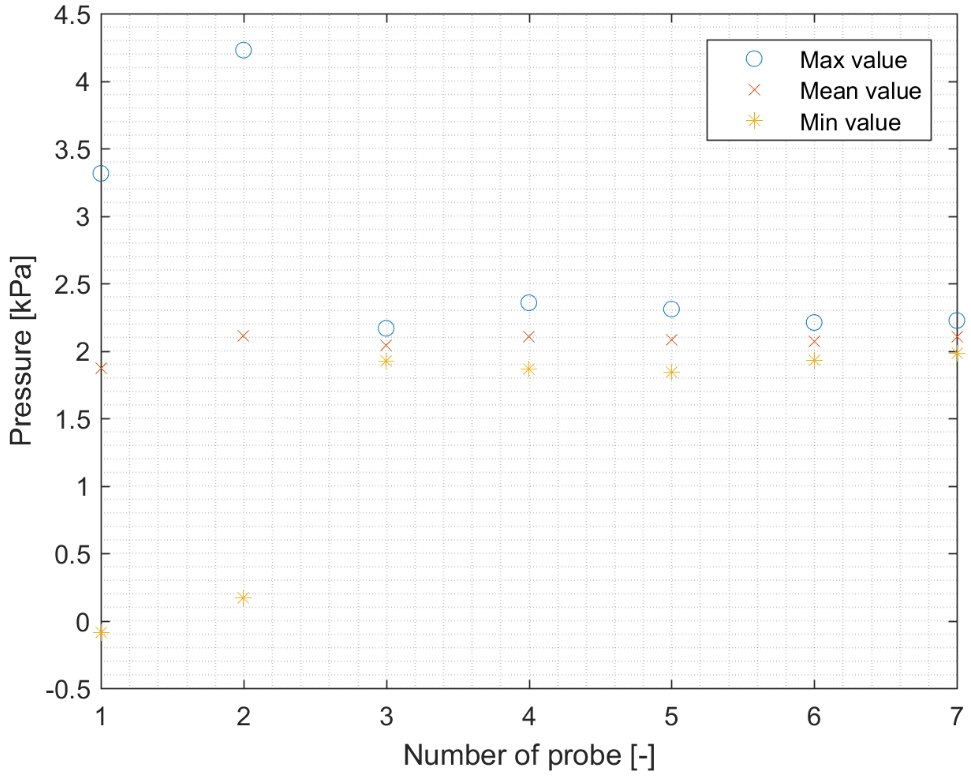

Figure 3.4. Pressure values within the probes for Fabian HFOi with the setting of bias flow 10 L/min, frequency 5Hz and ΔP 30 cmH_2O

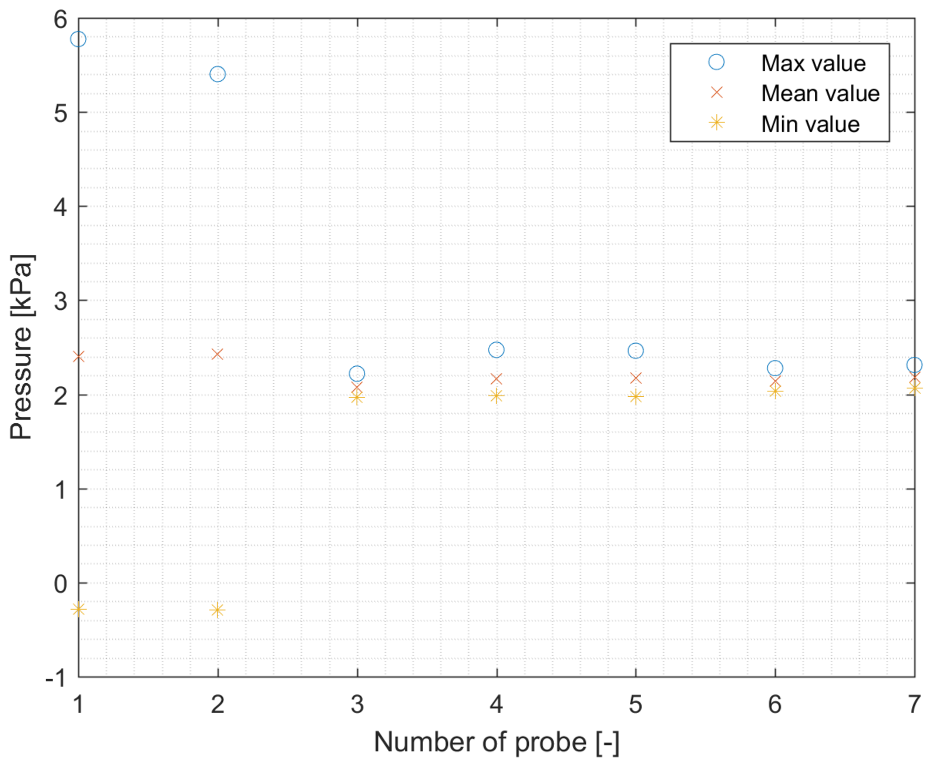

Figure 3.5. Pressure values within the probes for SensorMedics 3100A with the setting of bias flow 10 L/min, frequency 5Hz and ΔP 30 cmH_2O

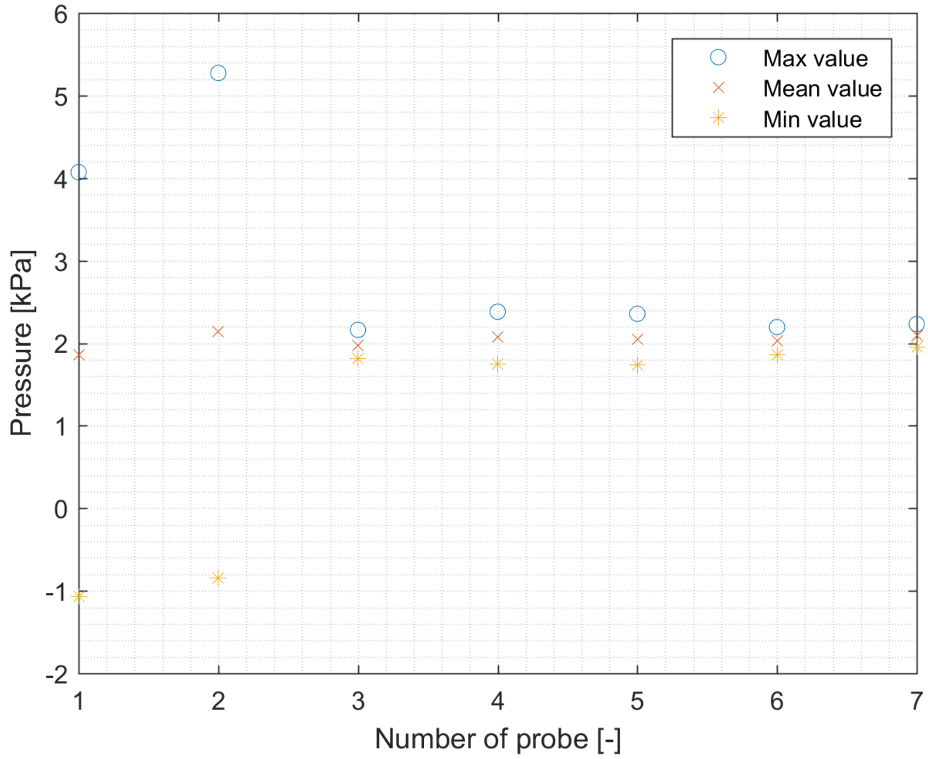

Figure 3.6. Pressure values within the probes for Fabian HFOi with the setting of bias flow 10 L/min, frequency 5Hz and ΔP 45 cmH_2O

