A pressure-time adaptive algorithm of a new simulated cough device based on pneumatic system

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Nowadays, assisted cough devices are widely used in airway mucus clearance for patients who cannot cough autonomously. However, these devices use an open loop system where the inspiration pressure and time cannot be adapted to each other, which may cause over or under-inflation. In this paper, a new simulated cough device based on pneumatic system is presented. Moreover, a pressure-time adaptive algorithm is proposed to settle the mismatching problem of inspiration pressure and time. Both simulation and experimental studies are conducted to estimate the applicability of this algorithm for different compliance in a simulated lung. This paper provides a constructive suggestion for the development of airway clearance technologies.

Keywords: assisted cough device, mucus clearance, adaptive algorithm, simulation, experiment
Target audience: Pneumatic System

1 Introduction

Cough is an active reaction that protects the respiratory system from infections and improves the secretion clearance. A normal cough process has four steps which are shown in Figure 1 /1/,/2/,/3/. It begins with a deep breath in order to attain maximum lung volume. Then the glottis closes and the pectoral and abdominal muscles contract to generate pressure in the chest. Finally, the glottis opens which releases a sudden burst of gas. Peak cough flow (PCF) is used to assess the effectiveness of the cough and has a direct impact on airway clearance /4/. It was reported that healthy people may produce a PCF as large as 720 L/min /5/. The minimum effective peak cough flow was inferred from patients who were being weaned from mechanical ventilation; successful extubation requires at least 160 L/min /6/, /7/, /8/, /9/.

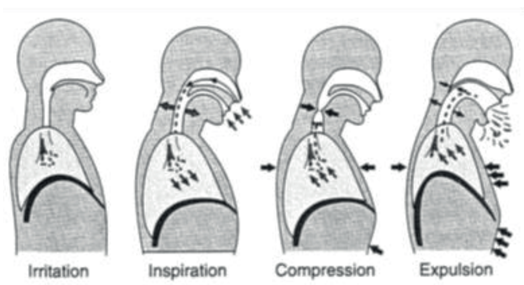

Figure 1. Four phases of a normal cough (From reference /1/).

As for ventilated patients, the epiglottis physiologic function may be lost and cough effectiveness may be severely reduced /10/,/11/,/12/. Moreover, due to the use of sedatives and muscle relaxants, the coughing capacity of ventilated patients may be further diminished /13/, /14/, /15/. Along with the impaired cough, mucus can accumulate in airways which may result in hypoventilation, respiratory failure and aggravation of the patient's hypoxia and carbon dioxide retention /16/, /17/, /18/.

Nowadays, assisted cough devices are widely used in airway mucus clearance, especially for respiratory muscle weakness (RMW) patients since 1993. The device delivers a positive pressure to the airway in order to expand the lung and then switches to a negative pressure that generates a high expiratory airflow. This simulates the process of coughing /19/, /20/. Many studies indicated that assisted cough device has benefits in improving PCF, oxygenation and airway clearance in amyotrophic lateral sclerosis (ALS) and other neuromuscular disease (NMD) patients. However, these devices use an open loop system which may cause the mismatch between the airway pressure and insufflation-exsufflation time for different patients' situations. The mismatch may result in over or under-inflation and airway collapse.

Therefore, a new simulated cough device based on pneumatic system is presented in this study. Moreover, a pressure-time adaptive algorithm is proposed to settle the mismatching problem between airway pressure and insufflation-exsufflation time. Both simulation and experimental studies are conducted to estimate the applicability of this algorithm for different compliance (C) in a simulated lung.

2 Mathematical model of the simulated cough device

The working principle of the simulated cough device can be considered as a process where a variable volume container inflates and deflates. Some assumptions are proposed:

- the air involved in the whole process is considered as ideal gas and follows the ideal gas laws;
- gas leakage does not exist in working process;
- atmosphere normal reference is considered;
- one-dimensional airflow is considered and it remains constant in each part of the device;
- quasi-balanced process is applicable to the air in the container.

