Development of a compact stand-alone esophageal pressure measurement device

Abstract: Mechanical ventilation requires optimal parameter setting for every single patient. For instance sufficient positive end-expiratory pressure (PEEP) may ensure oxygenation and prevent overdistension of lungs or alveolar collapse. To find optimal PEEP, transpulmonary pressure (airway pressure minus pleural pressure) guides as an indicator for both, chest wall mechanics and lung characteristic. Since measurement of pleural pressure is impractical in clinical routine, esophageal pressure can be used to estimate pleural pressure and may help to assure protective mechanical ventilation. We developed a PESO (derived from $P_{ESO} =$ esophageal pressure) measurement system, which provides a compact stand-alone device to measure the esophageal pressure during mechanical ventilation of patients. In addition to the esophageal pressure, airway pressure is also measured to provide the synchronized data independent of the ventilator manufacturer. The device works with two commercial pressure transducers, whose signals are conditioned and digitized with an Arduino Nano microcontroller, which samples data with 62 kHz and transmits averaged data with 100 Hz to a mobile tablet PC, which acts as process, display and record unit. The compact system provides a working time of 5 hours. Therefore, the system supports the progress for mechanical ventilation research. This paper describes technical details as well as functionality.

Keywords: esophageal pressure, transpulmonary pressure, mechanical ventilation.

https://doi.org/10.1515/cdbme-2018-0085

1 Introduction

Mechanical ventilation is one of the most important medical services in surgery, intensive care or emergency medicine. Concurrently, the optimal parameter setting for mechanical ventilation is very complex as it is influenced by many factors of the patient itself and thus varies from patient to patient. Especially in patients which have already suffered from lung diseases, e.g. chronic obstructive pulmonary disease (COPD) or acute respiratory distress syndrome (ARDS), special caution is needed because incorrectly selected ventilation parameters in mechanical ventilation can further increase mortality and decrease patient’s outcome. Moreover, due to incorrectly selected settings, lung diseases can also be caused by mechanical ventilation itself, e.g. ventilator-induced lung injury (VILI), which can be evoked by inadequate airway pressures including positive end-expiratory pressure (PEEP) or by insufficient tidal volumes [1-3].

Numerous studies have shown that PEEP has a particular influence on effective and protective mechanical ventilation because its patient individualized setting may ensure sufficient oxygenation and can prevent lung overdistension or alveolar collapse [1-6]. Transpulmonary pressure ($P_L$) controls lung inflation and guides as an indicator for both, chest wall mechanics and lung characteristic, which vary highly from patient to patient. Therefore, $P_L$, which is airway pressure ($P_{AW}$) minus pleural pressure ($P_{pl}$), may help finding the optimal PEEP for every single patient [2-6].

To obtain $P_{pl}$ it is possible to measure this parameter directly, which would lead to a highly invasive procedure with a high risk to damage the pleural cavity resulting in lung collapse. In addition, measurement of the pleural pressure cannot be performed easily and the procedure increases the inflammation risk, which also increases the patient’s mortality. However, various studies indicate that esophageal pressure can be used as a surrogate of pleural pressure [2-7].
Measuring this parameter is much easier and is also minimally invasive, resulting in a significant risk reduction.

In clinical practice, esophageal pressure ($P_{eso}$) is rarely used. Reasons are, e.g. the technical requirements or, on the contrary, the technical availability of systems that can be used to measure the esophageal pressure. As far as we know, currently offered measurement systems are either integrated directly into the ventilator or are very expensive stand-alone devices. The former leads to the fact that, especially in multicenter studies, all involved clinics would have to use the same ventilators in order to generate meaningful and reliable results, which would not be economically justifiable.

Therefore, we designed a mobile, cost-effective and easy-to-use system that allows reliable measurements at the bedside and can be used with any ventilators. With the so-called PESO (derived from $P_{eso}$ = esophageal pressure) system, we want to provide the opportunity to advance clinical trials, or even mechanical ventilation research at all, as well as using esophageal pressure in mechanical ventilation to reduce risk and mortality due to mechanical ventilation. Besides human usage, the PESO system is also designed for fundamental research using animal models.

2 Methods

The PESO measuring system consists of three components, a display element, a recording and amplification unit (R-A-unit) and two pressure transducers. An overview of the system is shown in Figure 1.

To ensure synchronization with the ventilator, the PESO measurement system has two measurement channels. Channel one (C1, see Figure 1) is for detecting esophageal pressure in the patient. For this, a cannula is inserted through the mouth or the nose (whereby nasogastric variant is more usual), past the larynx into the esophagus. This should be done before intubation because the intubation tube makes it difficult to insert the cannula into the esophagus. The second channel (C2, see Figure 1) is connected to the ventilator's tube system next to the patient and thus measures the airway pressure.