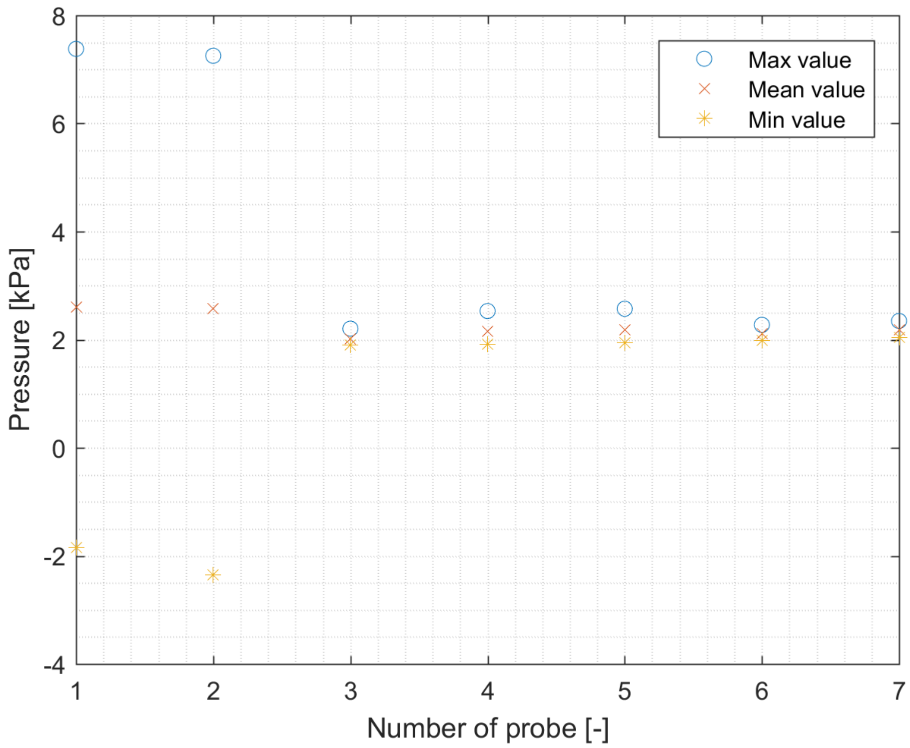

Figure 3.7. Pressure values within the probes for SensorMedics 3100A with the bias flow 10 L/min, frequency 5Hz and ΔP 45 cmH_2O

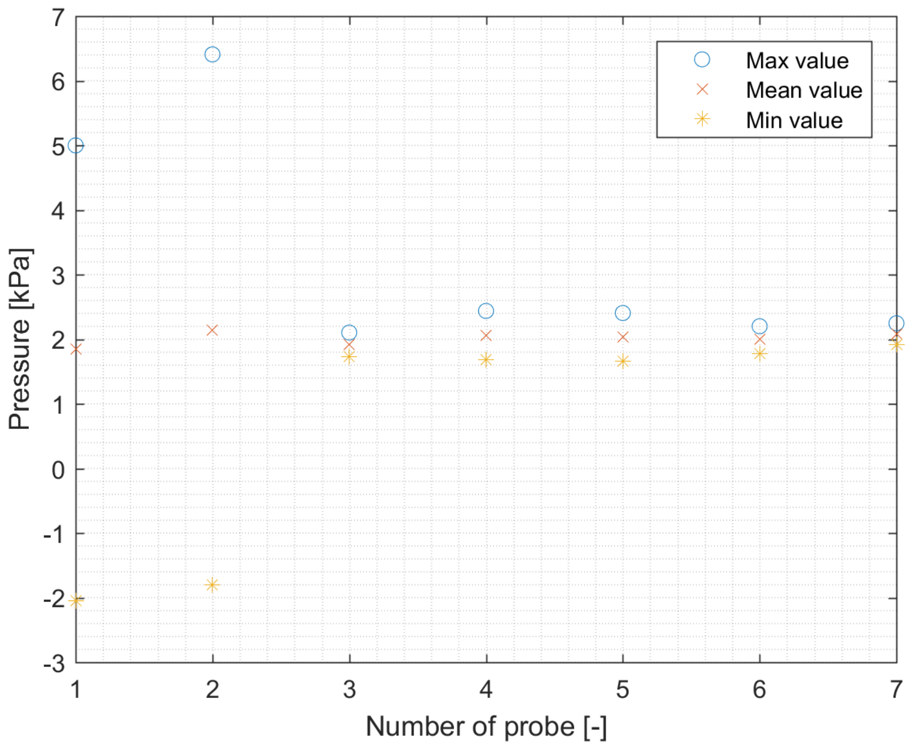

Figure 3.8. Pressure values within the probes for Fabian HFOi with the setting of bias flow 10 L/min, frequency 5Hz and ΔP 60 cmH_2O

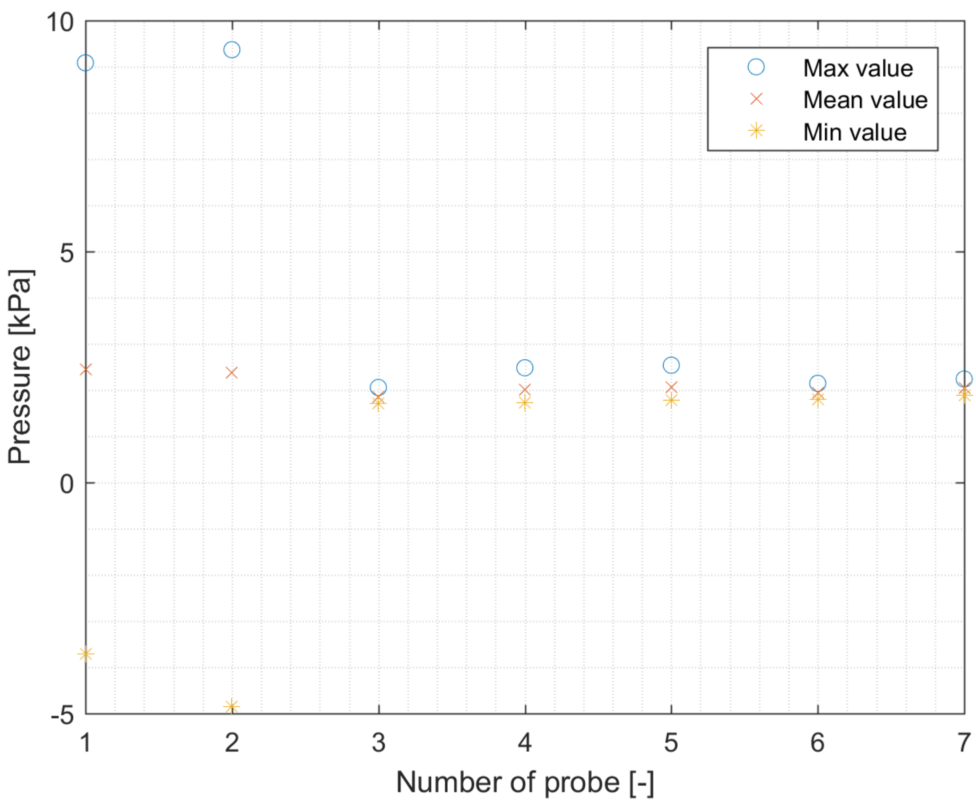

Figure 3.9. Pressure values within the probes for SensorMedics 3100A with the bias flow 10 L/min, frequency 5Hz and ΔP 60 cmH_2O

In the following part, there are presented the results for the evaluation of CO_2 elimination. The graph present visualizations for the time constants on different devices and they are based on the tables presented in Appendix C. On the bar charts as a y-axis represented time constants in seconds; x-axis represents groups of frequencies (Hz) and pressure amplitudes (cmH_2O), that were preset on the ventilator. Tables show the initial settings and maximum values of CO_2 recorded on Datex (in %), as well as tidal volume (mL) and minute ventilation (L), obtained from the Florian 2100.

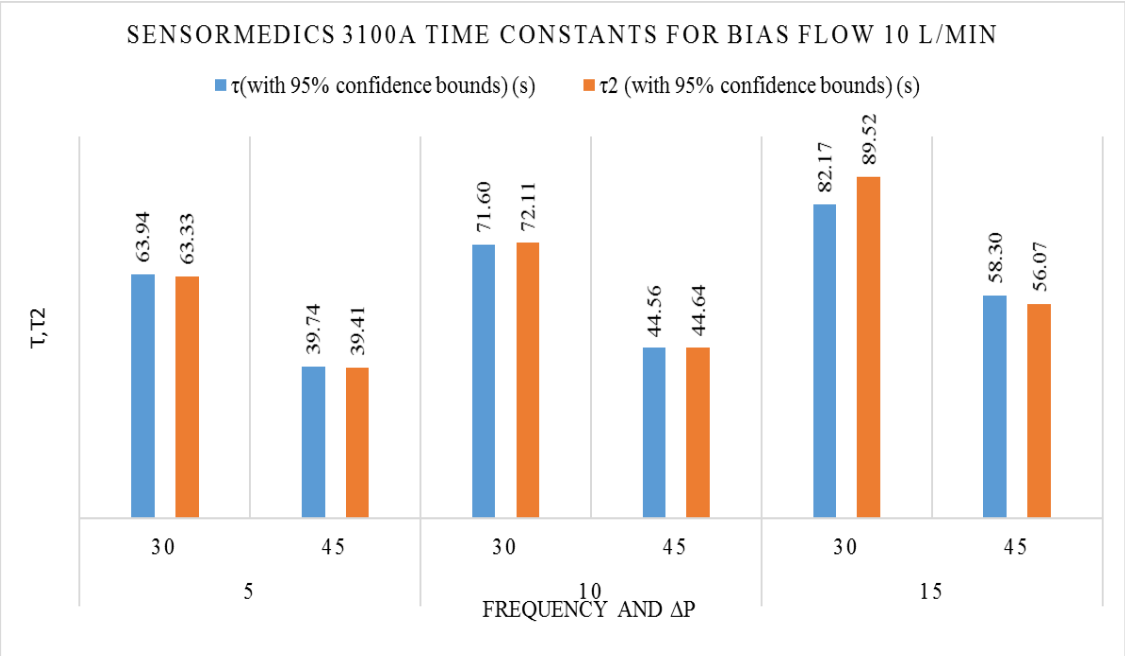

Figure 3.10 Time constants for SensorMedics 3100A with bias flow 10L/min

Table 3.5. Values of tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on SensorMedics 3100A for bias flow 10 L/min