2.1 Airflow equation

According to ISO 6358, mass flow equation can be obtained /21/, /22/, /23/. The equation is as follows:

$$q = \frac{n_f A p_u \sqrt{1-b}}{\sqrt{R\theta}} \sqrt{1-\left(\frac{\frac{p_d}{p_u}-b}{1-b}\right)^2} \tag{1}$$

where n_f is flow coefficient, when air flows into the simulated lung, it is 1. Inversely, when air exhausts from the simulated lung, it is −1. A is equivalent effective area. R is gas constant. θ means temperature. b is critical pressure ration. p_u is the pressure of upstream side. p_d is the pressure of the downstream side.

2.2 Simulated lung pressure equation

The simulated lung can be assumed as an isothermal system; the differential expression of ideal gas equation ($pV = mRT$) can be given:

$$\frac{dp}{dt} = \frac{1}{V} R\theta q - mR\theta \frac{1}{V^2}\frac{dV}{dt}, \tag{2}$$
$$\frac{dp}{dt} = \frac{R\theta q V}{V^2 + CmR\theta}.$$

where C is the compliance, V is the air volume, and m is the air mass.

2.3 Simulated lung volume equation

Based on the definition of compliance (C) /24/,

$$C = \frac{dV}{dp} \tag{3}$$

the volume of the simulated lung can be described as:

$$dV = Cdp \tag{4}$$

3 Pressure-time Adaptive Algorithm

The current assisted cough devices use an open loop system whose insufflation and exsufflation time are set manually by the medical staff. This open loop system has two disadvantages:

- When the patient's compliance is low and the insufflation time is long, the patient may be over inflated. Inversely, when the patient's compliance is high and the insufflation time is short, the patient lung are not fully expanded which may reduce the cough efficiency.
- When the exsufflation time is set long, the airway pressure may turns negative which may cause airway collapse.

Considering these disadvantages, a pressure-time adaptive algorithm is proposed to settle the mismatching problem between airway pressure and insufflation-exsufflation time.

According to the equation (1), when the airway pressure equals the air pressure in simulated lung, the flow is zero and the airway pressure is the same as insufflation pressure of the system. Meanwhile when the airway pressure equals zero in exsufflation process, the output pressure of the system should be set zero in order to prevent the airway collapse. The algorithm is presented in equation (5). The control block diagram is shown in Figure 2.

$$\begin{cases} e = p_{in} - p_a\,; \\ p_{out} = \begin{cases} p_{in}\,; & (if\ \ 0 \le e \le e_{set}\,) \\ p_{ex}\,; & (if\ e \le e_{set}\ and\ f \le f_{set}) \\ 0; & (if\ p_a \le 0) \end{cases} \end{cases} \tag{5}$$

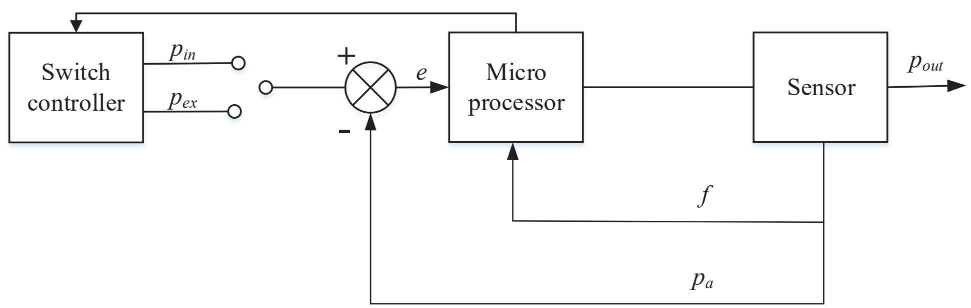

Figure 2: Control block diagram of the system.

Where p_{in}, p_{ex} and p_{out} are the insufflation pressure, exsufflation pressure and output pressure of the system, respectively. p_a is the airway pressure feedback signal and f is the flow feedback signal. e is the error of the p_{in} and p_a. Considering the fluctuation of signals, we choose e_{set} and f_{set} as the critical value for switching. The sensor collects the airway pressure and flow signal in real time. The signals are transferred to the microprocessor and processed. The switch controller receives the signal transferred from the microprocessor and switches the insufflation and exsufflation process.

