Original Article

Mechanical model for simulating the conditioning of air in the respiratory tract*

Nelson Bergonse Neto[1], Luiz Carlos Von Bahten[2], Luís Mauro Moura[3], Marlos de Souza Coelho[2], Wilson de Souza Stori Junior[1], Gilberto da Fontoura Rey Bergonse[4]

Abstract

Objective: To create a mechanical model that could be regulated to simulate the conditioning of inspired and expired air with the same normal values of temperature, pressure, and relative humidity as those of the respiratory system of a healthy young man on mechanical ventilation. **Methods:** Using several types of materials, a mechanical device was built and regulated using normal values of vital capacity, tidal volume, maximal inspiratory pressure, positive end-expiratory pressure, and gas temperature in the system. The device was submitted to mechanical ventilation for a period of 29.8 min. The changes in the temperature of the air circulating in the system were recorded every two seconds. **Results:** The statistical analysis of the data collected revealed that the device was approximately as efficient in the conditioning of air as is the respiratory system of a human being. **Conclusion:** By the study endpoint, we had developed a mechanical device capable of simulating the conditioning of air in the respiratory tract. The device mimics the conditions of temperature, pressure, and relative humidity seen in the respiratory system of healthy individuals.

Keywords: Thermodynamics; Respiration, artificial; Temperature.

* Study carried out at the *Pontifícia Universidade Católica do Paraná* – PUCPR, Pontifical Catholic University of Paraná – Curitiba (PR) Brazil.
1. Masters in Clinical Surgery from the *Pontifícia Universidade Católica do Paraná* – PUCPR, Pontifical Catholic University of Paraná – Curitiba (PR) Brazil.
2. PhD in Clinical Surgery from the *Pontifícia Universidade Católica do Paraná* – PUCPR, Pontifical Catholic University of Paraná – Curitiba (PR) Brazil.
3. PhD in Thermal Sciences from the *Pontifícia Universidade Católica do Paraná* – PUCPR, Pontifical Catholic University of Paraná – Curitiba (PR) Brazil.
4. Resident in Otorhinolaryngology at the University of São Paulo – USP – Bauru (SP) Brazil.
Correspondence to: Nelson Bergonse Neto. Rua Padre Agostinho, 227, apto. 11, Mercês, CEP 80410-020, Curitiba, PR, Brasil.
Phone 55 41 3224-3318/55 41 3259-6500. Fax 55 41 3232-0721. E-mail: bergonsent@terra.com.br
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Introduction

Human beings, like all homeotherms, present a complex body metabolism mediated by enzymatic systems, most of which are temperature-dependent. Therefore, it is vitally important that the core body temperature remain constant to allow the optimal functioning of the organism. Temperature is regulated by the hypothalamus, which maintains a balance between heat production and heat loss.[1]

During surgical procedures, the human organism is submitted to anesthesia, which inhibits the thermoregulatory mechanisms of the organism, and, if the ambient temperature is not maintained above a certain level, patients can develop hypothermia and suffer the potential consequences.[2-8]

Hypothermia has deleterious effects on the organism, such as alterations in the basal metabolism, in oxygen transport, in carbon dioxide transport, and in serum concentration of hydrogen, as well as electrolyte and hormonal changes.[1,2,9-11]

The respiratory system is responsible for conditioning the air in the respiratory tract, which is vitally important for respiration and maintenance of homeothermy. This conditioning is responsible for 25% of the calories burned by the body.[1,12]

The thermal reactions of the tracheobronchial tree are mainly dependent on the temperature and the relative humidity (RH) of the inspired air. Air temperature is the principal factor implicated in the heat exchange of the respiratory system, since the temperature of this air can be quite variable, and since heat gain or loss is directly related to the difference in temperature between the inspired air and the surface of the respiratory system.[13,14] Other important factors involved in these thermal reactions are the ventilation rate per minute, airway temperature, vasomotor changes, and changes in the mucous membrane.[15-19]