SensorMedics 3100A					
Initial settings			Measured values		
Bias Flow	Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO_2 (%)	V_T (mL)	MV (L)
10	5	30	49	10.50	3.30
		45	33	14.20	4.39
	10	30	51	6.20	3.70
		45	37	8.50	5.02
	15	30	51	4.00	3.41
		45	44	5.30	4.60

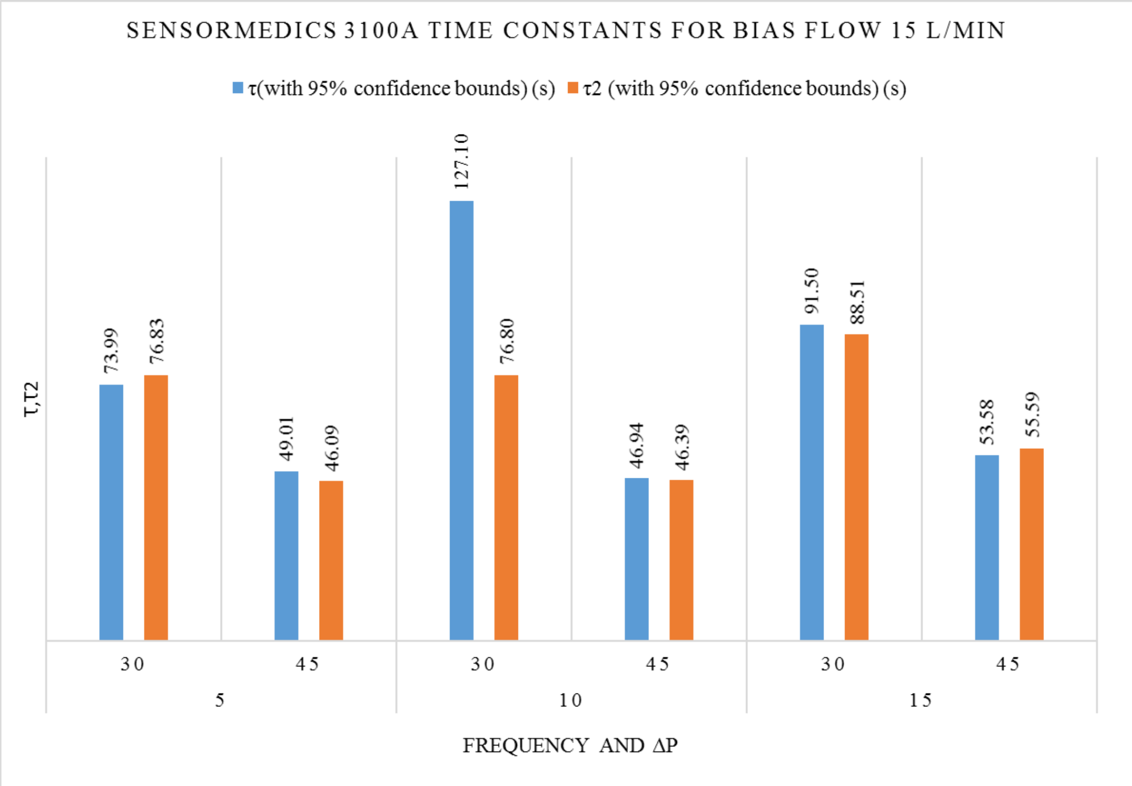

Figure 3.11 Time constants for SensorMedics 3100A with bias flow 15L/min

Table 3.6 Values of tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on SensorMedics 3100A for bias flow 15 L/min

SensorMedics 3100A					
Initial settings			Measured values		
Bias Flow	Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO2	V_T (mL)	MV (L)
15	5	30	50	9.50	3.03
		45	37	13.00	4.07
	10	30	51	6.10	3.55
		45	37	8.10	4.72
	15	30	50	3.80	3.44
		45	45	5.20	4.50

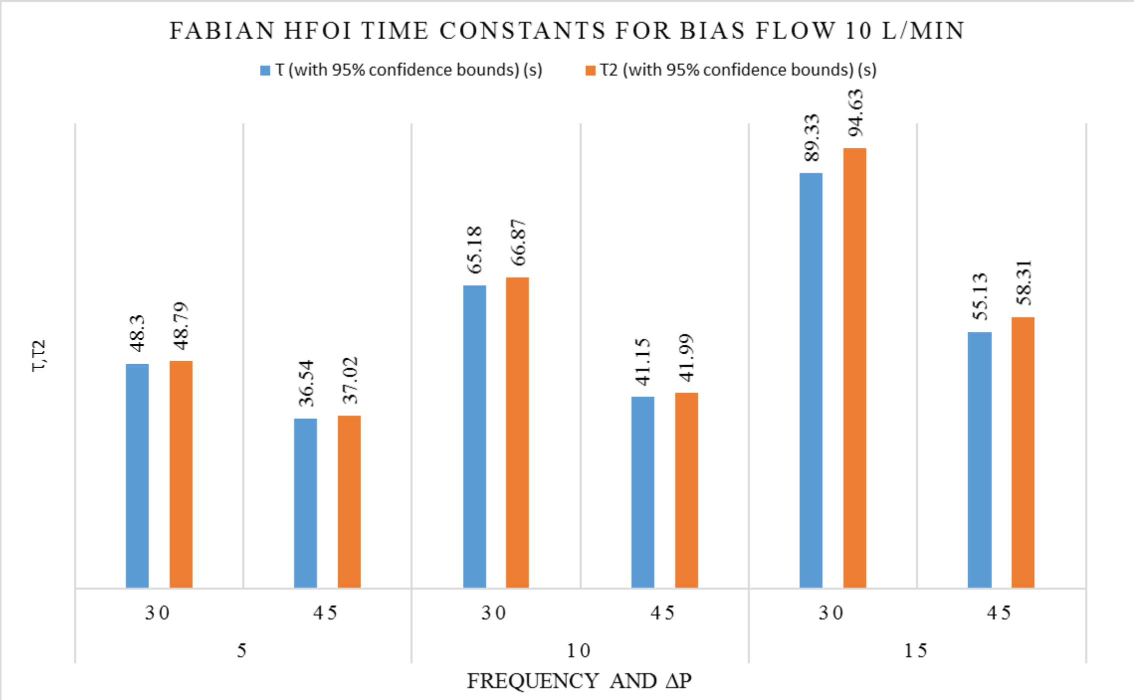

Figure 3.12 Time constants for Fabian HFOi with bias flow 10L/min

Table 3.7. Values of tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on Fabian HFOi for bias flow 10 L/min

Fabian HFOi					
	Initial settings		Measured values		
Bias Flow	Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO2	V_T (mL)	MV (L)
10	5	30	39	10.30	3.03
		45	30	13.60	3.96
	10	30	51	4.50	2.71
		45	32	6.30	3.73
	15	30	55	3.00	2.74
		45	43	3.90	3.56

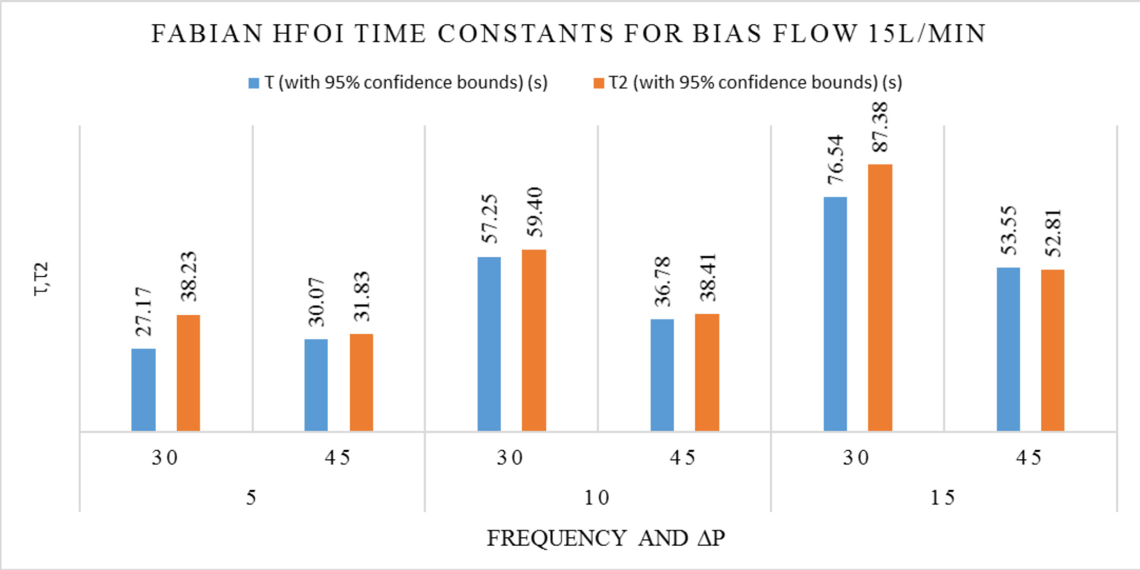

Figure 3.13. Time constants for Fabian HFOi with bias flow 15L/min

<u>Table 3.8. Values of tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on Fabian HFOi for bias flow 15 L/min</u>

