MEDWIN PUBLISHERS
Committed to Create Value for Researchers

Anaesthesia & Critical Care Medicine Journal
ISSN: 2577-4301

Appendix: Comparison with *In Vivo* Measurements in Adults

Introduction

In a previous paper the engineering pressure loss model was compared to in vivo data during mechanical ventilation in volume control mode in adult patients [1]. In this appendix model results are compared to in vivo data specifically to assess its capabilities to account for the dynamics of the respiratory cycle during mechanical ventilation in pressure control mode. This is accomplished via comparisons with dynamic in vivo measurements as measured by the ventilator during the wash-in phase of xenon anesthesia.

Methods

A description of the experimental protocol is provided elsewhere. Below the relevant methods for the pressure control mode measurements are provided [1].

Ethics

This physiological-pharmacological, observational, prospective non-randomised, investigator sponsored study was approved by the ethics committee French CPP Sud-Est 6 (IRB N° IRB00008526). A total of 10 male (6) and female (4) patients aged between 50 and 83, ASA 1 or 2 without history of respiratory disease scheduled for an abdominal surgery under xenon anaesthesia were enrolled in the study. The nature of the study was explained to the subjects and each one signed an informed consent form.

Measurements

Anaesthesia was induced with propofol and remifentanil administered with a target controlled technique (Base Primea Fresenius, France). Each patient's trachea was intubated with a size 7.5 or 8 mm Edgar type endotracheal tube (ETT) (Rusch, Ireland). The patients were ventilated using pressure control mode with pressure targets between 14 and 26 cm H_2O to achieve tidal volumes (V_T) between 8 and 10 mL/kg of theoretical ideal body weight and a frequency of 10 breaths per minute using a FELIX DUAL anaesthetic ventilator station (Air Liquide Medical Systems, France). The FELIX DUAL was specifically designed for xenon anaesthesia including flow calibration, xenon gas concentration, and a mode for economising gas usage [2,3]. The inspiratory/expiratory (I:E) ratio was 1:2 and a positive end expiratory pressure (PEEP) of nominally 5 to 10 cmH_2O was applied during the entire anaesthesia.

After endotracheal intubation and stabilisation, 100% oxygen was delivered for 10 minutes (that also allowed for partial denitogenation of the tissues) before a first set of measurements were recorded for approximately three breathing cycles (T1). Xenon (LENOXe, Air Liquide Santé International, France) was then introduced into the ventilatory circuit with an ultimate target of inhaled concentration of 60%. When the xenon concentration was between 28 and 32% a second data recording for three breathing cycles was made (T2a). After 5 minutes of stabilisation at 60% xenon the third recording of data of similar length was performed (T2). In effect, this protocol provided three test gas mixtures with different densities and viscosities.

Ventilation and respiratory data monitoring of flow rate, pressure at the Y-piece of the patient circuit, inhaled and expired volume, and concentration of oxygen, xenon, and carbon dioxide were recorded on the anaesthesia station and downloaded to a portable computer at a rate of 20 Hz (50 ms intervals). All these measurements were purely observational, realised without modification of the ventilation or any other intervention on the patients. The recorded resolution of the digital pressure and flow measurements were 1 cm H_2O and 1 l/min, respectively. The resolution of inhaled volume, based on the time integration of the flow signal, was 1 ml. The relevant variables for this study were found for each patient by analyzing one of the downloaded waveforms for each gas mixture (respiratory rate (RR), rise time, V_T, PEEP, pressure target during inhalation (P_{target}), peak inhalation flow rate ($Q_{inhal\text{-}peak}$), and the peak exhalation flow rate ($Q_{exhal\text{-}peak}$)). The lung compliance (C) was calculated based on $C=V_T/(p_{target}\text{-PEEP})$ for each gas mixture and averaged for use in calculations (provided in Table A1). The number of patients was arbitrarily fixed to 10.

Numerical Model

The numerical model is described in the main text. Property values for comparison with measurements are given in Table A1. The adult morphology for supine conditions is described below.

Gas	Viscosity x10^5 (kg/s-m)	Density (kg/m^3)
Oxygen (O2 100%)	2.113	1.257
Xenon (Xe/O_2 30/70%)	2.339	2.428
Xenon (Xe/O_2 60/40%)	2.395	3.599

Table A1: Property values at 1 atm. and 37°C [4].

