Medical Engineering and Physics 000 (2015) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Flow measurement in mechanical ventilation: A review

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ARTICLE INFO

Article history:
Received 29 May 2014
Revised 8 January 2015
Accepted 18 January 2015
Available online xxx

Keywords:
Flowmeter
Artificial ventilation
Fleisch pneumotachograph
Hot wire anemometry
Orifice meter
Ultrasonic flowmeter
Fiber optic sensor
Micromachined sensor

ABSTRACT

Accurate monitoring of flow rate and volume exchanges is essential to minimize ventilator-induced lung injury. Mechanical ventilators employ flowmeters to estimate the amount of gases delivered to patients and use the flow signal as a feedback to adjust the desired amount of gas to be delivered. Since flowmeters play a crucial role in this field, they are required to fulfill strict criteria in terms of dynamic and static characteristics. Therefore, mechanical ventilators are equipped with only the following kinds of flowmeters: linear pneumotachographs, fixed and variable orifice meters, hot wire anemometers, and ultrasonic flowmeters. This paper provides an overview of these sensors. Their working principles are described together with their relevant advantages and disadvantages. Furthermore, the most promising emerging approaches for flowmeters design (i.e., fiber optic technology and three dimensional micro-fabrication) are briefly reviewed showing their potential for this application.

1. Introduction

Accurate and continuous monitoring of gas exchange during artificial ventilation is pivotal, to avoid common side effects related to uncorrected ventilation, such as volutrauma or barotrauma (too high amount of gas delivered to patients). In this scenario flowmeters play a crucial role, being used to accurately measure the right amount of gas. Moreover, the volumes of gases exchanged by patients (e.g., minute volume and tidal volume) are estimated by passing the flow signal through an electronic integrator [1]. As a consequence, flowmeters must fulfill strict requirements in terms of both dynamic (i.e., adequate frequency response and short response time) and static (i.e., good accuracy and resolution, high sensitivity, and adequate turndown ratio) characteristics. The use of these sensors with critically ill patients does not allow frequent calibration, therefore zero and sensitivity drifts should be reduced as much as possible. Furthermore, the pneumatic resistance and the volume added to the breathing circuit should be minimized. Lastly, the sensors must be able to reject the influence of gas temperature and composition. This concern is important because both gas composition and gas temperature can experience large changes in mechanical ventilation. Therefore, the influence of gas temperature and composition and the influence of water vapor content on sensors' output must be negligible or well predictable.

The early 1970s, Hayward estimated more than 100 different types of commercially available flowmeters [2] with a mode of operation based on almost any physical domain. Furthermore, other approaches have been developed due to the advances of three dimensional techniques of micro-fabrication [3] and fiber optics technology [4]. On the other hand, the mentioned strict requirements limit the number of flowmeters suitable in mechanical ventilation. In fact, the commercial mechanical ventilators are equipped with few kinds of flowmeters: orifice meters, ultrasonic flowmeters, hot wire or hot film anemometers, Fleisch and screen (or Lilly) pneumotachographs.

Linear resistance pneumotachographs (both Fleisch and Lilly), which transduce flow rate in pressure drop across a linear resistance, have been largely employed in mechanical ventilation for years [1]. Good accuracy, compactness, mostly linear response and short response time are the main advantages; but their output suffers from the dependence on gas mixture composition and temperature, and the shift from linearity at high flow rate [5]. Orifice flowmeters show the same advantages and drawbacks with respect to linear pneumotachographs. The main difference is their quadratic response, however it could be linearized (variable area orifice meter). Hot wire anemometers are based on convective heat exchange. Their main advantages are: good accuracy, high sensitivity at low flow rate and short response time, the main drawback is their fragility [6]. The most

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http://dx.doi.org/10.1016/j.medengphy.2015.01.010
1350-4533/

popular ultrasonic flowmeters are based on time of flight, where the change in transit time through a streaming medium is related to the flow rate. The main advantages are: absence of mechanical parts, negligible pneumatic resistance, good dynamic response, and the possibility to make negligible the output dependence on gas composition and temperature [7–9]; on the other hand they seem to be less accurate than the above cited flowmeters.

In addition to the already well-established techniques, many research groups are working on the development of micromachined and fiber optic-based flowmeters. Micromachined sensors hold immense potential thanks to low energy consumption, good accuracy, and small size; moreover the continuous development of three dimensional technologies of micro-fabrication is improving their design [3]. Fiber optic technology allows developing sensors with good sensitivity, good accuracy, low pneumatic resistance, and large bandwidth [10,11]; moreover, their immunity from electromagnetic interferences enables the use of these sensors during magnetic resonance procedures.

This paper aims to provide a detailed description of the flowmeters employed in commercial mechanical ventilation, and an overview of the most promising emerging technologies. The working principle of such sensors is described in detail, then sensor advantages and weaknesses, considering the main critical issues due to the particular application field, are discussed (i.e., wide range of flow rates, dynamic performances, changes in gas concentrations, vapor condensation).

2. Traditional flow metering in mechanical ventilators

In this section, flowmeters traditionally used in mechanical ventilation are described. As shown in Table 1, commercial mechanical ventilators mainly use linear resistance pneumotachographs, described in Section 2.1; ultrasonic flowmeter, described in Section 2.2, hot wire anemometers, described in Section 2.3; and orifice meter described in Section 2.4.