Fabian HFOi					
Initial settings			Measured values		
Bias Flow	Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO2	V_T (mL)	MV (L)
15	5	30	30	10.7	3.14
		45	25	13.7	4.01
	10	30	47	4.6	2.73
		45	31	6.4	3.82
	15	30	55	3.1	2.75
		45	41	4.1	3.66

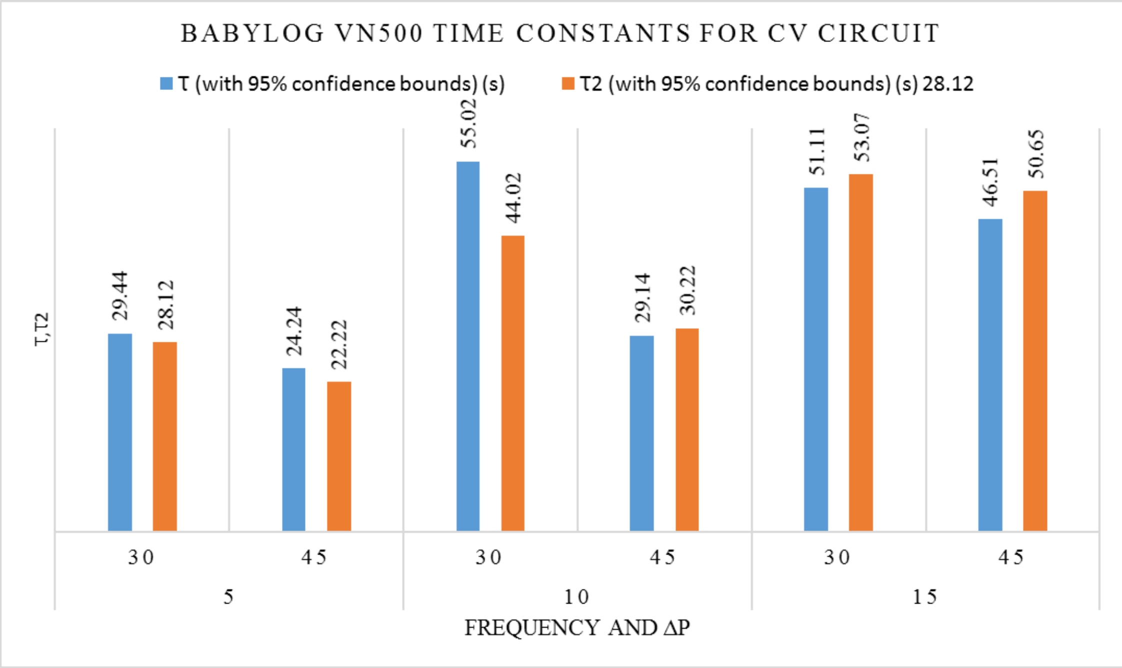

Figure 3.14 Time constants for Babylog VN500 with CV patient circuit

Table 3.9. Values of bias flow, tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on Babylog with the CV circuit

Babylog VN500 standard CV circuit					
Initial settings		Measured values			
Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO_2 (%)	Bias flow (L/min)	V_T (mL)	MV (L)
5	30	26	25	9.66	2.9
	45	20	25	12.50	3.74
10	30	38	22.8	4.96	2.98
	45	27	18.6	6.12	3.67
15	30	43	18.5	3.27	2.95
	45	43	19.3	3.31	2.98

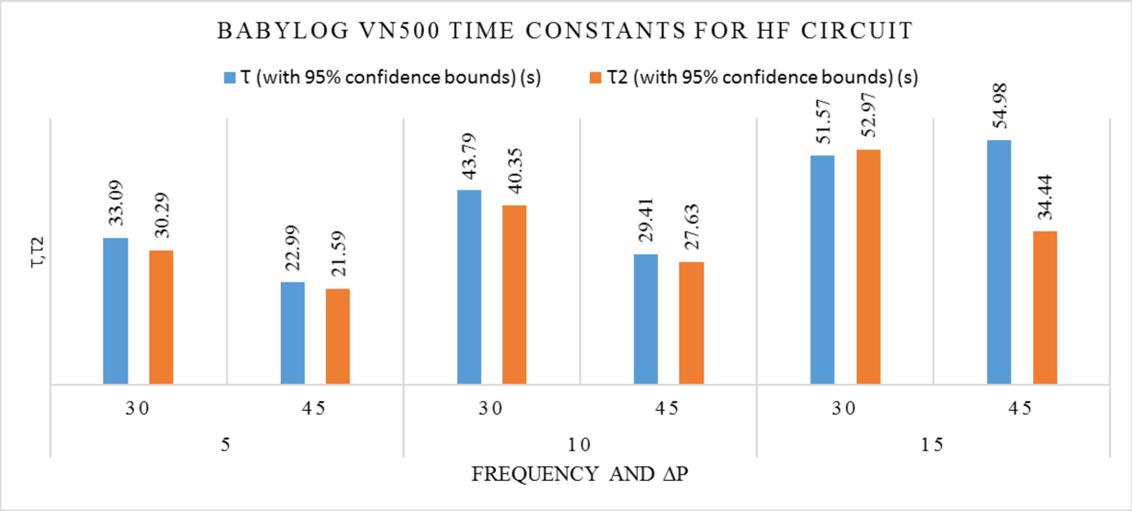

Figure 3.15 Time constants for Babylog VN500 with HF patient circuit

<u>Table 3.10. Values of bias flow, tidal volume, minute ventilation, and values of CO_2 saturation measured with Datex on Babylog with the CV circuit</u>

Babylog VN500 HF circuit					
Initial settings		Measured values			
Frequency (Hz)	ΔP (cmH2O)	Maximum value of CO_2 (%)	Bias flow (L/min)	V_T (mL)	MV (L)
5	30	25	25	8.66	2.6
	45	18	25	11.1	3.33
10	30	34	24.9	4.60	2.8
	45	24	25	6.00	3.6
15	30	41	24.4	3.11	2.8
	45	30	22.2	3.88	3.5

4 Discussion

The result of this project was a design of the experiment for comparison of multiple high-frequency oscillatory ventilators. As a part of the current project were completed the measurements of pressure within the multi compartment lung model, tidal volume and elimination of CO_2 on the available devices. For the evaluation of the gas withdrawal from the single compartment model were used of the ventilators: SensorMedics 3100A, Fabian HFOi and Babylog VN500. However, for the measurement of the pressure distribution there the device from Dräger company was not available due to the constant use in the clinic for the neonates in critical state. Nevertheless, enough data was collected from the 3100A and Fabian HFOi to compare two devices the use completely different ways for creation of oscillations.

For all measurements was used Florian 2100 to monitor the leakage flow and present the values of minute ventilation and tidal volume. Leakage flow was not obtained in any of the measurements.

External monitor was used for independent evaluation: SensorMedics 3100A doesn't provide V_T monitoring, while Fabian HFOi as well as Babylog VN500 do. As function of the ventilator, this measurement with build-in hot-wire anemometer might have been affected by the internal environment of the device. The tidal volume and frequency have been proven to be in linear dependency during the whole experiment. Parameters such as V_T, MV were not significantly different for different bias flows. Also between the both devices there was proven to be close correlation. The only limitation for this measurement was that on the SensorMedics 3100A it was not possible to set the amplitude of 60 cmH_2O or higher for the frequencies 10 and 15 Hz, with bias flow both 10 and 15 L/min. This is explained by the fact, that with those settings there were limitations with the controlling wheels. Also for lower amplitudes there have been found a problem: too low pressure for the device to run, so the SensorMedics would turn off the oscillations. For the Fabian HFOi this problem has not appeared and the maximum available amplitude was 80 cmH_2O (Tables 3.1-3.4)

Besides the maximum available pressure amplitude, the waveforms of the pressure waves were significantly different between the devices. While the pressure waves form the SensorMedics 3100A were with the sharp peaks and rapid change in height at the very top and bottom (Figure 3.1), the waveforms for the Fabian HFOi

(Figure 3.2) are smooth. Nevertheless, the pressure waves for the lung model are practically identical for both devices.

