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RESEARCH PAPER

A novel flow partition device for spirometry during large animal anaesthesia

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Abstract

Objective We describe and test a novel device for large animal anaesthesia monitoring that uses standard human medicine spirometry sensors.

Study design *In-vitro* study.

Methods The device consists of two adapters that enable the flow to be split evenly into four tubes in parallel, each tube containing a D-lite sensor. The performance of this flow partitioning device (FPD) over a range of flows from 100 to 700 L minute^{-1} was determined and the pressure versus flow relation, resistance and dead space was compared with a Horse-lite (Moens 2010).

Results Equipped with four D-lite sensors, and a flow of 700 L minute^{-1} the pressure drop of the FPD was 13.5 cmH_2O, resistance 1.17 cmH_2O second L^{-1} and volume (potential dead space) 182 mL, compared to 2.8 cmH_2O, 0.24 cmH_2O second L^{-1} and 54 mL respectively for the Horse-lite. The predicted value of the flow partition of ¼ could be confirmed. Limits of agreement were found to be 4.2% in inspiratory direction and 7.1% in expiratory direction.

Conclusions and clinical relevance The FPD is an affordable device that extends the specification of any commercially available human spirometry sensors to large animal applications. However, an increase in total resistance and dead space has to be taken into account. Therefore, the new device could be useful during equine anaesthesia.

Keywords large animal anaesthesia, monitoring, spirometry.

Introduction

Monitoring of ventilation is an important aspect of anaesthesia management in small and large animals (Hall & Clarke 1991). During spontaneous breathing and mechanical ventilation, the measurement of tidal and minute volumes gives essential information of the patients' respiratory function. For respiratory monitoring of small animals, spirometric equipment and sensors from human medicine can be used because the range of flow and tidal volume remains within the specification of standard paediatric or adult human sensors. Different types of spirometric sensors can be positioned at different places in an anaesthetic machine and ventilator (Dorsch & Dorsch 2011). Positioning the sensor directly between the endotracheal tube (ETT) and the breathing circuit provides the highest accuracy and is mandatory if mainstream volumetric capnography is also performed. Spirometric sensors have individual advantages and drawbacks. For example, the Fleisch pneumotachometer (Fleisch 1925) is highly accurate but sensitive to fluid accumulation as well as gas composition and is hence less suitable for clinical application. Many sensors used for clinical anaesthesia apply the Pitot-tube principle in combination with a resistive structure to generate

a flow dependent pressure difference. Such constructions are cheap, robust but have to be used with dedicated hard- and software that convert the pressure difference into flow and volume considering the non-linear transfer function as well as corrections for the gas composition and temperature (Moens et al. 1994). Examples are the D-lite sensor (Meriläinen et al. 1993; GE Healthcare, Finland), the Hamilton Flow sensor (Hamilton Medical AG, Switzerland) and the $NICO_2$ CO_2/Flow sensor (Respironics Inc., MA, USA). However, abovementioned sensors are designed for human use to be attached to the standard 15 mm diameter conical connection system and would create too much resistance when inserted in the large bore circle system for large animal anaesthesia. Thus they do not meet the flow and volume requirements encountered during large animal anaesthesia monitoring.

Moens et al. (1994) remodelled a D-lite sensor to a larger diameter (Horse-lite) and documented its accuracy by determining an appropriate conversion factor to calculate flow and volume values. Such a device enables the veterinary anaesthetist to optimize ventilatory management of large animals (Moens 2010). However, the Horse-lite needs to be custom made and individually tested *in situ* to determine an appropriate conversion factor to be applied to the readings of the monitor. The principle of enlargement of a human sensor is difficult to apply for mainstream capnography because of the integration of the optical pathway for a given CO_2 detector such as the $NICO_2$ Capnostat (Respironics Inc.) or the IRMA CO_2 sensor (Phasein AB, Sweden). As an alternative solution, we propose a universal flow partitioning device (FPD) which allows the use of any type of standard human sensors with or without a CO_2 detector for large animal anaesthesia monitoring. The aim of this study was to investigate the FPD equipped with four standard D-lite sensors in comparison with the Horse-lite sensor *in-vitro*.

Materials and methods

Working principle

Using a single bypass channel parallel to a conventional sensor will reduce the flow through the measuring device and may keep the flow within the specification limits even during large animal anaesthesia. The split ratio of the flows is a function of the individual resistances in the branches. Unfortunately, this ratio may not be constant over the required flow range. The flow pattern is likely to be turbulent in particular in the sensor device itself. Hence the split ratio is not constant and is a function of the flow value and may also be dependent on the flow direction. A more robust solution is to connect multiple identical sensors in parallel providing matched resistances in every branch independent of the applied flow. Theoretically, this approach results in a constant split ratio independent of the flow value. A custom-made highly symmetrical flow partitioning adapter that connects four identical human sensors in parallel is a practicable compromise, based upon the geometric considerations that the four 15 mm diameter bore holes arranged in a circle will fit closely in the 36 mm bore of the largest ETT size for horses. The spirometry monitor is connected only to one sensor and will measure therefore ¼ of the total flow. Flow reading as well as calculated parameters such as volume and compliance have to be multiplied by a factor of four to achieve a correct value. However, pressure measurement is not affected by such an arrangement and need not to be converted.

