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Adaptive control of a pressure-controlled artificial ventilator: A simulator-based evaluation using real COPD patient data

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ABSTRACT

The paper discusses the application of a direct adaptive controller to a pressure controlled artificial ventilation problem. In pressure controlled ventilators, the manipulated variable is the maximum flow applied to the patient during the active phase (inspiration), and the regulated variable is the peak pressure at end-inspiration. This simulation case study focuses on patients diagnosed with Chronic Obstructive Pulmonary Disease (COPD), which require artificial/mechanical ventilation. An adaptive PID controller ensures peak pressures below critical values, by manipulating the flow delivered by the ventilator. The simulation study is performed on fractional-order models of the respiratory impedance identified from lung function data obtained from 21 COPD patients. Additional simulation studies show the robustness of the controller in presence of varying model parameters from the respiratory impedance of the patient. Possibilities to implement the control strategy as an online adaptive algorithm are also explored. The results show that the design of the control is suitable for this kind of application and provides useful insight on realistic scenarios.

1. Introduction

Mechanical ventilation is a rescue therapy, applied to patients who require long-term ventilatory support, due to inefficiency in breathing parameters. Mechanical ventilators are either pressure based, or flow based controlled. It is usually the decision of the clinician to set an optimal value for the ventilator's manipulated variable [1,2]. However, a challenge in practice is that the patient's parameters are varying, requiring continuous updates of the ventilator to match the required pressure and flow values to achieve optimal ventilation of patient's lungs [2,3]. It is therefore crucial to develop feedback control techniques which can deal with changing parameters. Furthermore, these control techniques may also adapt the controller parameters, when significant changes in the system occur (i.e. changes in respiratory properties).

The idea of measuring first the respiratory impedance prior to ventilation has been discussed some decades ago, addressing the need to obtain knowledge-based mechanical ventilation assistance [2,4]. The need for adaptive control due to changes in the physiological parameters has been assessed and its advantages over conventional techniques shown minimizing several objective functions, e.g. work of breathing, preset alveolar pressure, respiratory rate, tidal volume [4,5]. For more than two decades, there has been a growing awareness of the potential for ventilator-induced injury, showing that deliberate use of low tidal volumes decreased mortality [2,5]. Given the diversity of ventilator modes and settings, it is difficult to define a 'standard mechanical ventilation' benchmark for testing closed loop performance for volume or pressure based control. Pressure-controlled ventilation mode is one of the recent modes introduced in clinical use [4–7], but volume controlled modes are also addressed [8]. Most of the

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controllers derived for minimizing some cost function in order to follow some preset requirements, are based on explicit function formulations [4,6–9]. Although providing 95% of the closed loop control in industry, the PID (Proportional Integral Derivative) controllers are not prevalent in clinical technology. Perhaps the reason is that knowledge-based functions using patient information and clinical practice seems more adequate for integrating medical expertise with physiology.

In this paper, we propose to make use of the PID control algorithm, the backbone of control algorithms. Since the mechanical parameters are known to vary significantly during surgery or ICU, adaptive control algorithms are required [5,7]. The focus of the simulation study discussed in this work lies on the artificial ventilation of patients. Hence, the investigation underlies the performance of a novel adaptive PID control algorithm, using respiratory impedance values measured from 21 patients. The specialized literature shows that the most prevalent in requiring mechanical ventilation are those patients diagnosed with Chronic Obstructive Pulmonary Disease (COPD) [1,2,5]. These patients are challenging from the control point of view due to their variability in respiratory mechanical parameters, such as airway resistance and compliance. Another group of patients requiring mechanical ventilation are those with lung injury, in which pressure levels are strictly limited for the safety of the patient. Both of these types of patients require a stable, robust and adaptive control strategy to ensure optimal ventilation parameters. In pressure controlled ventilators, the manipulated variable is the maximum flow applied to the patient during the active phase (inspiration), and the regulated variable is the peak pressure at end-inspiration. Simulators for mechanical ventilation exist in literature, but do not provide much choice to the clinical practice, although they enable insight into the problems and challenges one may expect [10–13]. This paper aims to provide a simulation study based on our previous results, including a suitable adaptive controller for this kind of application being, by its intrinsic nature, a discrete-time system: the DIRAC control algorithm [14].

The paper is organized as follows: the next section provides the details on the patients data and identified respiratory impedance models. Furthermore, the model of the ventilator with the implementation details to simulate the breathing cycle of the patient is given along with the control strategy. The results for all 21 COPD patients in the nominal case are described in Section 3, followed by discussions and robustness analysis. A conclusion section summarizes the outcome of this contribution and its prospective impact in clinical practice.

Table 1 – Biometric and spirometric parameters of the investigated (male) subjects. Values are presented as mean ± SD; % pred: predicted values; VC: vital capacity; FEV$_1$: forced expiratory volume in one second.

	COPD $n = 21$
Age (yrs)	58 ± 9
Height (m)	1.81 ± 0.08
Weight (kg)	76 ± 4.8
VC (% pred)	86 ± 6.7
FEV$_1$ (% pred)	43 ± 9

2. Materials and methods

2.1. Patient models

The patient models used for simulation in this paper originate from a previous study on patients diagnosed with COPD [15], with their biometric values given in Table 1. Briefly, the noninvasive forced oscillations lung function test (FOT) is applied to the patient, resulting in a frequency domain complex variable denoting input impedance [16,17]. Measuring the human respiratory impedance using FOT is an attractive method to explore lung and chest mechanics. It is fast, non-invasive, and requires only passive cooperation from the subject (i.e. normal breathing at rest). The amount of information that may be extracted from the data is essentially a function of the experimental conditions and of the frequency range over which the measurements are done. Typically, pressure and flow are measured at the mouth using the device schematically represented in Fig. 1. In this figure, the following notations apply: DSP – digital signal processing board; LS – loudspeaker; BT – bias-tube; BF – bias-flow; PN – pneumotachograph; bf – biological filter; A – amplifier; PT – pressure transducer; Q – flow and P – pressure, U_g – the generated input; U_r – the breathing signal; GUI – graphical user interface.

This conventional – commercially available – FOT set-up is based on superimposing a low-amplitude pressure oscillation at the mouth ($U_g(t)$ – an optimized multisine signal in a range of frequencies from 4 to 48 Hz) while the patient is breathing spontaneously [16]. The oscillation pressure is generated by a

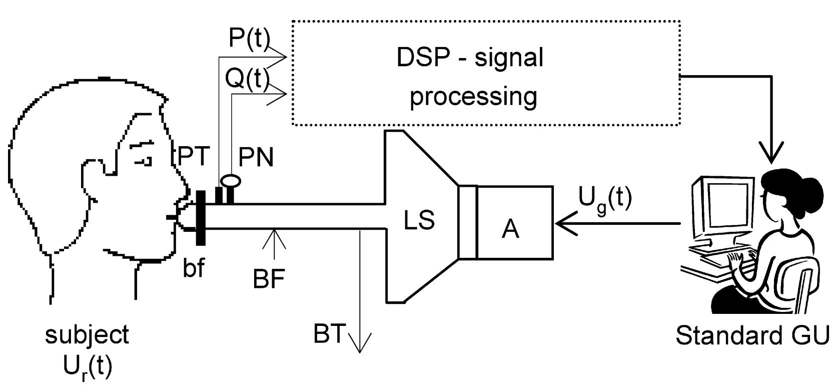

Fig. 1 – Standard FOT set-up.