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Viscosity and density of common anaesthetic gases: implications for flow measurements

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Although viscosity (μ) is a crucial factor in measurements of flow with a pneumotachograph, and density (ρ) also plays a role in the presence of turbulent flow, these material constants are not available for the volatile anaesthetic agents commonly administered in clinical practice. Thus, we determined experimentally μ and ρ of pure volatile anaesthetic agents. Input impedance of a rigid-wall polyethylene tube (*Z*t) was measured when the tube was filled with various mixtures of carrier gases (air, 100% oxygen, 50% oxygen+50% nitrogen) to which different concentrations of volatile anaesthetic inhalation agents (halothane, isoflurane, sevoflurane, and desflurane) had been added. μ and ρ were calculated from real and imaginary portions of *Z*t, respectively, using the appropriate physical equations. Multiple linear regression was applied to estimate μ and ρ of pure volatile agents. Viscosity values of pure volatile agents were markedly lower than those for oxygen or nitrogen. Clinically applied concentrations, however, did not markedly affect the viscosity of the gas mixture (maximum of 3.5% decrease in μ for 2 MAC desflurane). In contrast, all of the volatile agents significantly affected ρ even at routinely used concentrations. Our results suggest that the composition of the carrier gas has a greater impact on viscosity than the amount and nature of the volatile anaesthetic agent whereas density is more influenced by volatile agent concentrations. Thus, the need for a correction factor in flow measurements with a pneumotachograph depends far more on the carrier gas than the concentration of volatile agent administered, although the latter may play a role in particular experimental or clinical settings.

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The pneumotachograph is the most common device used for flow measurements in respiratory mechanics. Flow measurement via a pneumotachograph is based on the principle of detecting differential pressure across a resistive element within the device. Under laminar flow conditions, the differential pressure (also called the pressure drop) is proportional to flow and also to gas viscosity (μ). Changes in μ, therefore, affect the flow rate measured with a resistive-type pneumotachograph.[1 2] The density of a gas (ρ) also affects flow measurements under turbulent flow conditions[3] or when the flow is estimated by using rotating vane flowmeters. Additionally, pressure measurement with laterally positioned pressure transducers is affected by the gas density via the Bernoulli phenomenon.[4]

Although the viscosities and densities of carrier gases (air, oxygen, and nitrous oxide) can be extracted from physical tables,[5] and the density data for the volatile anaesthetic agents can be calculated based on their molecular structure, the viscosity values for carrier gases containing different concentrations of vaporized volatile anaesthetic agents are not available and cannot be readily deduced from theoretical physical equations. Consequently, it is not known how the commonly used volatile inhalation agents in different concentrations affect flow measurements with a resistive-type pneumotachograph. The aim of the present study was, therefore, to determine experimentally whether the different concentrations of clinically administered volatile anaesthetic agents affect the viscosities and

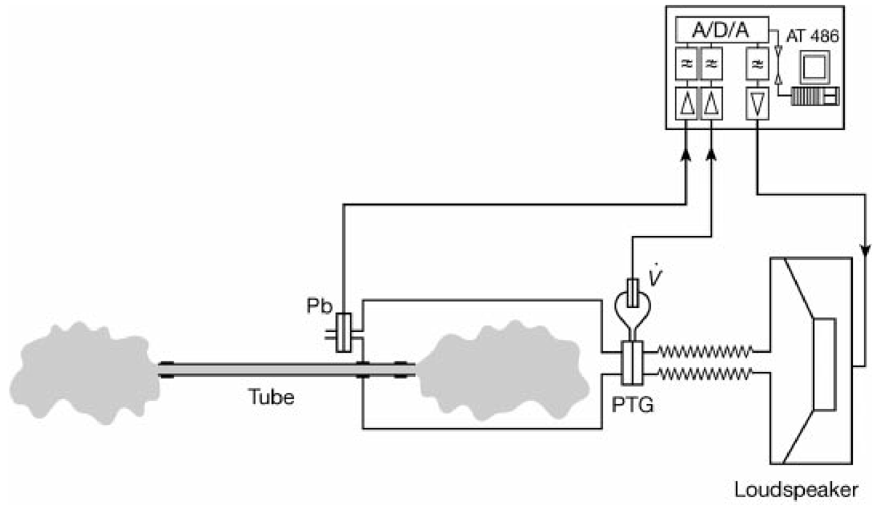

Fig 1 The measurement set-up. *P*b, box pressure; PTG, pneumotachograph; $\dot{V}$ box flow.