Adult Supine Morphology Model

The lungs are modeled as a symmetric, dichotomously branching network of stiff cylindrical tubes (the source of major losses) segmented into a series of bifurcating elements (the source of minor losses). The 23 generations (increasing incrementally from 0 at the trachea) are based on a morphology model for healthy adult male lungs; that is, mother and daughter diameters, length, and branching angle (θ=70°) at each bifurcation are specified [5]. However, because airway resistance is greater in the supine position [6] the morphology model was modified by changing airway cross section shapes from circular to ellipsoid. The major and minor axes were taken to be 1.2D and 0.8D, respectively; then the hydraulic diameter used for calculations was $D_H \approx 0.94D$ based on a relation for elliptical cross sections [7]. Thus in effect a smaller lung model was used to better represent the mixed gender and supine position of the subjects.

Results

Examples of typical in vivo measurements, in this case taken for patient #2, in the form of individual symbols are shown in Figures A1-A3; for 100% O_2, 30%/70% Xe/O_2, and 60%/40% Xe/O_2, respectively. For each of these figures panel A is the Y-piece pressure time trace and panel B is the flow rate (positive and negative values are for inhalation and exhalation, respectively) time trace. Superimposed on each graph are the in silico results in the form of continuous lines based on the equivalent simulation. The simulations reproduce the general form of the flow curve during inhalation and are quite accurate during exhalation. In Table A2 the measured quantitative parameters and those from simulations are listed for each patient and each gas mixture. Figure A3 shows comparisons of experimental and simulated: peak inhalation flow rate (panel A) and peak exhalation flow rate (panel B) for all the patients and all of the gases.

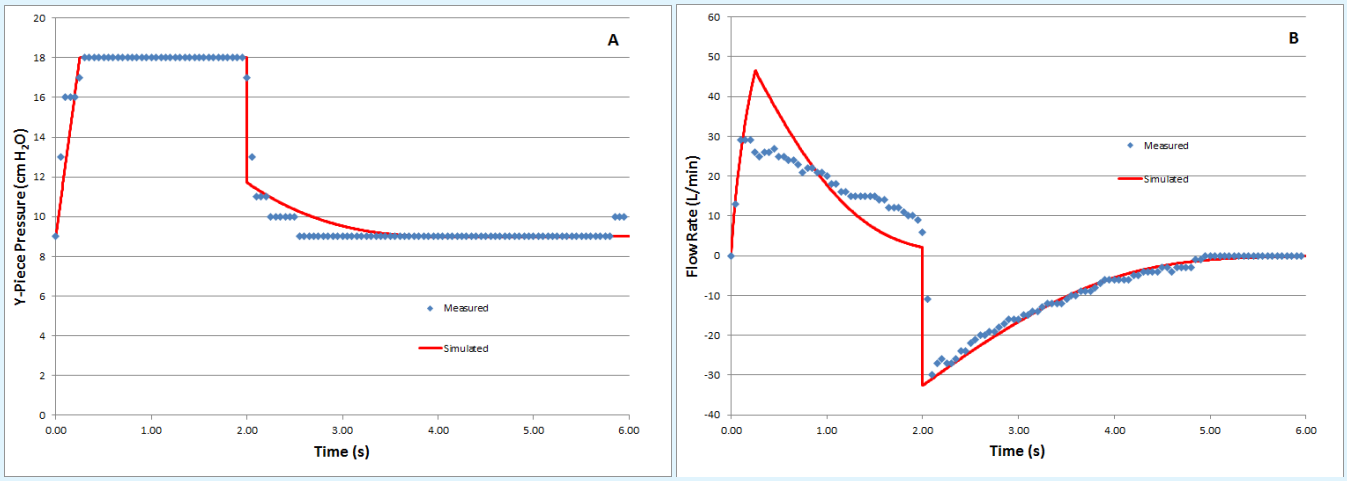


Figure A1: Panels A and B compare dynamic ventilatory parameters, Y-piece pressure and flow rate, respectively, for 100% O_2, measured from experiments (individual symbols) and simulation (solid lines) for patient #2.