4 Experiment system and results

The new simulated cough device based on pneumatic system shown in Figure. 3 consists of a micro turbofan that supplies the air, a vacuum pump that generates the negative pressure, a proportional valve (SMC ITV2090) that sets the value of negative pressure, a 10 L volume gas tank, two solenoid valves (SMC VX234), a flow-pressure sensor (Siargo Ltd FS6122), a simulated lung, a data acquisition card (Advantech USB-4711A), a computer (Lenovo)that receives the data and a controller that controls the micro turbofan, vacuum pump, proportional valve and solenoid valves.

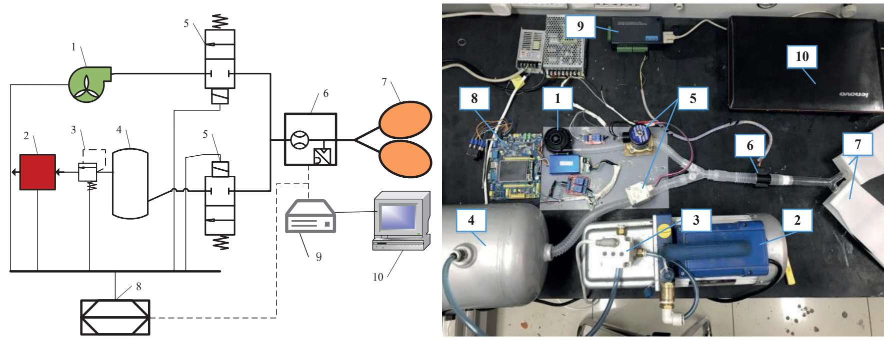

Figure 3: The scheme and prototype the simulated cough device.

1. Micro turbofan, 2. Vacuum pump, 3. Proportional valve, 4. Gas tank, 5. Data acquisition card, 6. Flow-pressure sensor, 7. Simulated lung, 8.Controllor, 9. Data acquisition card, 10. Computer

The input parameters of simulated cough device including p_{in}, p_{ex}, A, e_{set}, f_{set} and compliance (C) of simulated lung are presented in Table 1.

Parameter	p_{in} (kPa)	p_{ex} (kPa)	C (ml/Pa)	$A(mm^2)$	e_{set}(kPa)	f_{set}(L/min)
(Value)	2	-0.5	0.204	8	0.1	3

Table 1. The input parameters

4.1 Simulation and experimental results of airflow dynamics

Simulated and experimental results of airflow dynamics are shown in Figures 4 and 5. The response time of solenoid valve is neglected in simulation. From the results, we can see that:

- The experimental results are in wide agreement with simulation results which validates the mathematical model.
- During the insufflation phase, the airflow rises to the maximum with increasing insufflation pressure (p_{in}), followed by a slow fall after insufflation pressure (p_{in}) reaches its setting value. Then, airflow falls to zero when the air pressure in simulated lung trends to airway pressure.
- When the error (e) of pressure (p_{in}) and airway pressure reaches critical value for switching (e_{set}) and flow (f) reaches critical value for switching(f_{set}), the solenoid valve opens and the airflow rises sharply to its reverse maximum. Then, solenoid valve closes when the airway pressure reaches zero. Therefore, the airflow and airway pressure come to zero.

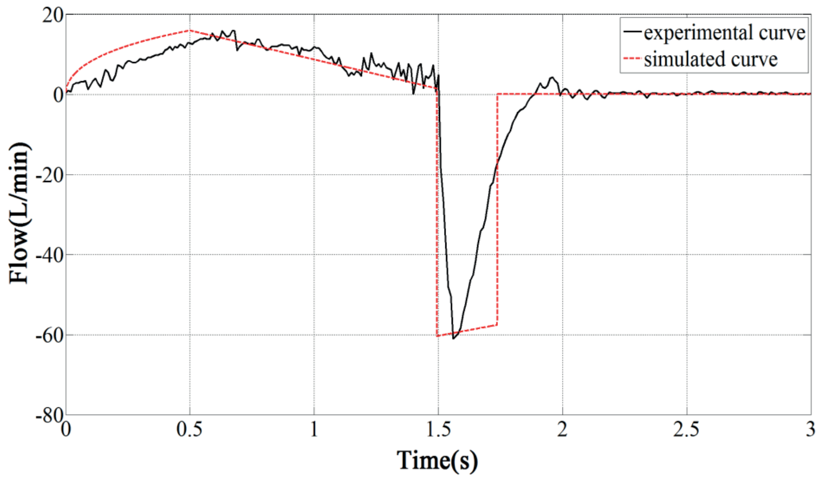

Figure 4: Curve of the airflow in simulated cough device.

