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Effects of helium–oxygen mixtures on endotracheal tubes: an in vitro study

Patrick Gerbeaux[a,*], Marc Gainnier[b], Jean-Michel Arnal[b], Laurent Papazian[b], Philippe Jean[a], Jean-Marie Sainty[b]

[a] *Emergency Department, Hôpital Conception, 147 Bd Baille, Marseille Cedex 5 13385, France*
[b] *Medical Respiratory Intensive Care Unit, Hôpital Salvator, Marseille, France*

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Abstract

Question: To determine flow pattern and critical Reynolds numbers in endotracheal tubes submitted to different helium–oxygen mixtures under laboratory conditions.

Materials and methods: Flow–pressure relationships were performed for seven endotracheal tubes (rectilinear position, entry length applied) with distal end open to atmosphere (predicted internal diameters: 6–9 mm). Nine helium–oxygen mixtures were tested, with FIHe varying from zero to 0.78 (increment: 10%). Nine flows were tested, with rates varying from 0.25 to 1.60 l s^{-1} (increment: 0.15 l s^{-1}). Gas flow resistance was calculated, and for each endotracheal tube, a Moody diagram was realised. Flow regime and critical Reynolds numbers were then determined (fully established laminar, nonestablished laminar, smooth turbulent, or rough).

Results: Even low concentration of helium in inspiratory mixture reduces endotracheal tubes resistance. Effect is maximal for high flows, small tube and high FIHe. Critical Reynolds numbers are inversely correlated to tube diameter.

Answer: Under laboratory conditions, flow pattern in endotracheal tubes varies from fully established laminar to rough. Knowledge of the critical Reynolds numbers allows correct application of fluid mechanic formula when studying tube or gaseous mixture effects on respiratory mechanisms.

Keywords: Endotracheal tube; Helium–oxygen mixture; Pressure drop; Mechanical ventilation; Heliox; Fluid-mechanics laws

1. Introduction

Helium–oxygen mixtures are studied in patients with airway obstructive diseases (Gluck et al., 1990; Polito and Fessler, 1995; Kass and Castriotta, 1995; Anderson et al., 1993; Manthous et al., 1995). In mechanically ventilated patients, the effect of the endotracheal tube (ETT) is not well defined. Numerous factors, such as real diameter, curvature, mucous deposition, kinetic energy dissipation at both ends of the tube can influence flow pattern and interfere with in vivo or in vitro results, leading to potentially erroneous conclusion (Isabey et al., 1995; Houck et al., 1990; Papamoschou, 1995; Comolet, 1994). However, applying fluid mechanics laws necessitate precise knowledge of the flow pattern studied (fully established laminar, nonestablished laminar, smooth turbulent, or rough). Critical Reynolds numbers (i.e. Reynolds numbers for which flow pattern change) are known for small ETT in natural curvature and without entry flow (Jarreau et al., 1999). These critical Reynolds numbers are unknown for adult ETT, under both laboratory and clinical conditions. The questions are: (1) What are, under laboratory conditions, the critical Reynolds numbers for adult ETT (6–9 mm of predicted internal diameter)? (2) What are, under laboratory conditions, flow limits for changes in flow pattern with different helium–oxygen mixtures?

2. Materials and methods

2.1. Study design

Helium was contained as a fixed mixture (78:22, helium and O_2, respectively) in a canister pressurised at

*Corresponding author. Tel.: +33-4-91-38-36-53; fax: +33-4-91-38-36-71.

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210 bar (Air liquide Santé International, Paris, France), and delivered at 3 bar into the ventilator inlet normally used for air. The FIO_2 set on the ventilator (Servo 300, Siemens-Elema, Solna, Sweden) was compared with the FIO_2 indicated by the ventilator's own O_2 sensor, and an external FIO_2 sensor (considered as reference) (oxygen monitor OM25ME, airox, Bio ms, Pau, France). Nine heliox mixtures (FIHe from zero to 78% and 10% increment) were tested (ATPD conditions). A Servo 300 was used because of its ability to deliver exact flow, volume and FIHe (Tassaux et al., 1999). Flows were controlled using a Fleisch pneumotachograph (No. 2) placed between the Y piece of the ventilator circuit and the ETT. The pneumotachograph was a part of the Visionair system (Visionair System. SARL Erime. France). It was calibrated for each gaseous mixture, using a 1 l syringe and the Visionair software. The software allows calibration of the pneumotachograph with different mixtures. The flow detected was corrected by the software, depending on density and viscosity of the mixture selected. Inspiratory volume was computed by integration of flow. The calibration of the Visionair was then controlled using a 1 l syringe filled with the adequate mixture. Volume-controlled mode was used, with constant flow pattern (0.25–$1.6\,cm^3\,s^{-1}$, $0.15\,cm^3\,s^{-1}$ increment).