2.1. Linear resistance pneumotachographs

As well known, the working principle of pneumotachographs is based on the placement of a resistance into a pipeline, in which the fluid is running full: the pressure drop (ΔP) across the resistance (i.e., the primary device) is linearly related to the flow rate (Q), according to the Hagen–Poiseuille law, under laminar regime. Therefore, the measurement chain needs a differential pressure sensor (i.e., the secondary device) to measure the change in pressure (ΔP).

Two configurations of pneumotachographs, which differ each other in the design of the resistance, are largely used: Fleisch pneumotachographs (FPs) (Fig. 1A), proposed by Fleisch in the early nineties [12], are constituted by a number of parallel capillary tubes; after few decades, Lilly introduced a different solution with a linear resistance based on a fine wire mesh (Fig. 1B) [13]. Fig. 1C schematically shows

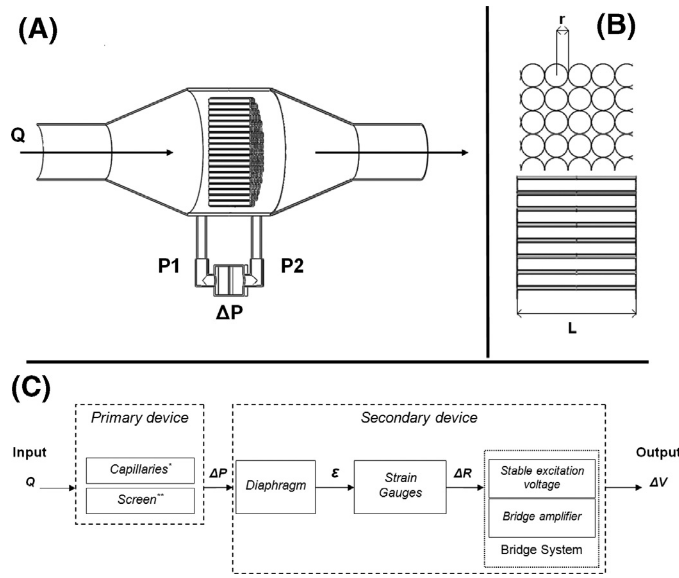

Fig. 1. (A) Design of a Fleisch pneumotachograph, (B) capillary tubes geometry, (C) working principle block diagram of a pneumotachograph (*Fleisch, **Lilly).

the entire measurement chain: ΔP, which is proportional to Q, can be generated by the fine wire-mesh screen or by the capillaries (primary device); then, this pressure is transduced by the secondary device (i.e., a differential pressure sensor) into a voltage output.

The linear relationship between Q and ΔP depends on the geometry of the resistance (capillary length L, capillary radius r, and number of capillaries n) and on the physical characteristics of the gas:

$$\Delta P = \frac{8 \cdot \mu \cdot L}{n \cdot \pi \cdot r^4} Q \tag{1}$$

where μ is the dynamic viscosity of the fluid. This linear model is the most popularly accepted relationship to describe FP behavior, although some authors have investigated a second order polynomial model [14,15], called Rohrer equation [16].

Considering valid the linear model, the sensitivity (S) of the FP can be expressed as:

$$S = \frac{\partial \Delta P}{\partial Q} = \frac{8 \cdot \mu \cdot L}{n \cdot \pi \cdot r^4} \tag{2}$$

Eq. (2) provides useful information to drive the design of FPs and to adjust the sensitivity by modifying the geometry of the resistance: S can be increased by extending the capillaries or by making smaller r. Moreover, Eq. (2) shows that the influence of r on S is higher than the one of L: for instance an increase by 50% of L causes an increase by 50% of S; an increase by 50% of r causes a marked sensitivity decrease which becomes 6% of the initial one. Therefore, the geometry

Table 1
Type of flowmeters used on several commercial mechanical ventilators.

Manufacturer	Mechanical ventilator	Working principle
Drager	Babylog® VN500; Evita	Hot wire anemometry
Maquet	Servo-n; Servo-U	Hot wire anemometry
CareFusion	AVEA© Ventilator System 200, 300; BEAR 1000	Hot wire anemometry
Covidien	Newport™ e360 Ventilator	Hot wire anemometry
Philips	Respironics V200	Hot wire anemometry
SLE	SLE5000	Hot wire anemometry
Life Medical Equipment Inc.	BEAR CUB™ 750vs Infant Ventilator	Hot wire anemometry
CareFusion	Bird 8400ST; Vela©	Variable orifice
Hamilton Medical	HAMILTON-C2; GALILEO	Variable orifice
eVent Medical	Inspiration Series Ventilator F7300000, F7200000, F7100000	Screen pneumotachograph
Maquet	Servo Ventilator 900 C/D/E	Screen pneumotachograph
Maquet	Servo-i Ventilator Siemens	Ultrasonic flowmeter

Please cite this article as: E. Schena et al., Flow measurement in mechanical ventilation: A review, Medical Engineering and Physics (2015), http://dx.doi.org/10.1016/j.medengphy.2015.01.010