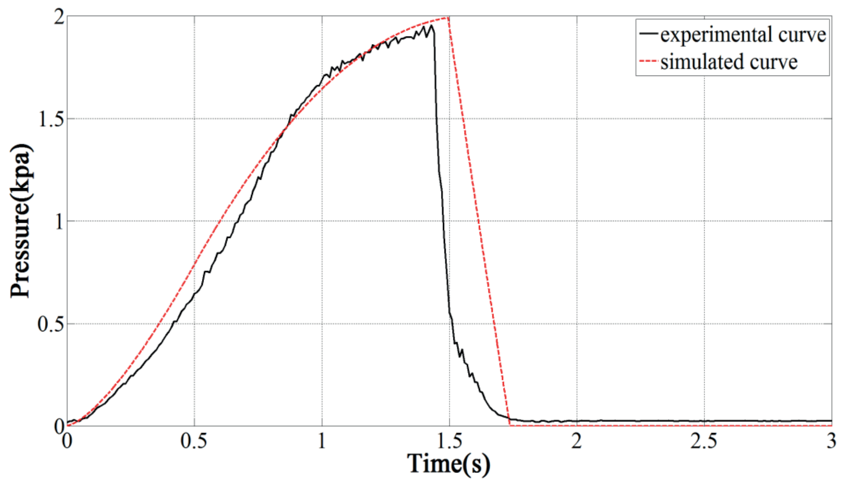

Figure 5: Curve of airway pressure in simulated cough device.

4.2 Influence of compliance on airflow dynamics

In order to estimate the applicability of the adaptive algorithm, three groups of experimental studies for differen compliance (C) are conducted. The input values are presented in Table 2. The experimental results are shown i Figure 6.

Group	C (ml/Pa)	p_{in} (kPa)	p_{ex} (kPa)	e_{set}(kPa)	f_{set}(L/min)
1	0.204	2	-0.5	0.1	3
2	0.51	2	-0.5	0.1	3
3	1.02	2	-0.5	0.1	3

Table 2. The input parameters of different C.

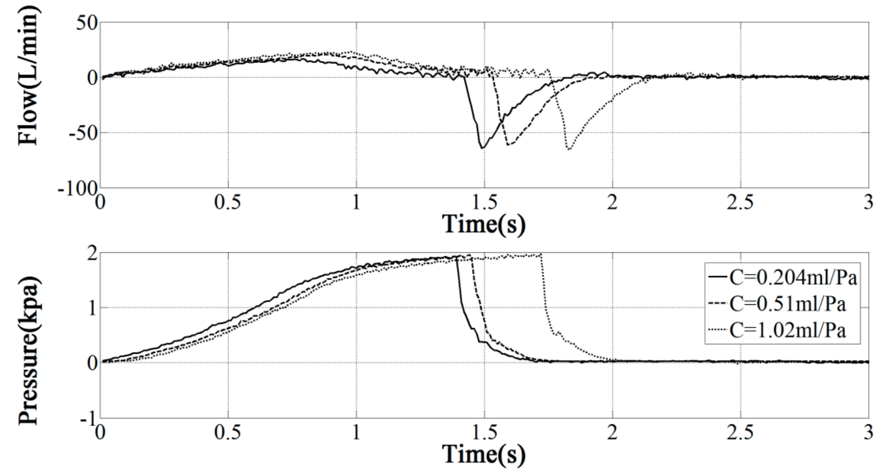

Figure 6: Airflow dynamics of different C.

Increasing the compliance(C) can increase the maximum insufflation flow and total insufflation volume. The variation trend slows down with the compliance(C) increasing. For different compliance(C) the insufflation-exsufflation time is adaptive to airflow and airway pressure which verifies the applicability of the adaptive algorithm.

4.3 Influence of p_{ex} on airflow dynamics

Because the PCF has a direct impact on airway clearance, three groups of different exsufflation pressure (p_{ex}) are set to study the influence of exsufflation pressure (p_{ex}) on PCF. The input values are presented in Table 3. The experimental results are shown in Figure 7.

