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NOTE

Influence of neonatal endotracheal tube dimensions on oscillometry-acquired reactance: a bench study

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Abstract

Objective. To examine the influence of the endotracheal tube (ETT) on respiratory reactance (X_{rs}) measured with the forced oscillation technique (FOT) and develop a correction method for it. *Approach.* In a bench study, the reactance of ETTs (X_{tube}) with different dimensions was measured on a breathing test lung in various respiratory settings. *Main results.* X_{tube} can be accurately predicted by a fitted formula, with an R^2 of 0.97, with negligible effects due to changes in respiratory pattern and lung volume. *Significance.* The developed formula offers the ability to measure ETT-independent X_{rs} values of patients, improving the potential of FOT for lung function testing in mechanically ventilated newborns.

Introduction

In recent years, the forced oscillation technique (FOT) has become available in neonatal intensive care to measure respiratory mechanics during respiratory support at the bedside. Clinically, FOT measurements have been found to be feasible in prognosticating the ventilatory support duration time and respiratory outcome, and in monitoring lung recruitment during PEEP optimization (Dellacà *et al* 2011, Zannin *et al* 2013, 2019, Veneroni *et al* 2019, 2020, Wallström *et al* 2020). The fabian HFOi (Vyaire Medical, Illinois, USA) neonatal ventilator has a built-in 10 Hz FOT modality that calculates the reactance of the respiratory system (X_{rs}) (Oostveen *et al* 2003, Marchal and Hall 2010). The X_{rs} measured at 10 Hz in neonates mostly reflects the compliant properties of the lungs (Veneroni *et al* 2020, Wallström *et al* 2020).

Unfortunately, values measured during mechanical ventilation are influenced by the endotracheal tube (ETT), which hampers the possibility to directly compare measured X_{rs} values to normative values for performing lung function tests (Oostveen *et al* 2003). In previous studies the reactance of the endotracheal tube was measured at the bedside, prior to intubation with the full length of the tube. In addition to being unpractical in a critical care setting, this reactance measurement is not very reliable as in most infants the endotracheal tube is shortened after intubation to reduce unnecessary dead space (Navajas *et al* 1990, Peslin *et al* 1993). A candidate for tube correction could be the use of a mathematical model describing the contribution of ETTs on X_{rs}, starting from the tube dimensions. It is expected that the reactance impact of the tube (X_{tube}) is constant and could be described by its compliant (C_{tube}) and inertant (L_{tube}) properties, dependent on the angular FOT frequency, ω (rad/s) (Stocks *et al* 1996):

$$X_{tube} = \omega L_{tube} - 1/\omega C_{tube}. \quad (1)$$

The inertance contribution to reactance ($X_{L,tube}$) of the ETT can be calculated using the ETT length, l (m); cross-sectional area, A (m^2); density of air, ρ (kg/m^3); and angular frequency:

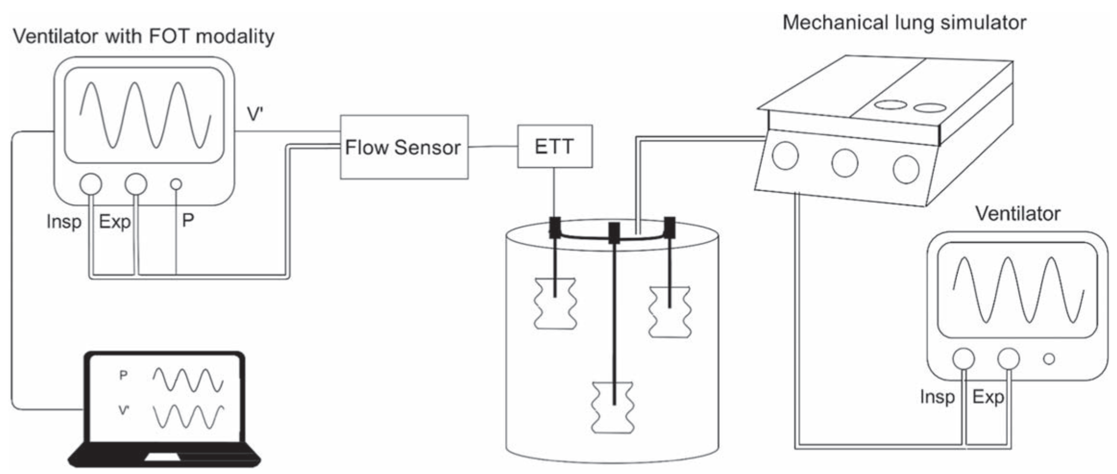

Figure 1. A schematic of measurement setup; the total lung volume of the model could be altered by opening/closing the connecting tubes between bellows. The mechanical lung simulator was added to induce breathing movements of the bellows and was powered by another ventilator. The bellows were connected to the ventilator (with the built-in FOT) through the flow sensor and standard respiratory circuit, consisting of an inspiratory (insp) and expiratory (exp) tube. A laptop was connected to the ventilator to store the ventilator pressure (P) and flow (V') signals.

$$X_{L,tube} = \omega \cdot (\rho l/A). \tag{2}$$

Unfortunately, the compliance of the ETT cannot be calculated according to static parameters. In addition, factors like lung volume, respiratory support and spontaneous breathing (SB) affect the flow regimen within the ETT but knowledge on their impact on X_{rs} is scarce (Czovek 2019).