During inspiration, the air is heated by the mucosa, which reflects the temperature of the blood. The exchange of heat in the airways depends on the bronchial circulation. However, in addition to depending on the terminal bronchioles, this exchange comes to depend on the pulmonary circulation.[16,20]

There are two major regions that condition air: the nasal and oral cavities (which constitute the principal region, reaching nearly maximal conditioning); and the tracheobronchial tree (which plays a secondary role and, toward the periphery of the lung, becomes less efficient at regulating the heat and humidity exchanges).[16-18,21]

The task of conditioning the air is already complete at the level of the seventh-generation bronchi, and the air reaches the alveoli under normal body conditions (temperature, 37 ± 0.6 °C; RH, 100%).[16,21]

The air humidification process is so efficient that, in intubated patients, the air reaches the trachea at an RH of 51% and the lobe bronchi at an RH of 100%.[15,20]

In order to study the thermal exchanges between the air and the respiratory system, there are variables of fundamental importance, such as the air pressure in the respiratory system, the volume of air circulating per minute in the respiratory system, and the volume of air that remains in the respiratory system at the end of expiration.[22]

The air pressure in the respiratory system is highly variable (from the 2-5 cmH_2O range up to the 20-30 cmH_2O range).[12]

The volume of air circulating in the respiratory system per minute (airflow) is the product of tidal volume (Vt) × respiratory rate (RR).[22]

The volume of air that remains in the respiratory system at the end of normal expiration is the functional residual capacity (FRC), which is important for being greater than the Vt and because this air is partially exchanged during each respiratory cycle, thereby affecting the changes in temperature and the humidity of the inspired air.

Although it is possible to estimate the normal values of total lung capacity (TLC), vital capacity (VC), Vt, and residual volume (RV) using mathematical formulas, it must be borne in mind that these values can vary by 15 to 20%.[22]

For men over age 15, VC is calculated using the formula devised by Baldwin, Cournand and Richards[22]:

$$VC\ (mL) = 27.63 - (0.112 \times age) \times height\ cm) \quad (1)$$

For individuals between 15 and 34 years of age, ^{TLC} is calculated using another formula devised by Baldwin, Cournand and Richards[22]:

$$TLC\ (ML) = VC/0.80 \quad (2)$$

The Vt ranges from 5 to 10 $mL.kg^{-1}$.[12]

Expiratory reserve volume and FRC cannot be calculated using formulas, and can only be measured through complementary examination.[22]

It is essential to emphasize that the calculations that use body mass should be based on a body mass index between 20 and 25 kg/m^2.

Although there have been studies evaluating the loss of thermal energy and humidity through the airways, none have done so during procedures requiring orotracheal intubation.[13,14,16-19]

The present study sought to create a device that could be adjusted to simulate the conditioning of air in the respiratory tract with the same normal values of temperature, pressure, and RH as those seen in the respiratory system of healthy individuals on mechanical ventilation. The objective of creating such device is to be useful to other studies on thermoregulation and mechanical ventilation without the need for previous animal studies.

Methods

This research was carried out in the Thermodynamics Laboratory of the Center for Exact and Technological Sciences of the Pontifical Catholic University of Paraná. Since this research involved a mechanical model and no experiments on animals, there was no need to obtain ethics committee approval.

In order to build the device, we used the following materials: plastics; metals; wood; glass; electrical components; electronic components; fixers and sealants; thermal insulation; and finish. Most of these elements required modification.

The plastics used were as follows: panels; polyvinyl chloride (PVC) tubes and connectors; 3-way unidirectional valves; hoses; A4 transparencies; polystyrene film; polyester cloth; a cylinder (6 L); and an orotracheal tube (8 mm).

The metals iron, brass, bronze, lead, and copper were used in the form of screws, washers, nuts, rods, registers, connectors, granulated lead, and screens. The wood used was pine. Formica was also used.