Group	p_{in} (kPa)	p_{ex} (kPa)	C (ml/Pa)	e_{set}(kPa)	f_{set}(L/min)
1	2	-0.5	0.204	0.1	3
2	2	-1	0.204	0.1	3
3	2	-2	0.204	0.1	3

Table 3. The input parameters of different p_{ex}.

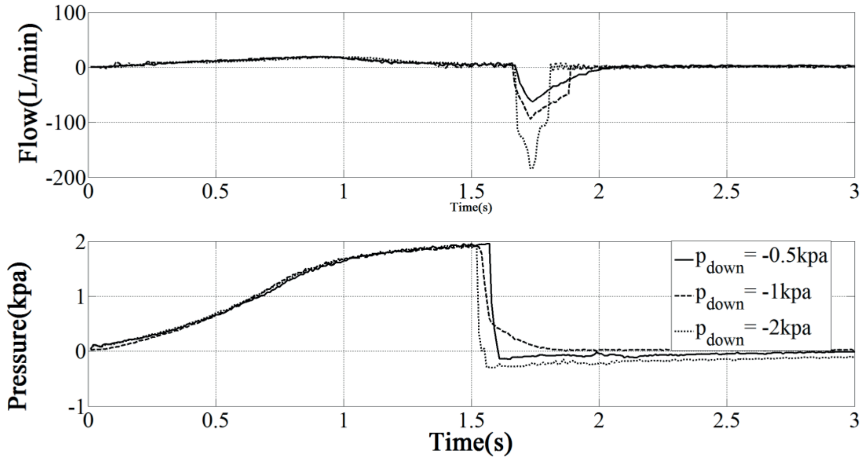

Figure 7: Airflow dynamics of different p_{ex}.

When the insufflation pressure (p_{in}) remains constant and exsufflation pressure (p_{ex}) reduces sharply like in Figure.4, the positive maximum airflow and total insufflation volume remain almost the same while the negative maximum airflow (PCF) greatly decreases. When the negative exsufflation pressure (p_{ex}) is -2kPa, the PCF exceeds 180L/min. Due to the decreasing of exsufflation pressure (p_{ex}) and response time of the solenoid valve, the airway pressure presents a slight negative pressure which is bigger than -0.2kPa.

5 Conclusion

In this paper a new simulated cough device based on the pneumatic system is proposed. The mathematical model of this system has been built and validated through the experiments. Moreover, a pressure-time adaptive algorithm is proposed to settle the mismatching problem between airway pressure and insufflation-exsufflation time. The experimental studies verify the applicability of this algorithm for different compliance (C). Airflow dynamics under different exsufflation pressure (p_{ex}) and compliance (C) conditions were obtained through experiments. The experimental results show that decreasing the exsufflation pressure (p_{ex}) can greatly increase the PCF. When insufflation pressure (p_{in}) is 2kPa and p_{ex} is -2kPa, the PCF can exceed the effective cough flow (180L/min). The airflow and airway pressure variation trend slows down with the compliance(C) increasing.

The shortcoming of this paper is that device and algorithm proposed in this paper have not been validated by a large number of experiments. That is primary goal in our future studies. However, the study method presented in this paper can be used as a reference for the development of airway mucus clearance device.

6 Acknowledgements

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Nomenclature

Variable	*Description*	*Unit*
q	Air Mass Flow	[kg/s]
A	Equivalent Effective Area	[m^2]
p_u	Pressure of Upstream Side (absolute pressure)	[Pa]
p_d	Pressure of Downstream Side (absolute pressure)	[Pa]
b	Critical Pressure Ration=0.528	
R	Gas Constant=287	[J/(kg·K)]
θ	Temperature=293	[K]
m	Air Mass	[kg]
V	Air Volume	[m^3]
p	Pressure of the simulated lung (absolute pressure)	[Pa]
C	Lung Compliance	[ml/Pa]
p_{in}	Insufflation Pressure (relative pressure)	[kPa]
p_{ex}	Exsufflation Pressure (relative pressure)	[kPa]
p_{out}	Output Pressure (relative pressure)	[kPa]

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