densities of the gas mixtures commonly applied in anaesthetic respiratory management, and hence to estimate the extent to which the amounts of the various components affect flow measurements with a pneumotachograph.

Methods

Measurement principle

To determine anaesthetic gases' viscosities and densities, we measured the input impedance of a rigid-wall polyethylene tube (*Z*t) when the tube was filled with the different gas mixtures. As *Z*t can be regarded as a frequency-independent resistance and inertance in series, the real part of *Z*t reflects the resistance of the tube, while the imaginary part (or reactance, *X*) that increases linearly with frequency can be attributed to the inertive effect of the gas ($X=j\omega I$, where ω is the angular frequency, *I* is the inertance and *j* is the imaginary unit $\sqrt{-1}$). At low frequencies, for which the Poiseuille law is still valid, the real part of *Z*t (resistance, *R*) is linearly related to the viscosity of the resident gas in the tube ($R=8\mu l/r^4\pi$, where *l* and *r* are the length and the radius of the tube, respectively). Furthermore, there is a linear relationship between the imaginary part of *Z*t and the density of the gas in the tube ($X=n\omega\rho l/A$, where ω is the angular frequency, and *A* is the cross-sectional area of the tube, and *n* is 4/3 in case of parabolic velocity profile and 1 if the velocity profile is blunt).[6] Accordingly, both μ and ρ of any gas in a tube with known geometry can be determined experimentally by measuring *Z*t.

Measurement apparatus

We adopted the experimental method of Lutchen and colleagues to measure *Z*t.[7] This technique allowed us to determine *Z*t in a wide frequency range in order to ensure the validity of the Poiseuille law, while it also permitted us to change the resident gas in the tube. The scheme of the measurement set-up is presented in Figure 1. A loudspeaker-in-box system generated a small-amplitude pseudorandom forcing signal in a rigid-walled plexiglass box (V_{box}=1.6 litre). The oscillatory signal contained seven frequency components in the range 0.117–6.04 Hz. The components in the forcing signal were selected according to the non-sum-non-difference rule[8] to minimize the effects of non-linearities and harmonics cross-talk. In particular, the 2nd, 5th, 11th, 19th, 31st, 59th, and 103rd harmonics of the fundamental frequency (0.0586 Hz) were included in the signal with component amplitudes decreasing with increasing frequency. A rigid polyethylene plastic tube (*l*=29 cm, *r*=1 mm) was led through the front panel of the box, and two similar-sized plastic bags were attached to the internal and external ends of the tube. As the bags were always flaccid, for example, the pressure in the bags was atmospheric, their influence on the impedance measurement could be neglected.

The input flow of the box ($\dot{V}$) was measured with a screen pneumotachograph connected to an ICS 33NA002D differential pressure transducer. The box pressure (*P*b) with reference to the atmosphere was detected with an identical pressure transducer. Signals of *P*b and $\dot{V}$ were 25 Hz low-pass filtered and sampled at 120 s^{-1} with a 12-bit analogue-to-digital board of an IBM-compatible computer.