The electrical and electronic components used were as follows: copper wires; plugs; light bulbs/sockets; an aquarium heater; electric switches; a luminous hose; a line filter; a fan; electronic thermostats; a personal computer; Agilent BenchLink software, version 1.4 (Agilent Technologies, Inc., Palo Alto, CA, USA); type 'T' thermocouples; Agilent 34970A data acquisition switch unit (Agilent Technologies, Inc.); and a mechanical ventilator (model Monterey 3; K. Takaoka Indústria e Comércio Ltda., São Paulo, Brazil).

Fixation and sealing were performed using clamps, glues (silicone, PVC, cyanoacrylate, polyurethane), adhesive tape, and insulating tape.

Thermal insulation was achieved using cardboard and Styrofoam, covered with sheets of contact paper. Glass tubes were also used.

The phases of the project were as follows: onstruction, assembly, adjustment, and experimentation.

Construction

Each component of the device was constructed separately: a positive end-expiratory pressure (PEEP) valve; a safety valve; the main cylinder; a bellows; pressure ballasts; a humidifier; manometers; a control panel; a hold; a storage box; and an air distributor.

The objective of the PEEP valve was to simulate the PEEP, maintaining expiratory pressure within the system between 0 and 30 cmH_2O. The valve was built using a tube that was 450 mm in length and 75 mm in diameter. The pressure was monitored using a water column.

The objective of the safety valve was to limit the maximal pressure within the system to 40 cmH_2O. The valve was built using a tube that was 550 in length and 75 mm in diameter. Again, the pressure was monitored using a water column.

The function of the main cylinder was to control the volume, the RH, and the air temperature within the system. We built a 6-L cylinder, into which we placed a plastic register (in order to monitor the inflow and outflow of air), a safety valve, a manometer, temperature sensors, and an aquarium heater. A 150-mm opening was made in the upper lid in order to accommodate the bellows. This cylinder had a 700- to 5200-mL scale for air and water.

The objective of the bellows, built using a tube that was 200 mm in height and 150 mm in diameter coupled to the main cylinder, was to simulate Vt. The bellows presented a volume regulation mechanism (0-2000 mL) and a compartment for the pressure ballasts.

The pressure ballasts, made of lead, were used to obtain the desired pressure in the system, which was calculated based on the area of the mouth of the bellows that would transmit the pressure to the air in the system. It was calculated that a mass of

158.36755 g applied to the mouth of the bellows would correspond to the pressure of 1 cmH_2O in the system. Ballasts that would create pressures of 1, 2, 5, and 10 cmH_2O were prepared.

The humidifier was built using a tube that was 100 mm in height and 100 mm in diameter (785.37 mL in volume) in order to increase the RH of the air to 100%. The humidification method used was bubble aeration of water. It was calculated that 1600 0.5-mm orifices would humidify the air without causing pressure overload.

The manometers, each of which had a scale ranging from −5 to +40 cmH_2O, served to measure the pressure in the storage box and in the main cylinder.

The control panel consisted of a PVC board divided into four sectors: temperature (thermostats); pressure (manometers); switches (breakers); and electrical power (a line filter to protect the equipment).

Coupled to the storage box, a drainage system was constructed in order to drain the various components of the device. This system was designated 'the hold',

The storage box, constructed of 3-mm-thick cardboard and lined with 3-mm-thick Styrofoam panels, served as a thermal insulation unit.

The air distributor was designed to control the inflow and outflow of air. It consisted of a unidirectional valve with three ports, together with a limiter to ensure that, when the valve was connected to the device, the intubation tube did not progress beyond the identification ring of the balloon.

Assembly

The system was mounted into the storage box using silicone glue to fix the main cylinder, the PEEP valve, the safety valve, and the humidifier in the bottom of the box. The drains were located beneath the components. Subsequently, we fixed a fan (for thermal homogenization) and two light bulbs (one for light and one for heat) to the floor of the box. The air distributor was fixed to the right wall of the box.

After securing the components within the box, we made the following connections in the order given: the distributor to the humidifier, the humidifier to the main cylinder, the main cylinder to the PEEP valve, and the PEEP valve back to the distributor. Other connections were made as follows: the main cylinder to the safety valve, the main cylinder to the safety valve air vent, and the main cylinder to the manometers.