Therefore, the aim of our study was to investigate X_{tube} in different settings to describe potential influences on the measured FOT parameters and ultimately provide a tool to correct for the ETT.

Method

Bench setup

X_{tube} was measured in a test lung consisting of serially-connected bellows of 50 ml (C = 1 ml/cmH_2O, Dräger, Lübeck, Germany), enclosed in a sealed cylindrical case. Lung volume could be altered by (dis)connecting additional bellows. The neonatal ventilator ventilated the bellows with intermittent positive pressure ventilation (IPPV, starting with positive end-expiratory pressure (PEEP) of 6 cmH_2O, peak inflation pressure (PIP) of 15 cmH_2O, flow of 10 l min^{-1}, inspiration time of 0.5 s and a rate of 40 min^{-1}. The cylindrical case was connected to a mechanical lung simulator (Michigan Instruments, Grand Rapids, United Stated) to mimic SB (respiratory rate of 20 min^{-1}) by generating negative pressure in it. This allowed performing both static (without SB) and dynamic (with SB) measurements.

The influence of tube diameter and length on X_{tube} was studied using Rüsch Safety Clear Magill uncuffed ETTs (Teleflex, Pennsylvania, US) with inner diameters (ID) of 2.0, 2.5, 3.0, 3.5, and 4.0 mm for two lengths ('long' and 'short'), based on a linear correlation between X_{tube} and ETT length (Westerhof *et al* 2010). 'Long' was defined as the full length of the tube, being 15 and 16 cm for ETT 2.0 and 2.5 and as 17 cm for the larger tubes (ID 3.0, 3.5, and 4.0). 'Short' was defined as a clinically used minimal length of 11 cm (Flinn *et al* 2015). All ETT's were inserted 5 cm into the bellow model, while ensuring the absence of leaks (see figure 1).

Measurements

10 Hz FOT measurements were performed for each pressure setting during a PEEP-trial (6, 10, 14 and 18 cmH_2O). We examined the static influence using test lung volumes of 50, 100 and 150 ml and the dynamic in a test lung of 50 ml. All conditions were measured with the patient circuit directly connected to the test lungs to obtain the baseline-X_{rs} and with ETTs in place to obtain ETT-X_{rs}. To reduce inter-measurement variations, all measurements were triplicated and averaged. The continuous raw pressure and flow waveforms were extracted from the ventilator.

Data analysis

The stored signals were used to calculate X_{rs} according to a least-squares algorithm using MATLAB (version R2018a, MathWorks, NA, USA), as described previously (Dellacà *et al* 2011). The average reactance values of the three repeated measurements at each pressure were used for the analysis. Subsequently, X_{tube} was obtained for

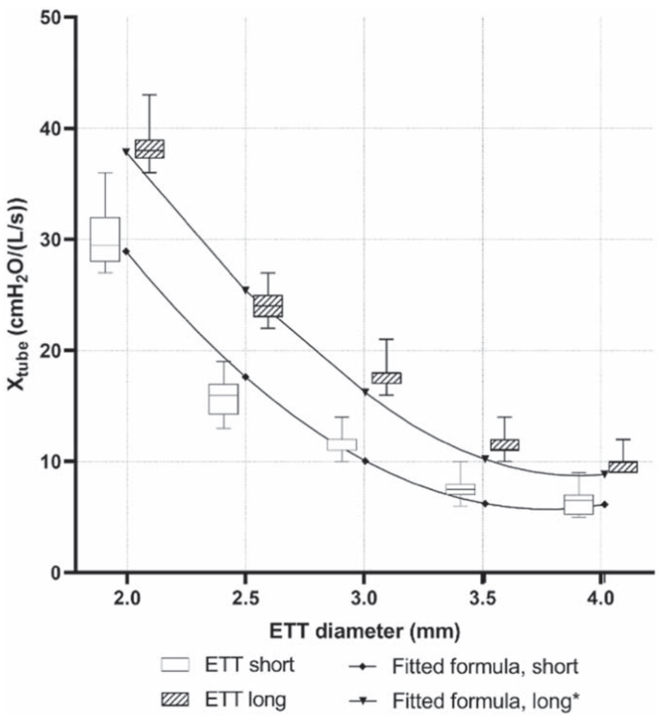

Figure 2. Relation between ETT diameter and reactance for all short and long ETTs. The boxes show the median of the measured data with its interquartile ranges for the ETT diameters. They are placed around the dotted diameter lines for clarity. The fitted formula (equation (3)) is shown for the long and the short tubes separately. *The maximal tube length of tube 2.0 and 2.5 was respectively 15 and 16 cm. The values of the curves shown are corrected for these lengths.

each measurement condition by subtracting the baseline value from the measured value with tube. Lastly, the ETT inertance was calculated ($X_{L,calc}$) according to equation (2), to investigate the balance between ETT inertance and compliance.