Procedure

All measurements were performed in the same climate-controlled laboratory under constant atmospheric conditions (970 hPa), with stable temperature (23°C) and humidity. Before each oscillatory measurement, the two bags were emptied by exposing them to direct vacuum until complete collapse. At the beginning of the experiment, the impedance of the box-tube system (*Z*c) was measured when the plastic bags and the tube were filled with air. Both plastic bags and the tube were then filled with different concentrations of various anaesthetic inhalation agents in turn (halothane, isoflurane, sevoflurane, and desflurane) in 100% oxygen, in a mixture of 50% oxygen+50% nitrogen, or in a mixture of 21% oxygen+79% nitrogen (air). The concentration of the volatile agents were varied between 0.75 and 4% for halothane, 1.25 and 5.4% for isoflurane, 2 and 9% for sevoflurane and 6 and 18% for desflurane by measuring four different concentrations of each within these ranges for each volatile gas. The highest concentrations were limited by the physical characteristics of the vaporizers. Gas mixtures were generated from an anaesthetic machine by the flow of 6 litres of carrier gas through the vaporizer; the outlet was sampled at a rate of 200 ml min^{-1} by means of a Datex AS3 monitor until a steady-state measurement was achieved. Both plastic bags and the tube were then filled with the resulting mixture via a 3-way tap. Before oscillatory measurements, the concentration of each component in the blended gas in the bags was analysed with a Datex AS3 monitor, which was calibrated before each use. Four sets of measurements were made on each gas mixture, the four resulting curves were averaged and used for further analyses (see below). Following a set of measurements with each gas mixture, the external end of the tube was plugged, and the impedance of the closed box (*Z*b) was determined.

Data analysis and statistics

Fast Fourier transformation was used to compute *Z*c ($Pb/\dot{V}$ with the tube open) and *Z*b ($Pb/\dot{V}$ with the tube closed) from the 30-s long recordings by using a 17-s time window and 95% overlapping. As *Z*c consists of *Z*b and *Z*t in parallel, *Z*t was calculated by parallel removal of *Z*b from *Z*c: $Zt = ZbZc/(Zb - Zc)$.

Our data analysis assumes that density and viscosity of a gas mixture change linearly with the density and viscosity values of the pure component gases. Linearity of density necessarily applies to mixtures of ideal gases and it can be assumed that deviations from linearity do not play a significant role in estimating the viscosity. Therefore, multiple linear regression analysis was used to estimate the viscosity and density values of the pure component gases by considering either viscosity or density values of the gas mixtures as dependent, and the amount of component gases as independent variables. Uncertainties in the parameter estimates were expressed as SE values.

Results

Representative input impedance data

The real and imaginary parts of the tube impedance determined experimentally when the system was filled with air or 100% oxygen are presented in Figure 2. The measured real parts for both gases were frequency-independent in the applied range, whereas the reactances increased linearly with increasing frequency.

Viscosity and density of the pure component gases

Viscosity and density values of the pure component anaesthetic gases are demonstrated in Tables 1 and 2, respectively. The viscosity values for pure volatile agents are generally lower than those for the carrier gases. Conversely, markedly greater density values were obtained for the volatile agents than those for the carrier gases.

Viscosity and density of commonly used gas mixtures

Viscosity and density values for gas mixtures commonly used in anaesthetic practice are summarized in Tables 3 and 4, respectively. Clinically applied concentrations of volatile agents have relatively small, although systematic, effects on the viscosity values of the gas mixtures with maximal decrease in viscosity of 3.3–3.5% at 2 MAC desflurane. However, density values of the common anaesthetic gas mixtures were markedly influenced by the volatile agents with maximal elevation in density of 47.5% at 2 MAC desflurane in air. The large changes with desflurane arise from the high concentrations of 1 and 2 MAC for that agent, not from unusually deviant values of viscosity and density.

Discussion

Viscosity and density of the gases commonly used in anaesthetic practice were determined in the present study. We demonstrated that the viscosity values of the common volatile agents are markedly lower than those of the carrier gases routinely applied in anaesthetic management. As in clinical practice the volatile agents are administered in very low concentrations, their net effects on the viscosity, and hence, on the flow measurement with a pneumotachograph do not exceed 4% for routinely used anaesthetic gas mixtures. The density of common anaesthetic gas mixtures was markedly influenced by the presence of volatile agents even at clinically applied concentrations with a possible increase in density of almost 50%.