The electrical wiring was appropriately connected.

Temperature sensors entered through the left wall. These sensors were placed at points considered strategic for the collection of data (Table 1).

Finally, the control panel was fixed to the face of the box, and all openings were sealed (Figures 1 and 2).

Adjustment

The device and the mechanical ventilator were adjusted using data specific to a 25-year-old, 80 kg, 1.88 m, healthy male.

The device was calibrated by introducing a solution of distilled water and 0.0005% methylene blue, which has physicochemical properties similar to those of water,[23] into each of the components.

The device was adjusted as follows: VC to 5000 mL, Vt to 800 mL, initial- and end-expiratory pressures to 20 cmH_2O, PEEP to 2 cmH_2O, and air temperature to 37 °C.[13,14,17,18] The safety valve was adjusted to 40 cmH_2O.[12]

Table 1 - Location and temperature monitored by the sensors.

Sensor	Location	Monitored temperature
a	Distributor air inlet	System air inlet
b	Main cylinder air inlet	Central air inlet
c	Inside the main cylinder	Water in the main cylinder
d	Inside the main cylinder	Air in the main cylinder
e	Main cylinder air outlet	Central air outlet
f	Distributor air outlet	System air outlet
g	Interior of the storage box	Interior of the storage box
h	Exterior of the storage box	External environment
i	Interior of the intubation tube	Inspired air

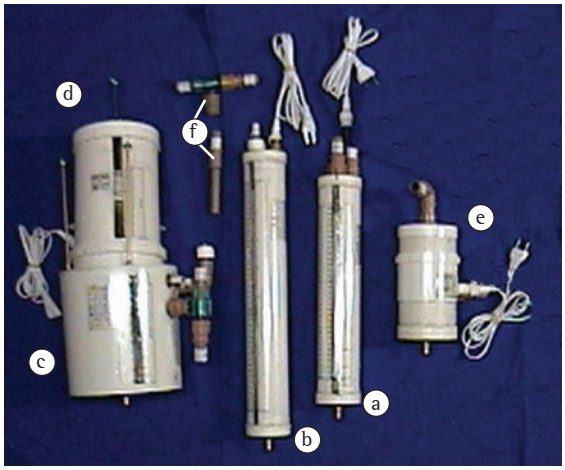

Figure 1 - Main components of the device in isolation: a) Positive end-expiratory pressure (PEEP) valve; b) Safety valve; c) Main cylinder; d) Bellows; e) Humidifier; and f) Air distributor.

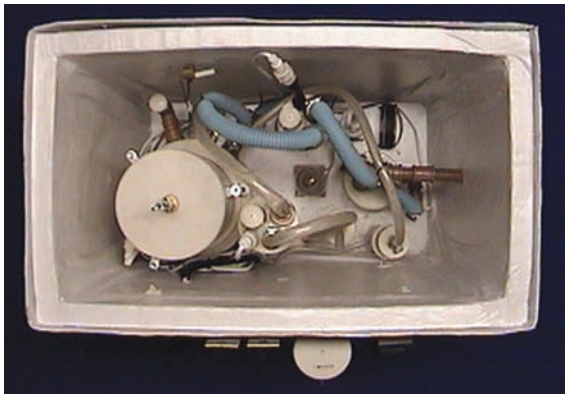

Figure 2 - Internal view of the assembled device: Components fitted into the storage box and their connections.

The mechanical ventilator was adjusted as follows: Vt to 800 mL, maximal inspiratory pressure to 20 cmH_2O, inspiratory flow to 40 $L.min^{-1}$, PEEP to 2 cmH_2O, RR to 17 breaths per minute, fraction of inspired oxygen to 0.21, and air temperature to that of the external environment.[24]

Experimentation

The device was activated and maintained at rest until the system achieved thermal balance at 37 °C. The orotracheal tube was connected to the device, at which point mechanical ventilation was started and maintained until thermal balance was again achieved (Figure 3).