Description of the device

The flow partitioning device (FPD) consists of two almost identical adapters made of polyoxymethylene (Fig. 1 upper left and upper right). One adapter partitions the airflow into four equal parts and directs the flow through four D-lite spirometry sensors (a) The 15 mm female conical port of the sensors fits to the brass-made 15 mm male connector (b) of the adapter. Transparent silicone tubes (18 mm × 2 mm) (c) connect the sensors to the second adapter that serves to direct all flows back to one. A metal rod (d) in the middle of the device keeps both adaptors in the appropriate distance. To achieve minimal extra resistance, the construction is made highly symmetrical considering aerodynamic requirements. Outside connectivity (e) is designed to fit to the Y-piece which in turn connects to the ETT. This arrangement provides a closely matched resistance in each of the four branches. A spirometry monitor dedicated for D-lite sensors is connected to one of the sensors measuring ports (two for the pressure difference, and one for gas sampling). The measuring- and sampling ports of the three other D-lite sensors need to be closed to prevent leakage.

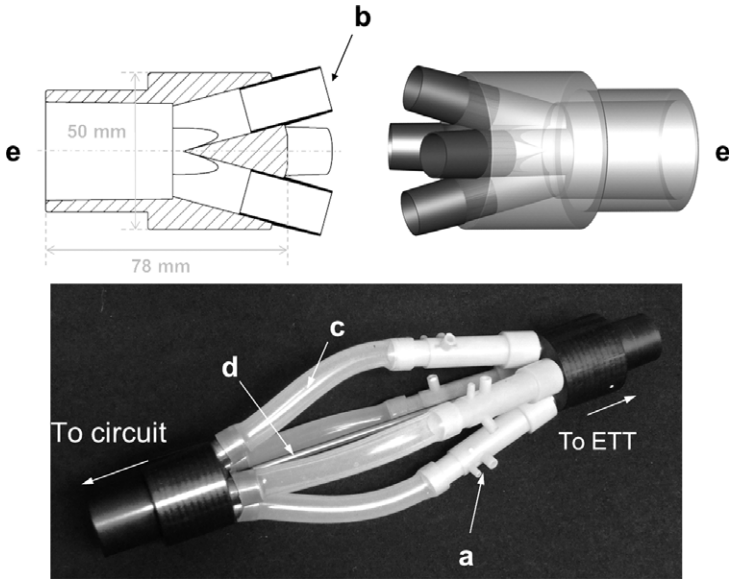

Figure 1 Cross section (upper left) and 3D representation (upper right) of flow partitioning adapter and respective setup (bottom) with four D-lite sensors (a). Male conical connectors 15 mm made of brass (b); transparent silicone tubes 18 mm × 2 mm (c); metal rod for stabilization (d).

Performance tests

The airflow resistance and the partitioning of flow of the FPD was measured *in-vitro*. The FPD was connected between two 1.5 m long straight connecting tubes with 32 mm inner diameter. One connecting tube was plugged to a flow generator (Godart 18987; Godart Statham Bilthoven, Holland) while the other was left open. The resulting pressure drop was measured via dedicated ports made of 14-gauge cannulae by cutting the tips. The latter were inserted perpendicular through the wall in the connecting tubes 15 cm before and after the FPD with their openings located in the centre of the bore. They were connected to calibrated electronic pressure transducers (Pressure Monitoring system Buzzer-II; Michael Roehrich, Austria). Resistance was calculated by the pressure difference caused by flows between 100 and 700 L minute^{-1} representing values typically encountered during large animal anaesthesia. Flow was applied in both directions. Exhalation or inhalation direction was determined by the sign of the pressure difference in relation to the sensor orientation. The sensor port that is intended to connect to the ETT was the female port, hence the flow out of this female port corresponded to inspiration. This orientation needed to be maintained also in the FPD.

The flow partition tolerance, the deviation from the nominal value ¼, was determined at a flow of 600 L minute^{-1} by measuring consecutively the pressure differences generated by individual sensors from the same manufacturing batch. Limit of agreement was calculated by ± twice the standard deviation of pressure differences.

In order to assess the potential increased dead space within a circuit that the FPD could cause, its volume of the FPD with and without sensors was determined by the weight of water needed to fill up the device. For comparison, the same protocol was used to measure the volume of a Horse-lite sensor.

Results

The pressure differences and the calculated resistance of the FPD without sensors, with four D-lite sensors and for the Horse-lite sensor in expiratory directions are given in Fig. 2. Room temperature, humidity and ambient pressure during the experiments were ranging 24–27 °C, 30–50%, and 99.5–100.3 kPa, respectively. Pressure drop across the FPD without sensors was 3.2 cmH_2O, and assembled with four D-lite sensors was 13.5 cmH_2O. In comparison, a Horse-lite sensor causes a pressure drop of 2.8 cmH_2O at 700 L minute^{-1}.