Methodological issues

Before discussing the implications of the present findings, as concerns the measurement of respiratory mechanics, some methodological issues need to be considered. First, the parameter estimations assume that the measurements were made in the presence of laminar flow in the tube.[6] To verify this assumption, we calculated the Reynolds number ($Re=rv\rho/\mu$) from our experiments, by calculating the axial velocity (v) from the measurements of flow on entry into the plastic box. This calculation revealed that the Reynolds numbers were lower (130–140) than the critical value

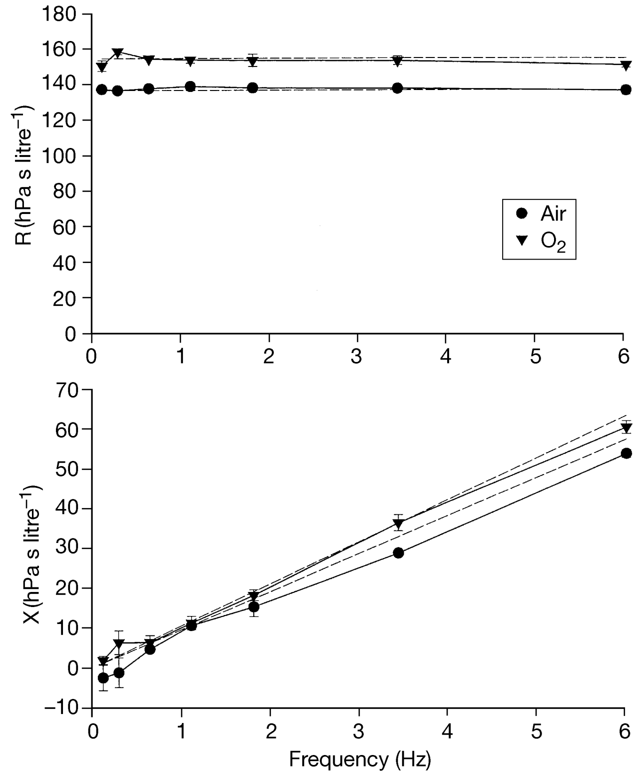

Fig 2 Resistance (*R*) and reactance (*X*) values for air and oxygen (the dashed lines indicate the calculated resistance and reactance values, and the continuous lines represent the resistance and reactance values measured with the present set-up). Error bars represent SD.

(1160). Thus, it can be concluded that laminar flow developed in the tube, and thus, the use of the Poiseuille equation to estimate viscosity was appropriate.

Second, on the basis of physical principles, *R* for a rigid tube increases with increasing oscillatory frequency.[10] Thus, if this phenomenon exerts a significant effect, we should overestimate the viscosity, as the Poiseuille law is valid for low frequencies. In this study, the real part was always almost entirely frequency-independent (e.g. Fig. 2). Therefore, averaging the *R* values over the frequency range studied did not seem to introduce any systematic error in the estimation of viscosity. Additionally, the *I* of a rigid tube decreases slightly with increasing oscillatory frequency.[10] In this study, we observed an almost perfect linear increase in *X* in the frequency range studied. Thus, the inertance can also be considered frequency-independent in our measurements and can be used to estimate the density of the resident gas mixture in the tube.

Validity and accuracy

As the analysis applied in the present study provides viscosity and density values for carrier gases (pure oxygen and nitrogen), comparing our values to those in reference tables[9] (the latter being corrected to temperature of 23°C and atmospheric pressure of 970 hPa) gives information regarding the reliability of the technique used in the present study. Viscosity values for oxygen and nitrogen determined experimentally in the present study are very close to their reference values (differences are 1.7 and 0.9%, respectively) suggesting that viscosity values of other pure component gases are also likely to be reliable. However, density values are slightly underestimated for both nitrogen and oxygen (6.7 and 1.5%, respectively). This small underestimation is most likely because of the slight distortion of the parabolic velocity profile, particularly at the entrance and at the exit of the tube, which decreases the factor '*n*' from 4/3 towards 1 in the equation relating inertance to density[6] (see above). Accordingly, a 1–7% underestimation can be expected in all density values reported in the present study.