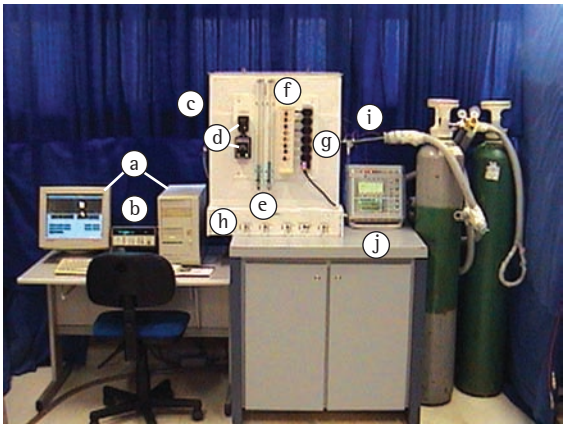

Figure 3 - Activated device on mechanical ventilation along with computerized data collection: a) personal computer with Agilent Benchlink software; b) data acquisition switch unit; c) conditioning device; d) thermostats of the control panel; e) manometers of the control panel; f) control panel switches; g) electrical power of the control panel; h) hold; i) 8-mm orotracheal tube; and j) mechanical ventilator.

The temperatures in the system were recorded very two seconds and then analyzed.

Results

At the beginning of the experiment, the temperatures registered by the thermal sensors were as follows: a = 21.4 °C; b = 21.4 °C; c = 21.7 °C; d = 21.6 °C; e = 21.6 °C; f = 21.8 °C; g = 21.8 °C; and h = 21.2 °C. In this phase, sensor i was disregarded. The device was activated and maintained at rest, recording temperatures every two seconds until thermal balance was achieved at 37 ± 0.6 °C.

After balance at rest was achieved, mechanical ventilation was started. Initially, the temperatures registered showed a slight decrease of 0.9 °C but quickly recovered. After 370 s, the system again achieved thermal balance and stabilized (Table 2).

The pressure in the storage box remained at 0 cmH_2O throughout the experiment, ranging from 2 to 20 cmH_2O in the main cylinder.

After 1788 s of mechanical ventilation, since the system had been in stable balance (no gain or loss of thermal energy) since the 370-s mark, the mechanical ventilator and the device were turned off. When the storage box was opened, it was found that the level of liquid used in order to calibrate each

Table 2 – Values of thermal balance of the device at rest and on mechanical ventilation.

Sensors	Temperature (°C)						Time to achieve balance	
	Rest			Ventilation			Seconds	
	Min.	Max.	Med.	Min.	Max.	Med.	Rest	Ventilation
Inspired air	-	-	-	22.4	23.0	22.9	-	0
Primary air inlet	37.3	38.8	38.2	31.5	31.7	33.9	3416	366
Main cylinder air inlet	38.5	39.6	39.1	35.7	38.5	37.3	3450	366
Water in the main cylinder	37.5	37.8	37.6	37.2	37.6	37.4	3308	0
Air in the main cylinder	37.8	38.0	37.9	36.9	37.7	37.3	3978	360
Main cylinder air outlet	37.6	38.7	38.1	35.6	36.6	36.1	3430	370
Primary air outlet	36.8	37.6	37.2	36.7	37.7	37.3	3406	0
Interior of the storage box	36.2	37.2	36.8	36.2	37.2	36.7	3416	0
External environment	21.0	22.2	21.8	22.2	22.9	22.6	0	0
Total time to achieve thermal balance							3978	370

of the components had not changed, the exception being that of the liquid in the humidifier, which had dropped by 129 mL (from 785.37 to 629.37 mL).

Discussion

To date, there have been no studies evaluating the loss of thermal energy in procedures requiring orotracheal intubation.[14,16-19]

Although there is as yet no scientific evidence to support the idea, the possibility of controlling the loss of heat and humidity through the airways, or even providing heat and humidity via those airways (in order to prevent and treat hypothermia), has been considered.

The present study sought to build a device that could be adjusted, according to the needs of the researchers, to simulate the conditioning of air in the respiratory tract. The objective of creating such device is to facilitate studies of thermoregulation and mechanical ventilation.