The distribution of the maximum, mean and minimum pressure values were represented on the Figures 3.4-3.9. It represents the values for the bias flow 10L/min, frequency 5 Hz and the pressure amplitudes of 30,45 and 60 cmH_2O. The mean pressure for all probes remained in the same range around 2kPa (with preset MAP of 1.5kPa), while the maximum and minimum values significantly varied for the same settings on both ventilators. SensorMedics 3100A had proven to provide higher pressure values, in comparison with Fabin HFOi. This has been evidenced for all measurements where the settings were comparable.

Obtained negative pressure is explained by the suctioning of the air, which presents as a part of the active expiration.

Calculated mean pressure was different form the settings of CDP, and this diversity in applied and calculated values is explained by the possible distortion of the patient circuit during the measurements and error of measurement, as well as the usage of analog-to-digital converter within the Chobotnice might slightly affect the results.

Elimination of CO_2 was evaluated with the time constants. That means, that for increasing parts of the graphs, when the greater the time constant—the slower comes the saturation of the carbon dioxide. So, the elimination is effective at that stage. Moreover, the τ_2 for the decreasing part of graph was also considered. The smaller this value is, the faster the ventilator withdraws the CO_2 from the model. One of the most effective devices in is Babylog VN500 (Tables 3.9-3.10; Figures 3.14-3.15). It is important to mention, that the CV circuit had worse carbon dioxide elimination. As for the SensorMedics 3100A it is crucial to control the piston position at the central positon, as shift to any side can cause change in CO_2 elimination [15].

5 Conclusion

Designed experiment, that is described in this project, can be used for comparison of HFOV with same initial conditions. Performed measurements prove, that this setup can be applied for different devices, since it is based on similarities patient circuit among all high frequency oscillatory ventilators. Efficiency of CO_2 elimination can be evaluated by the presented approach. The newer devices tend to present lower values of the delivered pressure in comparison with older SensorMedics 3100A, elimination of carbon dioxide was the most effective in Babylog VN500 and for some settings in the SensorMedics 3100A. Fabian HFOi allows a wide range of settings, independent form each other, while the values on SensorMedics 3100A are interconnected and the Babylog VN500 automatically presets the values.

In the future studies, it is possible to add the pressure distribution evaluation for the Babylog VN500. Also, taking into consideration its way of estimation the bias flow, and checking those settings on the other devices, will provide more sophisticated data. Moreover, adding automatization as a next step of data processing would increase the speed of data analysis as well as minimize the risk of the mistakes, while working with data.

Performed experiments allows to conclude that the newer devices have rather different outcomes from the older once. Controlling of several parameters should allow to increase the safety for the patients. For the medical staff, it is important to be aware of the fact, that type of used patient circuit affects the CO_2 elimination, for some specific combinations on SensorMedics 3100A it is valuable to control the pressure level to avoid the switching off the machine, and to count with the smaller delivered in the newer devices.

References

[1] BOHN, D. *The history of high-frequency ventilation.* Respiratory Care Clinics of North America. 2001. Vol. 7, no. 4, p. 535-548. DOI 10.1016/s1078-5337(05)70005-8. Elsevier BV. Available at: https://www.ncbi.nlm.nih.gov/pubmed/11926755

[2] COOLS F.— HENDERSON-SMART DJ.— OFFRINGA M.—ASKIE LM. *Elective high frequency oscillatory ventilation versus conventional ventilation for acute pulmonary dysfunction in preterm infants*. Cochrane Database Syst Rev, 2009; (3):CD000104.

[3] COOLS F.—ASKIE LM. — OFFRINGA M. — ASSELIN JM. —CALVERT SA. — COURTNEY SE, et al., *Elective high-frequency oscillatory versus conventional ventilation in preterm infants: a systematic review and meta-analysis of individual patients' data.* The Lancet. 2010. Vol. 375, no. 9731, p. 2082-2091. DOI 10.1016/s0140-6736(10)60278-4. Elsevier BV

[4] CLARK, R. H.—NULL, D. M.—GERSTMANN, D. R.— DELEMOS, R.A. *Prospective Randomized Comparison of High-Frequency Oscillatory and Conventional Ventilation in Respiratory Distress Syndrome.*Pediatrics, American Academy of Pediatrics, 1992, 89 (1), 5-12

[5] BOUCHUT, JEAN-CHRISTOPHE. —GODARD, J.— CLARIS, O. *High-frequency Oscillatory Ventilation.* Anesthesiology [online], 2004. Vol. 100, no. 4, pp. 1007–1012. Retrieved z: doi:10.1097/00000542-200404000-0035. Available at: http://anesthesiology.pubs.asahq.org/article.aspx?articleid=1943214

[6] High Frequency Oscillatory Ventilation (HFOV). *Newborn Services Clinical Guideline* [online]. 2010 [cit. 2017-01-29]. Available at: http://www.adhb.govt.nz/newborn/Guidelines/Respiratory/HFOV/HFOV.htm

[7] GRAZIOLI, S.—KARAM, O.—RIMENSBERGER, P. C. *New Generation Neonatal High Frequency Ventilators: Effect of Oscillatory Frequency and Working Principles on Performance*. Respiratory Care. 2014. Vol. 60, no. 3, p. 363-370. DOI 10.4187/respcare.03048. Daedalus Enterprises

[8] VENTILATORS PLUS. *Image of SensorMedics 3100A* [online]. Available at: http://www.ventilatorsplus.com/3100_A.jpg

[9] CAREFUSION.*3100A® High frequency oscillatory ventilator Operator's manual* [online].2010.Available at: http://www.carefusion.com/documents/guides/user-guides/RC_3100A-HFOV_UG_EN.pdf

[10] CITY ELECTRO-MEDICS CO: *Image of Dräger Babylog VN500* [online]. Available at: http://www.cemcbd.com/admin-cemc/img/20140301033859.jpg

[11] *Fabian HFOi Our 4-in-1 device* [online]. Acutronic. Available at : https://www.acutronic-medical.ch/products/fabian-hfoi.html

[12] MUDERS, F. — PFEIFER,M. — MÜLLER,T. *Metodik und Anwendung der Hochfrequenzoszillationventilation (HFOV) bei akuter Lungenschädigung und ARDS.* Intensivmedizin und Notfallmedizin. 2003. Vol. 40, no. 6, p 515-522.DOI 10.1007/s00390-003-0365-4. Springer Nature

[13] STRÁNSKÁ, Anežka. *Studium distribuce tlakových amplitud v respiračním systému při HFJV*. Kladno, 2015. Diplomová práce. ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE. Vedoucí práce Ing. Petr Kudrna.

[14] HŘIBALOVÁ, B.— KUDRNA, P. *The effect of orifice plate used as flow meter on elimination of carbon dioxide in high frequency ventilation*. 2015.

[15] HAMEL, Donna S, Andrew L KATZ, Damian M CRAIG, John D DAVIES a Ira M CHEIFETZ. *Carbon Dioxide Elimination and Gas Displacement Vary With Piston Position During High-Frequency Oscillatory Ventilation.* Respiratory Care [online]. 2005. Available at: http://rc.rcjournal.com/content/50/3/361.short

[16] VAN HEERDE, M.— VAN GENDERINGEN,H.— LEENHOVEN, T.— ROUBIK, K.— PLÖTZ, F.— MARKHORST, D. *Imposed work of breathing during high-frequency oscillatory ventilation: a bench study.* Critical Care [online]. 2006. Vol. 10, no. 1, p. R23. DOI 10.1186/cc3988. Available at: http://ccforum.biomedcentral.com/articles/10.1186/cc3988 Springer Nature

[17] General Electric Company. *Datex-Ohmeda S/5TM Compact Anesthesia Monitor S/5TM Compact Critical Care Monitor: Technical Reference Manual* [online]. Available at: http://www.frankshospitalworkshop.com/equipment/documents/ecg/service_manuals/Datex-Ohmeda_S-5_Anaesthetic_Monitor_-_Technical_reference_manual_(2006).pdf

[18] SLE Limited. *SLE Reusable Flow Sensor: For use with SLE Infant Ventilators* [online]. Available at: https://prhoinsa.com/images/pdf/sle/accesorios/Sensor_de_flujo_(Reutilizable).pdf

[19] Datex-Ohmeda Division, Instrumentarium Corporation. *Datex-Ohmeda S/5TM Collect User's Reference Manual* [online]. 2003. Available at: http://clin.au.dk/fileadmin/www.ki.au.dk/afdeling_t/it/s5collectmanual.pdf

[20] HŘIBALOVÁ, Barbora. *Vliv senzoru průtoku pro monitoraci vysokofrekvenční plicní ventilace na fyziologické parametry animálního modelu*. Kladno, 2015. Diplomová práce. ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE. Vedoucí práce Ing. Petr Kudrna.