The precision of estimates for oxygen and nitrogen is excellent in the present experiment with standard errors lower than 2%. Nevertheless, our estimates for the viscosity and density values of volatile inhalation agents display lower accuracy. In the present study, the concentration of volatile agents delivered was limited to the physical capacities of the vaporizers. Thus, extrapolation of the physical parameters for pure volatile gases was based on measurements when these agents were present only at very low concentrations. Indeed, the accuracy of our estimate increased markedly with increasing volatile agent concentration in the carrier gas, with lowest accuracy for halothane (maximum concentration 4%) and highest for desflurane (maximum concentration 18%).

Implications

Flow measurement is sensitive to the viscosity of the gas, as the pressure drop across the resistive element of a pneumotachograph (either screen or Fleisch) is linearly related to this parameter.[3] Thus, a decrease in gas viscosity underestimates the real flow and overestimates the resistance and the elastance, and vice versa. Accordingly, without applying a correction factor, this phenomenon biases the results of studies on respiratory mechanics. In recent publications, following a change in the nature of the inhaled gas, no correction factor was applied to flow measurements, which may have biased their results to some extent.[11 12]

In the present study, as expected, the viscosity of the carrier gas increased significantly when the oxygen content increased. Therefore, calibrating a pneumotachograph with air and using a different carrier gas with high oxygen content will lead to an underestimation of respiratory mechanical parameters. However, for a given carrier gas, the presence of a volatile agent in low concentration is not likely to significantly affect the resulting viscosity. Thus, our results suggest that the effect of the viscosity alteration as a result of volatile agent administration may not be physiologically significant (approximately 4% at most) when a single reading of a respiratory mechanical parameter is made in a given clinical setting. However, when repeated measurements are performed in animal studies or under clinical circumstances in order to compare different agents or populations, it may be important to take into account viscosity changes in the different gas mixtures in the evaluation of respiratory mechanics under different experimental conditions.[13] Given that we determined viscosity values of pure volatile agents, the impact of the altered viscosity on flow measurement can be estimated and in future studies the importance of applying a correction factor will depend on the particular experimental condition.

The density of the gas mixture was affected by the amount of both oxygen and the volatile agents (Table 4). Although the density of the gas in the lungs does not play a very significant role under most experimental conditions, this physical parameter may influence the measured mechanical parameters via the Bernoulli effect in lateral pressure measurements[4] and/or in the event of turbulent flow.[6 14] It may be noted that, as the measurement of flow with a pneumotachograph is based on the detection of a differential pressure between the two ports, the influence of density via the Bernoulli effect is cancelled out in such differential pressure measurements.[3] However, the measurement of pressure at an airway opening is more likely to be affected by the Bernoulli effect and thus by density. Furthermore, density affects flow measurements under conditions of turbulence, when the Reynolds number exceeds a critical value.[14] In this regard, Bates and colleagues[4] proposed an experimental method for determination of the correction factor to be applied at high Reynolds numbers. Our measurements suggest the need for such a correction if either the oxygen content or the volatile agent concentration of the intrathoracic gas is changed during the experimental procedure.

In conclusion, we adopted a measurement technique[7] to determine the physical properties of volatile agents commonly administered in anaesthetic management. The measurements were validated by comparing viscosity and density values of oxygen and nitrogen to their reference values.[9] We conclude that volatile agents in commonly used clinical concentrations slightly affect the gas mixture viscosity. However, the oxygen content in the carrier gas and the nature of the volatile anaesthetic agent affect the density of the gas mixture significantly. Therefore, our results suggest that attention should be paid to the compositions of the commonly used inhalation anaesthetic gases during respiratory mechanical measurements; application of a gas-dependent correction factor may be necessary for accurate flow measurements with a resistive-type pneumotachograph.