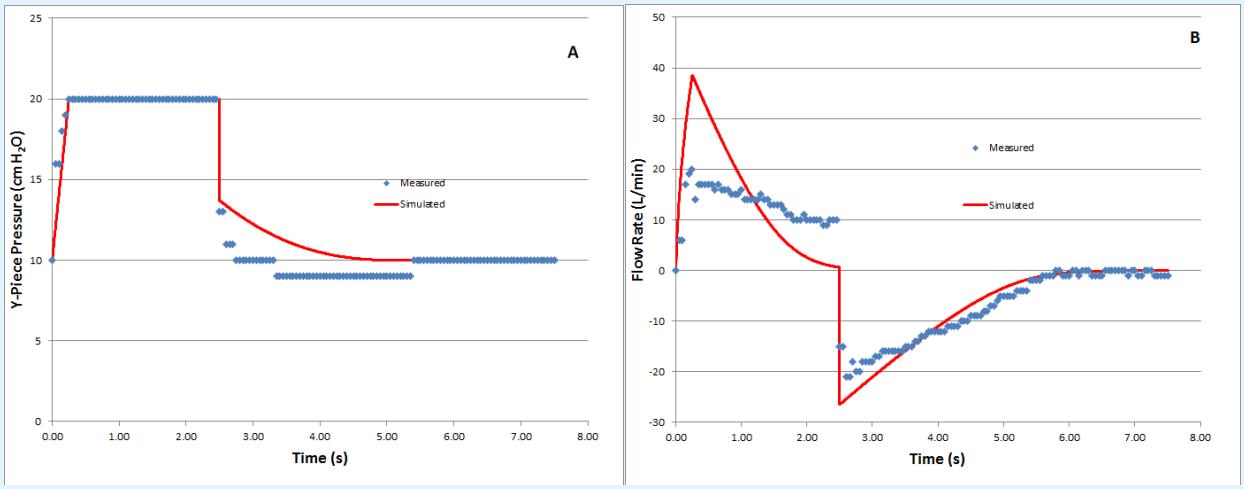


Figure A2: Panels A and B compare dynamic ventilatory parameters, Y-piece pressure and flow rate, respectively, for 30%/70% Xe/O_2, measured from experiments (individual symbols) and simulation (solid lines) for patient #2.

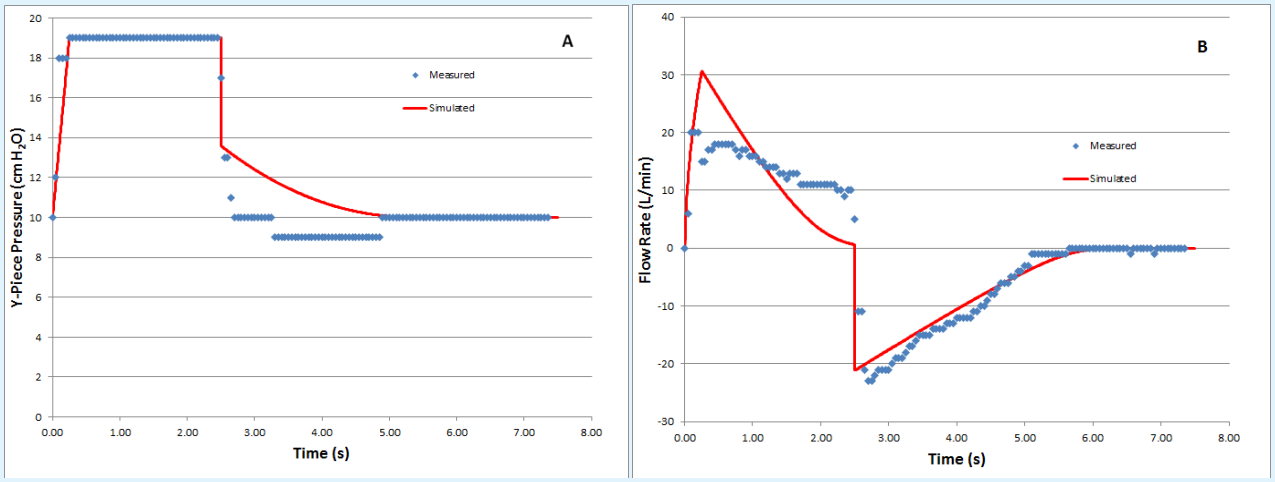


Figure A3: Panels A and B compare dynamic ventilatory parameters, Y-piece pressure and flow rate, respectively, for 60%/40% Xe/O_2, measured from experiments (individual symbols) and simulation (solid lines) for patient #2.