Appendix A Code for processing pressure distribution

```
function main( directory )

MAP = 1.5; %MAP in cmH2O
folders = dir(directory);
directories = {folders([folders.isdir]).name};
directories = directories(~ismember(directories,{'.','..'}));
%dividers = getDivider('C:\Users\Kuba\Desktop\New
Folder\Florian.xlsx');
%dividers = getDivider('C:\Users\Kuba\Desktop\New Folder\SM.xlsx');

for k = 1:length(directories)
    [start,ending]=getTime();
    path =
strcat(directory,'\',directories(k),'\',directories(k),'.xlsx');
    inputData=loadData(path{1});
    figure
    values=zeros(size(inputData,2),3);
    for i = 1:size(inputData,2)
        [time,data] = visualisation(inputData,i,start,ending);
        values(i,:) = [max(data),mean(data),min(data)];
        plot(time,data)
        hold on;
    end
    path = strcat(directory,'\',directories(k),'\');

    calculatedValues =
[values(:,1)/(MAP+dividers(char(directories(k)))/2)...
                        values(:,2)/ MAP...
                        values(:,3)/(MAP-
dividers(char(directories(k)))/2)];
    calculatedValues = abs(calculatedValues);
    saveData(path,[values;calculatedValues]);
    xlabel('Time [s]')
    grid on
    title('Pressure distribution')

    figure

plot(1:7,calculatedValues(:,1),'o',1:7,calculatedValues(:,2),'x',1:7,c
alculatedValues(:,3),'*')
    grid minor
    ylabel('Distribution of pressure [%]')
    xlabel('Number of probe [-]')
    legend('Max value','Mean value','Min value')

    figure
    plot(1:7,values(:,1),'o',1:7,values(:,2),'x',1:7,values(:,3),'*')
    grid minor
    ylabel('Pressure [kPa]')
    xlabel('Number of probe [-]')
    legend('Max value','Mean value','Min value')

end
end
```

```
function cellVectors= loadData(name)
display(name)
[~, ~, raw] = xlsread(name,'Sheet1');
raw(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),raw)) = {''};
cellVectors = raw(:,:);
end


function [ start,stop ] = getTime
start = input('Enter start time: ');
stop = input('Enter ending time: ');
end


function [x_axes,y_axes]= visualisation(data, number_of_probe,time1,
time2)

probeData = cell2mat(data(:,number_of_probe))/10e5;

%create if you want to see the whole range of the measurements

t=(0:1/2000:length(probeData)/2000)';
t=t(1:end-1);

x_axes = t((t < time2 & t > time1));
y_axes = probeData((t < time2 & t > time1));

end

function dataOut = getDivider(pathToFile)

sheet = ['MulticomptPressureMeasBF10'; 'MulticomptPressureMeasBF15'];
for k = 1:size(sheet)
    [~,~,datePart]=xlsread(pathToFile,sheet(k,:),'E2:E2');
   %[~,~,Mfiles] = xlsread(pathToFile,sheet(k,:),'E4:E15'); %%Fabian
file
    [~,~,Mfiles] = xlsread(pathToFile,sheet(k,:),'E4:E13'); %SM file
    if k == 1
        files = strcat(datePart,Mfiles);
       %values = xlsread(pathToFile,sheet(k,:),'B4:B15'); %%Fabian
        values = xlsread(pathToFile,sheet(k,:),'B4:B13'); %SM
    else
        files = [files;strcat(datePart,Mfiles)];
       %values = [values;xlsread(pathToFile,sheet(k,:),'B4:B15')];
%Fabian
        values = [values;xlsread(pathToFile,sheet(k,:),'B4:B13')]; %SM
    end
end
dataOut = containers.Map(files,values);


function saveData(path,data )
way = strcat(path,'data.xlsx');
xlswrite(way{1},data);
end
```

Appendix B Code for evaluation of CO_2 elimination

Similar code is for the other devices is places on the attached CD

```
clc;
clear all;
%SensorMedics 3100A
test1waves=cell2mat(loadData2SM('SMCO2\waves1'));
test2waves=cell2mat(loadData2SM('SMCO2\waves2'));
test3waves=cell2mat(loadData2SM('SMCO2\waves3'));
test4waves=cell2mat(loadData2SM('SMCO2\waves4'));
test5waves=cell2mat(loadData2SM('SMCO2\waves5'));
test6waves=cell2mat(loadData2SM('SMCO2\waves6'));
test7waves=cell2mat(loadData2SM('SMCO2\waves7'));
test8waves=cell2mat(loadData2SM('SMCO2\waves8'));
test9waves=cell2mat(loadData2SM('SMCO2\waves9'));
test10waves=cell2mat(loadData2SM('SMCO2\waves10'));
test11waves=cell2mat(loadData2SM('SMCO2\waves11'));
test12waves=cell2mat(loadData2SM('SMCO2\waves12'));
t0=0;
t1=length(test1waves)/25;
t2=length(test2waves)/25;
t3=length(test3waves)/25;
t4=length(test4waves)/25;
t5=length(test5waves)/25;
t6=length(test6waves)/25;
t7=length(test7waves)/25;
t8=length(test8waves)/25;
t9=length(test9waves)/25;
t10=length(test10waves)/25;
t11=length(test11waves)/25;
t12=length(test12waves)/25;
x1=(t0:1/25:t1);
x2=(t0:1/25:t2);
x3=(t0:1/25:t3);
x4=(t0:1/25:t4);
x5=(t0:1/25:t5);
x6=(t0:1/25:t6);
x7=(t0:1/25:t7);
x8=(t0:1/25:t8);
x9=(t0:1/25:t9);
x10=(t0:1/25:t10);
x11=(t0:1/25:t11);
x12=(t0:1/25:t12);
k1=x1';
k2=x2';
k3=x3';
k4=x4';
k5=x5';
k6=x6';
k7=x7';
k8=x8';
k9=x9';
k10=x10';
k11=x11';
k12=x12';
i1=k1(1:end-1);
i2=k2(1:end-1);
i3=k3(1:end-1);
i4=k4(1:end-1);
i5=k5(1:end-1);
```

```
i6=k6(1:end-1);
i7=k7(1:end-1);
i8=k8(1:end-1);
i9=k9(1:end-1);
i10=k10(1:end-1);
i11=k11(1:end-1);
i12=k12(1:end-1);

%Increasing
% indexForZoom1 = (i1 < 261 & i1 > 22); %range of interest
% indexForZoom2 = (i2 < 209 & i2 > 20);
% indexForZoom3 = (i3 < 189 & i3 > 20);
% indexForZoom4 = (i4 < 196 & i4 > 15);
% indexForZoom5 = (i5 < 141 & i5 > 15);
% indexForZoom6 = (i6 < 258 & i6 > 21);
% indexForZoom7 = (i7 < 197 & i7 > 13);
% indexForZoom8 = (i8 < 179 & i8 > 17);
% indexForZoom9 = (i9 < 166 & i9 > 14);
% indexForZoom10 = (i10 <192 & i10 > 20);
% indexForZoom11 = (i11 < 126 & i11 > 14);
% indexForZoom12 = (i12 < 193 & i12 > 16);

% %Decreasing
indexForZoom1 = (i1 < 588 & i1 > 261); %range of interest
indexForZoom2 = (i2 < 424 & i2 > 210);
indexForZoom3 = (i3 < 488 & i3 > 189);
indexForZoom4 = (i4 < 370 & i4 > 196);
indexForZoom5 = (i5 < 450 & i5 > 141);
indexForZoom6 = (i6 < 468 & i6 > 256);
indexForZoom7 = (i7 < 450 & i7 > 197);
indexForZoom8 = (i8 < 319 & i8 > 179);
indexForZoom9 = (i9 < 451 & i9 > 168);
indexForZoom10 = (i10 <356 & i10 > 192);
indexForZoom11 = (i11 < 453 & i11 > 126);
indexForZoom12 = (i12 < 406 & i12 > 193);

xx1=i1(indexForZoom1);
y1=test1waves(indexForZoom1);
xx2=i2(indexForZoom2);
y2=test2waves(indexForZoom2);
xx3=i3(indexForZoom3);
y3=test3waves(indexForZoom3);
xx4=i4(indexForZoom4);
y4=test4waves(indexForZoom4);
xx5=i5(indexForZoom5);
y5=test5waves(indexForZoom5);
xx6=i6(indexForZoom6);
y6=test6waves(indexForZoom6);
xx7=i7(indexForZoom7);
y7=test7waves(indexForZoom7);
xx8=i8(indexForZoom8);
y8=test8waves(indexForZoom8);
xx9=i9(indexForZoom9);
y9=test9waves(indexForZoom9);
xx10=i10(indexForZoom10);
y10=test10waves(indexForZoom10);
xx11=i11(indexForZoom11);
y11=test11waves(indexForZoom11);
xx12=i12(indexForZoom12);
y12=test12waves(indexForZoom12);
%Increasing
% shift1=xx1-22;
```

```
% shift2=xx2-20;
% shift3=xx3-20;
% shift4=xx4-15;
% shift5=xx5-15;
% shift6=xx6-21;
% shift7=xx7-13;
% shift8=xx8-17;
% shift9=xx9-14;
% shift10=xx10-20;
% shift11=xx11-14;
% shift12=xx12-16;

%Decreasing
shift1=xx1-261;
shift2=xx2-210;
shift3=xx3-189;
shift4=xx4-196;
shift5=xx5-141;
shift6=xx6-256;
shift7=xx7-197;
shift8=xx8-179;
shift9=xx9-168;
shift10=xx10-192;
shift11=xx11-126;
shift12=xx12-193;
```