Statistical analysis

Statistical analysis was performed with SPSS Statistics (Version 27, IBM, New York, USA). First, differences in X_{tube} for the various lung volumes and pressures were analyzed with a repeated measures ANOVA. Differences between no SB and SB were analyzed using a Wilcoxon signed rank test. The differences between X_{tube} values of short and long tubes for all ETT diameters were examined with a one-way ANOVA and subsequent paired t-tests. A p-value <0.05 was considered statistically significant and an absolute X_{rs} difference >2 cmH$_2$O was defined as clinically relevant, since X_{rs} measured with FOT is known to have a repeatability of 1–2 cmH$_2$O/(L/s) (Hall *et al* 2007, Alblooshi *et al* 2017). Data were presented as mean (SD) or median (interquartile range, IQR), as appropriate.

For the parameters that showed a significant influence on X_{tube}, the fit with the highest accuracy per parameter (R^2) was chosen. These were combined into a single formula to correct reactance for the ETT characteristics.

Results

The measured reactance data is visualized for all the tube sizes in figure 2, together with the fitted curve. Statistical significance was found with respect to pressure, lung volume and static versus dynamic conditions ($p < 0.05$). However, all changes were less than 2 cmH$_2$O/(L/s), which is within the margin of reproducibility of FOT. Therefore, the data for different lung volumes, breathing patterns and pressure levels were combined into one dataset for further analysis on the influence of tube dimensions.

With respect to ETT length, short tubes had a significantly lower X_{tube} value than long tubes ($p < 0.01$). With respect to ID X_{tube} was significantly different between all tube diameters ($p < 0.01$), except for the largest tubes (3.5 versus 4.0, $p = 0.07$). The $X_{L,calc}$ values for the different tube lengths and diameters were reminiscent to the averaged X_{tube} values as all differences were <2 cmH$_2$O/(L/s), except for ETT with ID 2.0, which had a 4 and 3 cmH$_2$O/(L/s) difference for the short and the long tube respectively (see online supplement).

An inverse quadratic correlation was found between ID and X_{tube} ($R^2 = 0.95$). The slope of the linear correlation between tube length (l) and X_{tube} also had an inverse quadratic correlation with tube diameter ($R^2 = 0.99$). The formula fitted to the measured data ($R^2 = 0.97$) was determined as:

$$X_{tube} = 4.07ID^2 - 26.02\mathrm{ID} + (0.03ID^2 - 0.28ID + 0.65) \cdot l + 40.16 \quad (3)$$

in which ID and l are presented in mm, respectively.

Discussion

To our knowledge, this is the first study to systematically investigate the influence of neonatal ETT dimensions on reactance, measured with FOT. We were able to define a correction formula that can be used in clinical practice, as only ETT length and ID are the required parameters for this correction. We recommend to incorporate the developed formula in the ventilator for easy correction of the X_{rs} for the ETT in-use.

The results showed that lung volume, pressure, and SB did not affect X_{tube} in a clinically relevant way, which suggests that the model can be applied under different lung conditions and ventilator settings. ETT ID and length respectively showed an inverse quadratic and a linear correlation with X_{tube}. The measured X_{tube} values matched the $X_{L,\,calc}$ very well, suggesting a negligible influence of tube compliance on the measured reactance. Only the error of an ETT 2.0 exceeded the ± 2 $cmH_2O/(L/s)$ threshold, which could be caused by the additional hole at the distal end of this ETT.

It should be noted that the developed formula is only applicable for 10 Hz single frequency FOT measurements. Even though the used 10 Hz FOT is already integrated and validated in a neonatal ventilator for X_{rs} evaluation over time, it is unclear how this formula would relate to single frequency FOT at frequencies other than 10 Hz or to multi-frequency FOT measurements. Therefore, future studies are required for the identification of a mathematical correction in those conditions.

While interpreting the results, one should keep in mind that the bench study was done without air leaks. In a clinical setting, tube leaks can be a problem, which influences FOT measurements.(Czovek 2019) Nevertheless, air leak generally occurs after the ETT, leading just to an increased flow through the tube, which has minimal impact on X_{tube}. Therefore, we postulate that the developed formula can still be used under conditions of ETT leakage.

Conclusion

In conclusion, our bench study showed that X_{rs} values measured with single frequency FOT are affected by ETT dimensions. We identified and validated a correction formula which can be implemented in future clinical studies and potentially in clinical practice to standardize neonatal lung function testing by FOT in mechanically ventilated newborns.

Acknowledgments

RP, RvL, AS, JH and FJ conceptualized the study. RP performed the measurements, analysed the data and wrote the first version of the manuscript. All authors contributed to the interpretation of the study results and critically reviewed and contributed to the final draft of the manuscript.

Ethical statement

This note describes the results of a bench study and therefore did not receive an ethical declaration.

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