Table 1 Viscosity of commonly used anaesthetic gases. Numbers between brackets: reference values (9). All values are given at temperature of 23°C and atmospheric pressure of 970 hPa

	Mean (Pa s$\times 10^{-5}$)	SE of estimate
Nitrogen	1.812 (1.781)	0.0082
Oxygen	1.999 (2.018)	0.0073
Halothane	1.249	0.3529
Isoflurane	0.892	0.2439
Sevoflurane	1.276	0.1688
Desflurane	1.452	0.0706

Table 2 Density of commonly used anaesthetic gases at temperature of 23°C and atmospheric pressure of 970 hPa. Numbers between brackets: reference values (ρ_{ref}) transformed to 23°C and 970 hPa ($\rho_{ref}=\rho_0\ P_m T_0/P_0 T_m$, where P_m=970 hPa, T_0=273 K, P_0=1010 hPa, T_m=300 K and ρ_0=1.429 kg/m^3 for oxygen and ρ_0=1.25055 kg/m^3 for nitrogen) (9)

0	Mean (kg m^{-3})	SE of estimate
Nitrogen	1.02 (1.093)	0.017
Oxygen	1.23 (1.249)	0.015
Halothane	6.48	0.72
Isoflurane	5.19	0.50
Sevoflurane	6.12	0.34
Desflurane	5.44	0.14

Table 3 Viscosity values (Pa s$\times 10^{-5}$) of common anaesthetic gas mixtures. Numbers between brackets: relative change in the viscosity because of administration of the volatile agents. The MAC values for halothane, isoflurane, sevoflurane, and desflurane are 0.75, 1.15, 2, and 7.25%, respectively

	Halothane		Isoflurane		Sevoflurane		Desflurane	
	1 MAC	2 MAC	1 MAC	2 MAC	1 MAC	2 MAC	1 MAC	2 MAC
100% oxygen	1.9934 (99.7)	1.9878 (99.4)	1.9862 (99.3)	1.9735 (98.7)	1.9809 (99.0)	1.9629 (98.1)	1.9662 (98.3)	1.9334 (96.7)
Air	1.8457 (99.7)	1.8401 (99.4)	1.8385 (99.3)	1.8258 (98.6)	1.8332 (99.0)	1.8152 (98.1)	1.8185 (98.2)	1.7857 (96.5)
50% oxygen	1.8999 (99.7)	1.8943 (99.4)	1.8927 (99.3)	1.8800 (98.7)	1.8874 (99.1)	1.8694 (98.1)	1.8727 (98.3)	1.8399 (96.6)

Table 4 Density values (kg/m^3) of common anaesthetic gas mixtures. Numbers between brackets: relative change in the density because of the administration of the volatile agents. The MAC values for halothane, isoflurane, sevoflurane, and desflurane are 0.75, 1.15, 2, and 7.25%, respectively

	Halothane		Isoflurane		Sevoflurane		Desflurane	
	1 MAC	2 MAC	1 MAC	2 MAC	1 MAC	2 MAC	1 MAC	2 MAC
100% oxygen	1.273 (103.2)	1.312 (106.4)	1.279 (103.7)	1.325 (107.4)	1.356 (109.9)	1.478 (119.8)	1.486 (120.5)	1.739 (141.0)
Air	1.104 (103.7)	1.143 (107.4)	1.110 (104.3)	1.156 (108.6)	1.187 (111.5)	1.309 (123.0)	1.317 (123.7)	1.570 (147.5)
50% oxygen	1.166 (103.5)	1.205 (107.0)	1.172 (104.0)	1.218 (108.1)	1.249 (110.9)	1.371 (121.7)	1.379 (122.4)	1.632 (144.9)

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