P#	RR	TV (ml)	Rise Time (s)	Lung Compliance (ml/cm H2O)	Ptarget (cm H2O)	PEEP (cm H2O)	Qinhal-peak (l/min))	Qexhal-peak (l/min))	Simulated Qinhal-peak (l/min)	Simulated Qexhal-peak (l/min)
1										
2	10	650	0.25	72.2	18	9	29	-30	39.5	-30.9
3	8	460	0.25	41.8	20	9	32	-38	48.4	-37.4
4	8	450	0.25	40.9	21	10	37	-39	43.2	--35.9
5	14	320	0.25	40.0	14	6	26	-26	31.2	-29.2
6	8	480	0.25	40.0	18	6	30	-37	41.7	-37.9
7	8	510	0.25	42.5	18	6	40	-40	42.9	-37.9
8	8	490	0.25	49.0	18	8	35	-37	47.0	-35.3
9	12	530	0.25	53.0	18	8	36	-38	47.9	-35.0
10	8	460	0.25	51.1	15	6	30	-36	44	-33.0

T1 100% O_2

P#	RR	TV (ml)	Rise Time (s)	Lung Compliance (ml/cm H2O)	Ptarget (cm H2O)	PEEP (cm H2O)	Qinhal-peak (l/min))	Qexhal-peak (l/min))	Simulated Qinhal-peak (l/min)	Simulated Qexhal-peak (l/min)
1										
2	8	550	0.25	61.1	19	10	20	-21	35.9	-24.9
3	8	420	0.25	24.7	26	9	30	-37	40.5	-34.5
4	8	490	0.25	44.5	20	9	25	-27	33.3	-27.0
5	8	400	0.25	44.4	15	6	21	-23	29.2	-24.0
6	8	530	0.25	48.2	17	6	29	-28	33.7	-27.0
7	8	450	0.25	40.9	17	6	30	-29	32.9	-27.0
8										-
9	8	520	0.25	43.3	17	5	28	-30	41.6	-29.4
10	8	550	0.25	55.0	16	6	30	-28	38.1	-26.5

T2a 30% Xe

P#	RR	TV (ml)	Rise Time (s)	Lung Compliance (ml/cm H2O)	Ptarget (cm H2O)	PEEP (cm H2O)	Qinhal-peak (l/min))	Qexhal-peak (l/min))	Simulated Qinhal-peak (l/min)	Simulated Qexhal-peak (l/min)
1	10	510	0.25	34.0	23	8	27	-31	33.6	-26.8
2	8	600	0.25	60.0	20	10	20	-23	32.6	-22.3
3										
4	8	440	0.25	55.0	18	10	19	-23	24.1	-19.1
5	8	380	0.25	38.0	14	4	18	-19	26.5	-21.7
6	8	520	0.25	40.0	18	5	24	-21	31.2	-24.9
7	8	450	0.25	50.0	15	6	20	-21	25.6	-20.4
8	8	570	0.25	71.3	16	8	20	-18	28.9	-19.8
9	8	470	0.25	47.0	15	5	21	-22	31.8	-22.4
10	8	530	0.25	66.3	14	6	21	-20	28.7	-19.8

T2 60% Xe

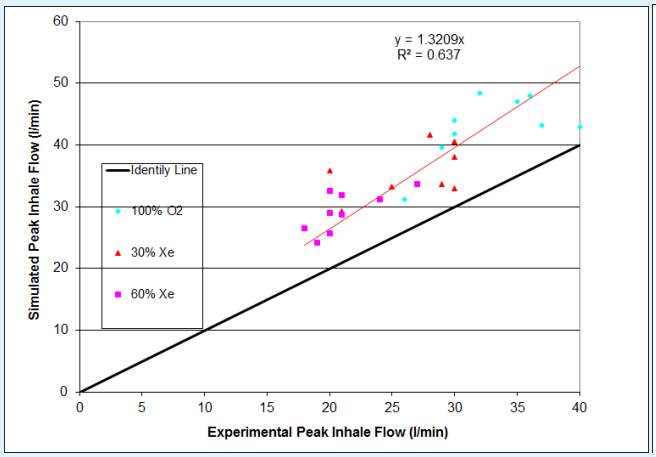
Table A2: The measured quantitative parameters and those from simulations for each patient and each gas mixture. Crossed out rows indicate experimental data that was not available.

Discussion

Presented in this appendix are the in silico results in terms of ventilatory parameters of a numerical model compared to in vivo data collected from a ventilator in pressure control mode during the wash-in phase of xenon anesthesia in adult patients without respiratory disease. The direct comparisons of model and experimental time histories of Y-piece pressure and flow rate shown in Figures A1-A3 and the summarized comparisons in Figure A4 and Table A2, indicate that with knowledge of the gas composition, ETT size, and lung compliance the dynamic ventilatory parameters can be predicted. Even the peak inhalation flow rate, while over predicted by the simulation, is consistent in terms of all the variables including gas composition such that a correction is possible.