The resistance of the FPD without sensors was 0.27 cmH_2O second L^{-1} and with D-lite sensors

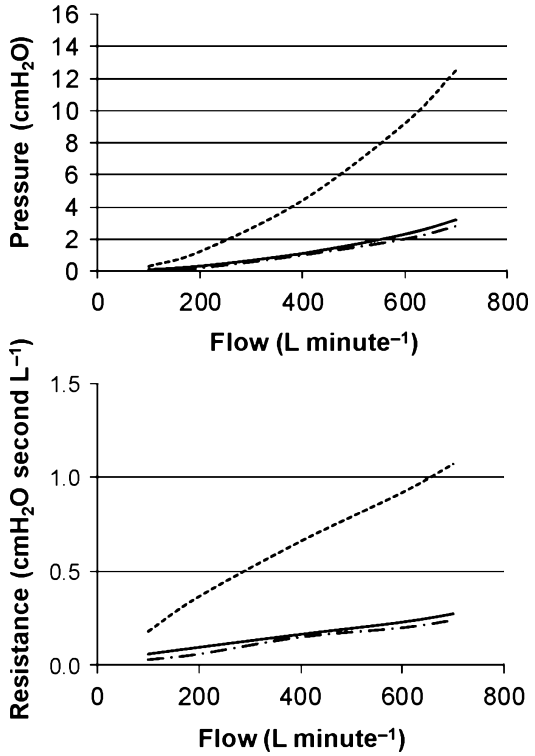

Figure 2 Pressure drop (upper) and resistance (lower) at different flow rates of the flow partitioning device with flows in expiratory direction. Solid line: device without sensors, dashed line: device with 4 × D-lite sensors, dash-dotted line: Horse-lite.

1.17 cmH_2O second L^{-1}. In contrast, the Horse-lite had a resistance of 0.24 cmH_2O second L^{-1}. The flow partition factor of the FPD was confirmed to be ¼. Limit of agreement was found to be 4.2% in inspiratory direction and 7.1% in expiratory direction.

The volume (dead space) of the FPD without sensors was 144 and 182 mL equipped with D-lite sensors. In contrast, a Horse-lite sensor had a volume of 54 mL.

Discussion

The FPD extends the use of any standard human spirometry or mainstream capnography sensors to large animal applications. The advantage of the novel device is its simplicity and universality. This concept does not necessitate the individual determination of a conversion factor. Furthermore a large-scale redesign of a sensor as was done in the Horse-lite design is laborious and – in case of mainstream volumetric capnography – hardly possible.

We investigated the flow partitioning property, the additional resistance and the dead space of the device in comparison with the Horse-lite. The device was tested with flows between 100 and 700 L minute^{-1} (1.67–11.67 L second^{-1}) which are well within the expected range of an adult horse during spontaneous breathing (Lekeux 2005). The resistance increased linearly with flow (Fig. 2) which suggests the presence of a transient or turbulent flow pattern. However, total resistance was primarily caused by the sensors, and the flow adapters contributed 23% to the total resistance. Resistance will be influenced by gas composition, pressure and temperature but we do not anticipate any influence on the split ratio by these parameters. With four D-lite sensors, the total resistance of the FPD at 700 L minute^{-1} (11.67 L second^{-1}), was 4.8 times higher than in the Horse-lite. However, considering a typical flow in a spontaneous breathing adult horse of about 5 L second^{-1} (Lekeux 2005), the pressure drop would then be about 3 cmH_2O, which can be considered acceptable. In applications where a minimal resistance and minimal dead space is key, the use of a Horse-lite is recommended.

In practice, deviation from the conversion multiplier 4 could be caused by individual differences of sensors but by using some of the same manufacturing batch the error should be negligible. Accumulation of water droplets or airway secretions may cause different resistances in the four branches. To avoid this effect, an option would be to heat the FPD from outside. The use of transparent tubes allows an easy perception of depositions. A tilted positioning of the device may let water and mucus drain out continuously.

Another possible cause for non-matched flow is that the flow velocity profile in the tube before and after the device may be not circularly symmetrical. A deviation from symmetry occurs when the airstream flows through a curved tube (Pedley & Drazen 1986) such as are some types of the ETT. In addition, the attached Y-piece causes *per se* a different flow pattern between the inspiratory and expiratory direction. When using the FPD application, we recommend connecting the monitor to a sensor that is located perpendicular to the plane of the curved ETT and the Y-piece to minimize such effects.

In vivo and *in vitro* data (Lammer et al. 2011; Ambrisko et al. 2013) demonstrated that the bias ± limits of agreement were −6 ± 6%. Calibration of a system by means of a super syringe may further

improve accuracy when required for specific research applications.

A limitation of this study is that we tested only one prototype. Therefore, we could not identify manufacturing tolerances of the design. However, such a device can be made with narrow mechanical tolerances comparable to the single use spirometry sensors manufactured by injection moulding.

In conclusion, the FPD is a universal and easy to make device that extends the specification of commercially available adult spirometry sensors to large animal anaesthesia applications. However, a moderate increase in total resistance and dead space will occur with its use.

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