For the measurement of the pressure values, invasive blood pressure transducers are used (disposable transducer, B. Braun Melsungen AG, Germany). The analog voltage signals are conditioned and digitized by the R-A-unit, which consists of an Arduino Nano V3.0 and a self-made analog amplifier circuit. While the sampling rate of the PESO system (analog-digital-conversion rate) is about 62 kHz, the transmission rate (transmission of averaged data to the tablet PC) is 100 Hz, which is sufficient even in small animals with high breathing frequencies.

In addition to the respiration, the heart rate is also measured reliably in order to either display it during placement of the esophageal balloon catheter or to filter out the interfering heart rate digitally from the esophageal or respiratory pressure to avoid artifacts. However, the system is designed for both human and animal use. That is why the mouse heart’s signal is adopted as the fastest signal. This amounts to about 700 beats per minute which is approximately 12 Hz, which can be reliably scanned with the specified transmission rate.

The data is transmitted via a USB interface to the display element, which is a Windows tablet (TRAVELline T8-E3, bluechip Computer AG, Germany). The signal processing and display function has been implemented in LabVIEW (National Instruments, USA). The tablet powers the R-A-unit as well as the pressure transducers with 2.56 V, thus no dangerous voltages exist and ensure a long battery life.

Figure 1: Outline of the PESO measurement system connected to a supine patient. Pressure transducer C1 is connected to a nasogastric cannula to measure esophageal pressure. Transducer C2 is connected to a tracheal tube to measure both, airway pressure as well as for synchronization purpose with the ventilator. The obtained signals are transmitted via USB to the recording and amplification unit (B), which conditions and digitalizes the signals. Then data is transmitted to the touch display (A), which shows the recorded data and where the system can be configured and the pressure transducers are calibrated.
Moreover, the software provides the possibility to calibrate the sensors, which should be done once before first using. For this, a calibration unit was designed to perform a two point calibration at zero point (environmental pressure) and 20 cmH2O.

Several studies discuss, that for supine human patients a correction factor of 5 cmH2O must be subtracted from the measured esophageal pressure due to gravitational effects of mediastinal structures and the heart [3, 4, 6]. Therefore, the software provides the possibility to subtract a user-defined value.

3 Results

Figure 2 shows the customized and compact housing of the R-A-unit from both front side and back side. On the front side, the connectors for the pressure transducer are placed. At the back side, the mini USB connector, linking the device with the tablet PC, is positioned. In addition, dimensions of the housing are shown.

Figure 3 shows a screenshot of the developed user interface of the firmware. It displays the measured pressure courses in the diagram (A), which is scalable in both amplitude and time resolution. On the left side, parameters like the estimated transpulmonary pressure or the mean values of the pressure courses are shown (B). Moreover, there is a notice field, which can be saved, too (C). Furthermore, the software offers the possibility to store the recorded data and to load and watch already recorded data (D). In addition, the software provides a fast zeroing button (E). The second tab (F) is linked to the calibration menu for the pressure transducers, described in section 2.

Due to the compact design, PESO provides a mobile period of use of approximately 5 hours.

A test paradigm was performed to show functionality of the device. For this, human air way pressure signal as well as electro cardiac signal were modeled using Matlab (The MathWorks, Inc., USA). For the respiratory signal, a ventilation frequency of 15 breaths per minute and for the cardiac signal, a heartbeat frequency of 75 beats per minute was assumed. Both signals were superimposed and transmitted (ArbExpress®, Tektronix, Inc., USA) to a function generator (Tektronix AFG3102, Tektronix, Inc., USA), which drives the signal. The output was connected to both channels of the microcontroller. The software of the PESO system was used to record data, which was then analyzed in Matlab.

Figure 4 shows the results for the test paradigm described before. Subfigure (A) depicts separate modeled electro cardiac (top) as well as airway pressure (bottom) signal. The superimposed result of both signals, which drives the function generator, is shown in subfigure (B). Subfigures (C) and (D) contain the signals, which are recorded with the PESO system. The signal courses from subfigures (C) and (D) are almost congruent with the modeled signal in subfigure (B) and the superimposed electro cardiac components are detectable (QRS-complex peak is indicated with a * in all subfigures).
4 Discussion

A compact and stand-alone device simplifying the measurement of the esophageal pressure to estimate the pleural pressure was developed. This provides a system which supports the progress for mechanical ventilation research, especially for an optimal PEEP setting for sufficient and protective mechanical ventilation and advance fundamental research using animal models. The advantages of this device are the compact housing, the mobility which allows measurements at the bedside, the cost efficiency, the simple control of the software as well as the synchronization with any ventilator independent from manufacturer and a high sampling rate of 62 kHz which allows the application in humans and animals with different ventilation frequencies. In addition, the system is custom made and offers the possibility to extend the existing device easily.

Author Statement

Research funding: The author acknowledges from Deutsche Forschungsgemeinschaft under project number KO2967/3-1.

Conflict of interest: Authors state no conflict of interest.

Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: This study was performed without any human testing.

References