The materials were chosen based on various criteria: ease of acquisition and handling; weight and volume (lowest possible); resistance; cost; thermal insulation capacity; sealing and fixation capacity; and transparency.

In terms of thermal exchange, each material presents its own behavior, which is related to its specific heat and its thermal diffusion constant.[23] In order to avoid the complications that these characteristics would cause, the thermal exchange through the wall of the materials was minimized using a thermostat and using a heater for the air in the system and another one for the air in the storage box, thereby nullifying the temperature gradient between the two systems and preventing the exchange of thermal energy.

The creation of a device that simulated a lung in terms of inspiration, expiration, pressure, RH, temperature, and gas volume showed us that the reference values of these data were quite broad, and were related to height, weight, age, and gender. In addition, it showed us that it was essential that the device be adjustable. Since the device could be mechanically adjusted for whatever data on weight and height, the relevant data to our study were gender and body mass index (20-25 kg/m^2). The reference standard was randomly defined as a healthy young (25 years) male weighing 80 kg. Since the body mass index of this individual should be normal (22.5 kg/m^2), his height was calculated as 1.88 m.

The idea for volume regulation was to create components with a fixed volume, and partially replace their internal volume of air with another substance (water) that would remain trapped in these components

Pressure regulation was performed using two valves and lead ballasts. The pressure valves were based on water column systems due to their ease of application and low cost.

The ballasts were useful for controlling inspiratory and expiratory pressures.

Since gas temperature should be maintained at 37 ± 0.6 °C, we resorted to the use of electronic thermostats, which allowed a maximum variation in temperature of 0.5 °C.

In the present experiment, there was a need for sensors that could rapidly and accurately monitor temperature. We opted for using type 'T' thermocouples. These thermocouples are small (1 mm), rapidly respond to changes in temperature, and have high sensitivity.[2]

Not being saturated and having a temperature lower than 37 °C, the air entering the system would, upon being heated, absorb water and decrease the calibration levels of the components of the device.[23] Therefore, we created the humidifier that would saturate the air at 100% upon its entering the system. The efficiency of the humidifier was proven only at the end of the experiment, at which point we found that the water in the components of the device had not been consumed. The evaporation rate in the humidifier was calculated as 4.32 mL/min, demonstrating that, in terms of air humidification, the device has an autonomy of slightly more than 3 h. This autonomy can be increased by replacing this humidifier for one of greater volume.

During the first sealing test, various small air and liquid leaks were identified but were readily corrected using silicone glue.

The temperature and RH in the experiment room did not interfere with the experiment since it was a thermally insulated environment.

In order to calibrate the device, rather than using FRC, which is the ideal, we used VC, since FRC cannot be calculated using formulas.

Although VC is greater than FRC, this did not interfere negatively with the experiment since the variable of interest was Vt. In fact, the use of a greater volume allowed greater dilution, greater length of time in the system, and greater ease in the conditioning the air.

The pressure values measured revealed that the pressure ballasts and the PEEP valve worked perfectly.

The evaluation of the temperatures registered revealed that the device latency time was 3978 s, and that the outflow temperature of the air in the system, which was the principal measure, was 37.3 °C. Since the device is thermally insulated, when it reaches the temperature regulated by the thermostats, the system achieves thermal balance, which means that the gas temperature will remain constant indefinitely as long as the electrical power is not interrupted.

The device developed in the present study was based solely on mechanical principles, each of its components being easily adjusted to the values desired in terms of temperature, volume, and pressure. Only RH is fixed at 100%. In view of this peculiarity of the device, we can state that the device can simulate the conditioning of air in individuals of different biotypes.

We hope that the creation of this device will be useful to other studies on the field of respiratory system thermodynamics, allowing, in some cases, initial experiments on living beings to be dispensed with.

By the study endpoint, we had developed a device capable of simulating the conditioning of air in the respiratory tract. The device mimics the conditions of temperature, pressure, and humidity seen in the respiratory system of healthy individuals.

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