Appendix C Results for CO_2 elimination

Table C.1. Calculated values for the CO_2 elimination curve, measured of SensorMedics 3100A

Initial settings and conditions on the			Results of the measurements for SensorMedics 3100A					
			Increasing part of the graph			Decreasing part of the graph		
Bias Flow (L/min)	Frequency (Hz)	ΔP cmH_2O	T (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (–)	T2 (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (–)
15	5	30	73.99 (73.82, 74.15)	8.345 (8.338, 8.352)	0.9982	76.83 (76.69, 76.97)	7.995 (7.985, 8.005)	0.997
		45	49.01 (48.88, 49.15)	5.216 (5.211, 5.22)	0.9975	46.09 (46.06, 46.12)	5.149 (5.146, 5.151)	0.9997
	10	30	127.1 (119.2, 135.1)	10.33 (9.927, 10.73)	0.7896	76.8 (76.76, 76.83)	7.375 (7.372, 7.377)	0.9998
		45	46.94 (46.87, 47.01)	5.221 (5.218, 5.223)	0.9992	46.39 (46.36, 46.43)	5.126 (5.124, 5.129)	0.9997
	15	30	91.5 (91.08, 91.92)	9.954 (9.926, 9.982)	0.9989	88.51 (88.48, 88.55)	7.421 (7.419, 7.423)	0.9998
		45	53.58 (53.52, 53.64)	6.243 (6.241, 6.245)	0.9994	55.59 (55.56, 55.62)	6.229 (6.226, 6.231)	0.9998
10	5	30	63.94 (63.78, 64.09)	7.104 (7.098, 7.111)	0.9987	63.33 (63.3, 63.36)	6.605 (6.603, 6.608)	0.9998
		45	39.74 (39.67, 39.81)	4.525 (4.522, 4.528)	0.999	39.41 (39.38, 39.43)	4.475 (4.473, 4.478)	0.9998
	10	30	71.6 (71.43, 71.78)	7.957 (7.947, 7.966)	0.9993	72.11 (72.07, 72.15)	6.977 (6.975, 6.98)	0.9998
		45	44.56 (44.48, 44.63)	5.087 (5.085, 5.09)	0.9991	44.64 (44.61, 44.67)	5.109 (5.106, 5.111)	0.9998
	15	30	82.17 (81.85, 82.49)	9.68 (9.657, 9.703)	0.9993	89.52 (89.48, 89.56)	7.17 (7.168, 7.172)	0.9998
		45	58.3 (58.17, 58.43)	6.366 (6.361, 6.372)	0.9988	56.07 (56.03, 56.1)	6.207 (6.204, 6.21)	0.9998

Table C.2.Calculated values for the CO_2 elimination curve, measured of Babylog VN500

Initial settings and conditions on the ventilator			Results of the measurements for Babylog VN500					
			Increasing part of the graph			Decreasing part of the graph		
Circuit	Frequency (Hz)	ΔP (cmH2O)	T (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (−)	T2 (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (−)
CV circuit	5	30	29.44 (29.34, 29.54)	3.431 (3.428, 3.434)	0.9967	28.12 (28.08, 28.16)	3.642 (3.638, 3.645)	0.9993
		45	24.24 (24.14, 24.33)	2.697 (2.694, 2.7)	0.9963	22.22 (22.18, 22.25)	2.761 (2.758, 2.765)	0.9993
	10	30	55.02 (51.53, 58.51)	5.161 (5.022, 5.299)	0.5641	44.02 (43.98, 44.07)	5.018 (5.014, 5.021)	0.9994
		45	29.14 (29.07, 29.21)	3.571 (3.569, 3.574)	0.9982	30.22 (30.18, 30.26)	3.835 (3.831, 3.839)	0.9994
	15	30	51.11 (51, 51.23)	6.039 (6.034, 6.044)	0.9988	53.07 (53.03, 53.11	5.801 (5.798, 5.804)	0.9997
		45	46.51 (46.39, 46.63)	5.751 (5.747, 5.756)	0.9976	50.65 (50.61, 50.69)	5.624 (5.621, 5.627)	0.9996
HF-circuit DC	5	30	33.09 (32.9, 33.28)	3.558 (3.551, 3.565)	0.9942	30.29 (30.25, 30.32)	3.462 (3.46, 3.465)	0.9995
		45	22.99 (22.9, 23.08)	2.533 (2.53, 2.536)	0.9972	21.59 (21.55, 21.63)	2.684 (2.681, 2.688)	0.9991
	10	30	43.79 (43.6, 43.97)	4.621 (4.614, 4.628)	0.9967	40.35 (40.31, 40.39)	4.717 (4.714, 4.72)	0.9995
		45	29.41 (29.3, 29.51)	3.297 (3.293, 3.301)	0.9982	27.63 (27.59, 27.66)	3.251 (3.248, 3.254)	0.9995
	15	30	51.57 (51.49, 51.65)	5.825 (5.822, 5.829)	0.9994	52.97 (52.93, 53.01)	5.586 (5.583, 5.589)	0.9996
		45	54.98 (52.87, 57.09)	4.447 (4.374, 4.521)	0.8245	34.44 (34.41, 34.46)	4.07 (4.068, 4.073)	0.9997
HF-circuit DC 2 waves	15	30	57.01 (56.77, 57.25)	5.974 (5.965, 5.984)	0.9965	53.63 (53.6, 53.66)	5.718 (5.716, 5.72)	0.9998

Table C.3. Calculated values for the CO_2 elimination curve, measured of Fabian HFOi

Initial settings and conditions on the ventilator			Results of the measurements for Fabian HFOi					
			Increasing part of the graph			Decreasing part of the graph		
Bias Flow (L/min)	Frequency (Hz)	ΔP (cmH_2O)	T (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (−)	T2 (with 95% confidence bounds) (s)	c_f (with 95% confidence bounds) (%)	R^2 (−)
15	5	30	27.17 (26.95, 27.39)	4.063 (4.055, 4.071)	0.9676	38.23 (38.17, 38.29)	4.328 (4.323, 4.333)	0.9988
		45	30.07 (30.01, 30.12)	3.446 (3.444, 3.447)	0.999	31.83 (31.8, 31.86)	3.606 (3.603, 3.608)	0.9997
	10	30	57.25 (57.08, 57.42)	6.374 (6.368, 6.379)	0.9956	59.4 (59.29, 59.51)	6.449 (6.441, 6.457)	0.9977
		45	36.78 (36.69, 36.87)	4.175 (4.172, 4.178)	0.9977	38.41 (38.38, 38.43)	4.3 (4.298, 4.302)	0.9998
	15	30	76.54 (76.2, 76.87)	8.775 (8.758, 8.792)	0.9966	87.38 (87.36, 87.41)	8.084 (8.083, 8.086)	0.9999
		45	53.55 (53.49, 53.61)	5.721 (5.719, 5.723)	0.9995	52.81 (52.78, 52.83)	5.628 (5.626, 5.63)	0.9999
10	5	30	48.3 (48.25, 48.36)	5.327 (5.326, 5.329)	0.9996	48.79 (48.77, 48.82)	5.341 (5.339, 5.343)	0.9999
		45	36.54 (36.51, 36.58)	4.061 (4.06, 4.062)	0.9996	37.02 (37, 37.05)	4.163 (4.162, 4.165)	0.9998
	10	30	65.18 (65.11, 65.24)	7.116 (7.113, 7.118)	0.9996	66.87 (66.84, 66.91)	7.283 (7.281, 7.286)	0.9998
		45	41.15 (41.11, 41.2)	4.579 (4.577, 4.581)	0.9997	41.99 (41.97, 42.02)	4.497 (4.495, 4.499)	0.9999
	15	30	89.33 (89.19, 89.47)	9.899 (9.89, 9.908)	0.9998	94.63 (94.59, 94.66)	7.949 (7.947, 7.951)	0.9998
		45	55.13 (55.08, 55.19)	6.25 (6.247, 6.252)	0.9998	58.31 (58.29, 58.33)	6.727 (6.725, 6.729)	0.9999

Appendix D Example of file with the pressure values

The rest of results presented as tables in Excel names “data” in respective folders. The data organized in following manner Example for Fabian HFOi pressure distribution with following settings: ΔP 30 cmH_2O, frequency 5 Hz, bias flow 10 L/min. In the “data” files the values are not signed due to the code’s properties.