Seven different ETT (6–9, Mallinckrodt, Inc., Glens Falls, NY) were tested in rectilinear position to avoid pressure drop linked to curvature (Comolet, 1994). Original length was kept for each ETT (31 cm (ETT 6), 33 cm (ETT 6.5), 33.5 cm (ETT 7), 34 cm (ETT 7.5 and 8), 36.5 cm (ETT 8.5 and 9)). Each ETT's real diameter was controlled using a volumetric procedure. The ETT, in rectilinear position, was filled with a precise volume of water (V_w). The volume of a rectilinear tube is equal to $(L\,\pi\,D^2)/4$). So, the diameter was calculated equal to the square root of $((V_w\,4)/(L\,\pi))$. An entry length was applied between the pneumotachograph and the ETT to obtain a fully developed flow in the ETT (Comolet, 1994; Lofaso et al., 1992). The distal end of the ETT was open to the atmosphere. The pressure transducer was connected to a hole 1 mm in diameter drilled in the ETT connector (Fig. 1).

For each gaseous mixtures, flow rate and ETT, five successive measurements of pressure and flow were performed at a 200 Hz frequency and averaged. Gas flow resistance was calculated by dividing pressure (P) by flow (v). For each ETT, a Moody diagram was realised. The Moody diagram plots the ETT resistance coefficient (Λ) against the Reynolds number (Re) using a double logarithmic scale. It allows determination of the flow regimen (fully established laminar (slope –1), nonestablished laminar (slope –0.5), smooth turbulent (slope –0.25) or rough (slope 0)) and critical Reynolds numbers. Results are expressed using CGS units system. Pressure (P) is expressed in $g\,cm^{-1}\,s^{-2}$ (1 cm H_2O = $980\,g\,cm^{-1}\,s^{-2}$). Flow (v) is expressed in $cm^3\,s^{-1}$. Gas flow resistance (R_{gas}) is expressed in $g\,cm^{-4}\,s^{-1}$ (1 cm $H_2O\,s\,l^{-1}$ = $0.98\,g\,cm^{-4}\,s^{-1}$). The Reynolds number (Re) was determined using the classical formula

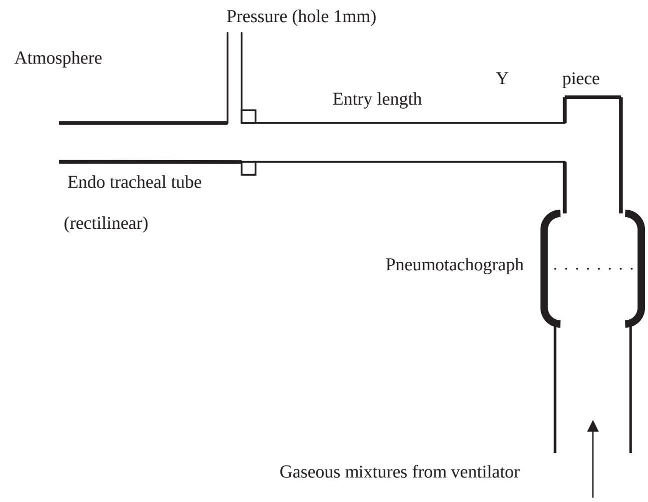

Fig. 1. Schematic representation of set-up used.

$$Re = (4v\rho)/(\pi D\mu), \tag{1}$$

where v is the flow ($cm^3\,s^{-1}$), ρ the volumic mass ($g\,cm^{-3}$), D the internal diameter of the ETT (cm), and μ the dynamic viscosity ($g\,cm^{-1}\,s^{-1}$) (Papamoschou, 1995; Comolet, 1994; Wright et al., 1989; Slutsky et al., 1980). Eq. (1) shows that, for fixed ETT and flow, the Reynolds number of an helium–oxygen mixture is always smaller than the Reynolds number of a mixture containing solely oxygen. Re is a governing parameter in pipe flow. ETT is ranked as a pipe, with a length, a diameter and a wall stress (τ, in $g\,cm^{-1}\,s^{-2}$) (Papamoschou, 1995). Wall stress is related to the resistance coefficient Λ

$$\tau = \Lambda\rho U^2 0.125, \tag{2}$$

where U is the velocity (flow/cross-sectional area, in $cm\,s^{-1}$). It is also related to the pipe characteristics and the viscous dissipation pressure (P_{vd}):

$$\tau = P_{vd} D L^{-1} 0.25. \tag{3}$$

So, using experimental data, the resistance coefficient Λ can be calculated as (Papamoschou, 1995; Comolet, 1994)

$$\Lambda = 2(P_{vd} D L^{-1})/(\rho U^2).$$

The general form of the $\Lambda - Re$ relationship, called the Moody diagram, is

$$\Lambda = A\ Re^{n-2}, \tag{4}$$

where A and n are constants depending on the flow pattern and pipe roughness (Houck et al., 1990; Comolet, 1994).

The pressure drop in a pipe is estimated using the generalised Bernouilli formula (Comolet, 1994):

$$\Delta P = P_{vd} + P_{ke},$$