However, clearly the real experimental flow rates have a different, slower response than the simulations. This can be explained by noting that the real rapid pressure rise during pressure control mode tends to increase the dynamic aspects of the flow not included in the quasi-static model. In particular, the rigid morphology of the numerical model probably is missing changes in airway caliber during the pressure rise. This can be deduced by the fact that the error is somewhat proportionally to lung compliance as shown in Figure A5. This observation provides a rationale for using pressure control model for neonates, in that they have very low lung compliance compared to adults (~10%) Such that the error due to inertial effects should be <5%.

Regarding the overall accuracy of the simulations, there are some inconsistencies between the in vivo and in silico results that originate from limitations of both the model and the experiments. These issues are discussed in the previous paper [1].



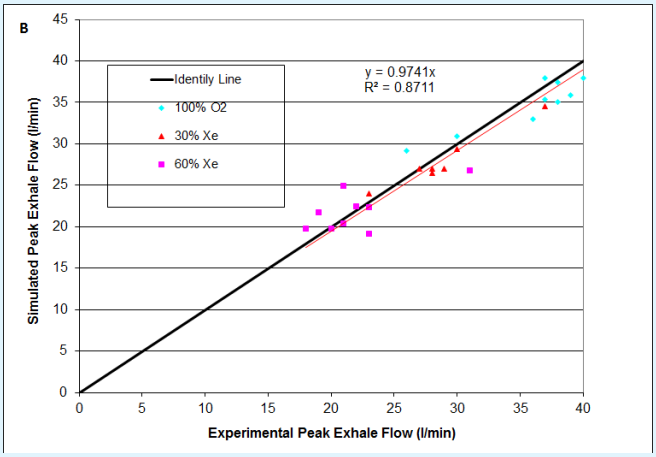


Figure A4: Comparisons of experimental and simulated: peak inhalation flow rate (Panel A) and peak exhalation flow rate (shown as positive values) (Panel B) for all the patients and all of the gases. The solid black line is the identity line indicating perfect agreement. The red line is a linear regression.

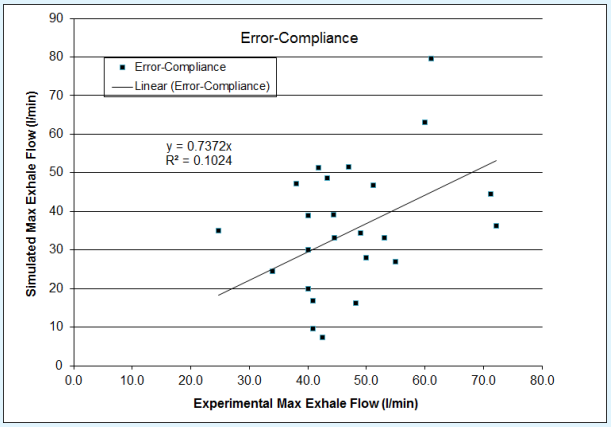


Figure A5: Rationale for using pressure control model for neonates is based on their having very low lung compliance compared to adults (~10%) [4] Such that the error due to inertial effects is estimated to be <5%.

References

1. Katz IM, Majoral C, Daviet C, Bazin J-E, Georges Caillibotte (2017) In Silico Simulations Compared to In Vivo Measurements of the Effects of Fluid Properties on Dynamic Ventilation Parameters during Xenon Anesthesia. Appl Cardiopulm Pathophysiol 21: 3-17.

2. Stoppe C, Fahlenkamp AV, Rex S, Veeck NC, Gozdowsky SC, et al. (2016) Feasibility and safety of xenon compared with sevoflurane anaesthesia in coronary surgical patients: a randomized controlled pilot study. Br J Anaesth 111(3): 406-416.

3. Stoppe C, Rimek A, Rossaint R, Rex S, Stevanovic A, et al. (2013) Xenon consumption during general surgery: a retrospective observational study. Med Gas Res 3(1): 12.

4. Katz I, Caillibotte G, Martin AR, Arpentinier P (2011) Property value estimation for inhaled therapeutic binary gas mixtures: He, Xe, N_2O, and N_2 with O_2. Med Gas Res 1: 28.

5. Soong TT, Nicolaides Py, Yu CP, Soong SC (1979) A statistical description of the human tracheobronchial tree geometry. Respir Physiol 37(2): 161-172.

6. Attinger EO, Monroe RG, Segal MS (1956) the mechanics of breathing in different body positions. I. In normal subjects. J Clin Invest 35(8): 904-911.

7. Shaughnessy EJ, Katz IM, Schaffer JP (2005) Introduction to fluid mechanics. Oxford University Press New York.