Table D.1. Example of the data organization

	Acual values of pressure from the selected signal [kPa]		
Meaning	Maximum	Mean	Minimum
Probe 1	3.32	1.87	-0.09
Probe 2	4.23	2.11	0.17
Probe 3	2.17	2.04	1.92
Probe 4	2.36	2.11	1.87
Probe 5	2.31	2.08	1.84
Probe 6	2.21	2.07	1.93
Probe 7	2.23	2.11	1.98
	Ratio in persentage to the initial values (%)		
Probe 1	0.20	1.25	0.01
Probe 2	0.26	1.41	-0.01
Probe 3	0.13	1.36	-0.14
Probe 4	0.14	1.40	-0.14
Probe 5	0.14	1.39	-0.14
Probe 6	0.13	1.38	-0.14
Probe 7	0.13	1.40	-0.15

Appendix E Example of curve fitting for CO_2 elimination

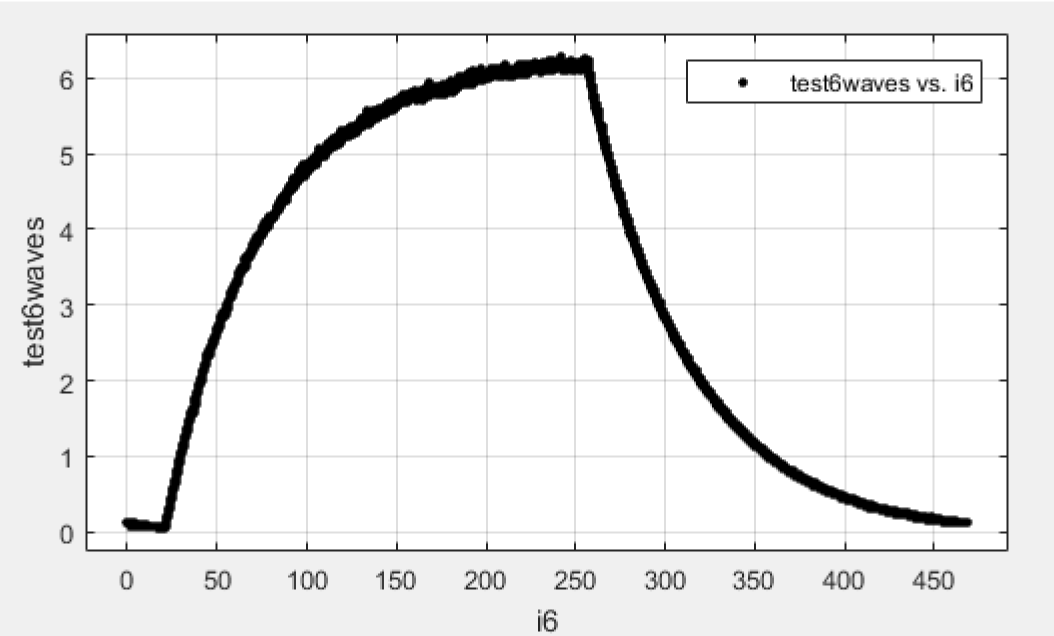

Figure E.1.Overall representing of the graph for CO_2 concentration change over time

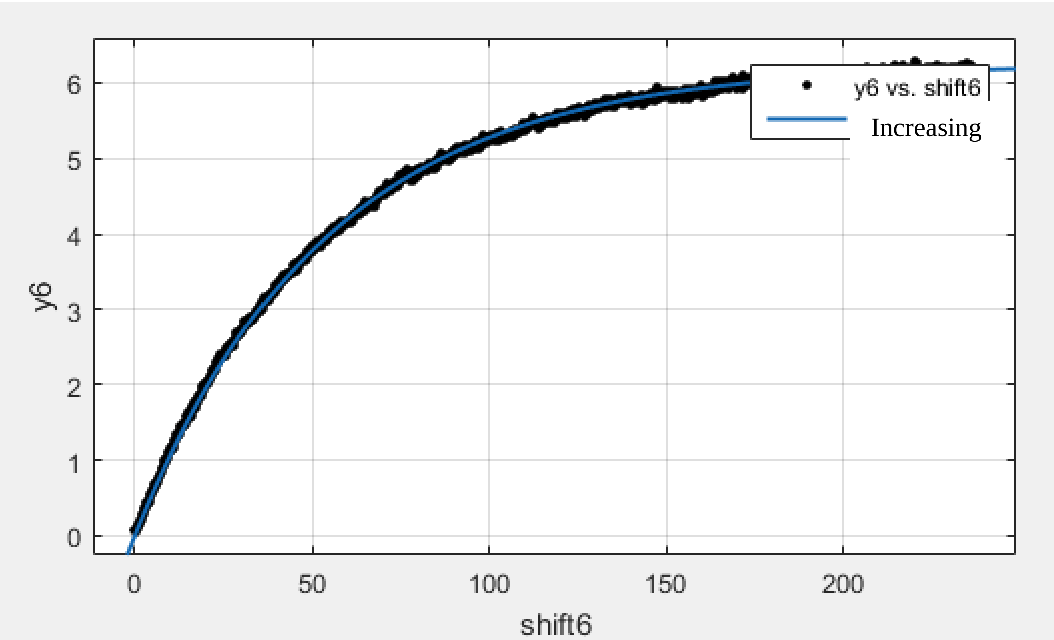

Figure E.2. Increasing part of the graph with the first time constant

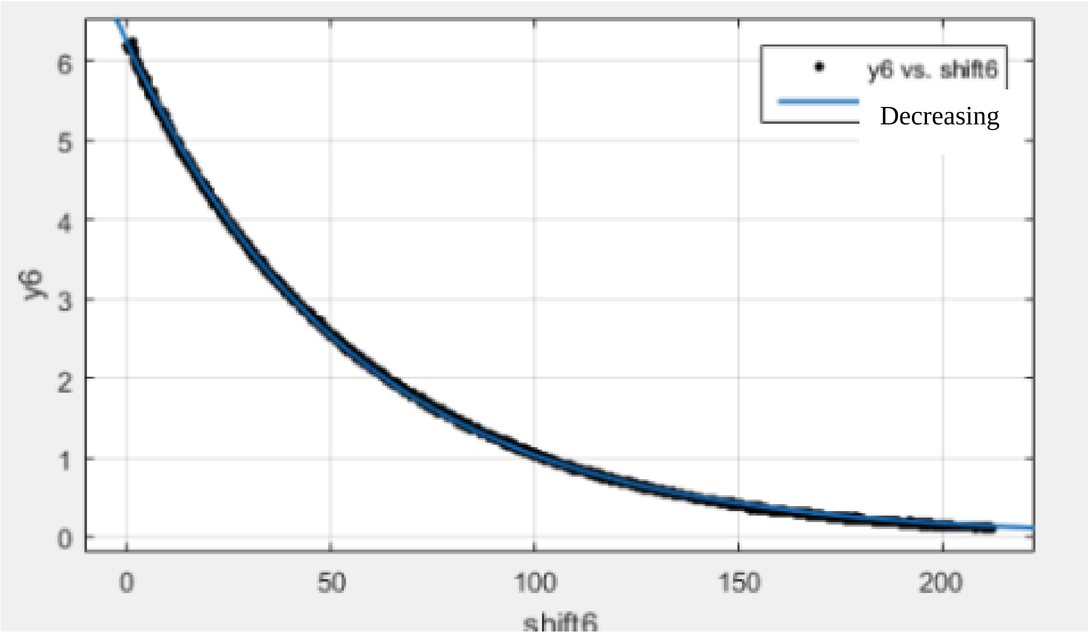

Figure E.3.Decreasing part of the graph with the second time constant.

Appendix F CD content

- Key words
- Abstract in Czech
- Abstract in English
- Scan of the assignment of the topic of the diploma thesis
- The complete diploma thesis
- Codes
- Experiments and data from calculations