An experimental set-up to test heat-moisture exchangers

Abstract Objectives: The purpose of this study was to build an experimental set-up to assess continuously the humidification, heating and resistance properties of heat-moisture exchangers (HMEs) under clinical conditions. Design: The experimental set-up consists of a patient model, measurement systems and a ventilator. Setting: Surgical ICU, University Hospital of Rotterdam. Materials: A clinically used HME. Measurements and results: The air flow, pressure in the ventilation circuit, pressure difference over the HME, and partial water vapour pressure and temperature at each side of the HME were measured. The resistance, absolute humidity, humidification efficiency and temperature difference at the patient side of the HME were calculated. Measurements were performed during 24 h. The temperature output, humidity output and lung mechanics of the patient model were similar to values found in mechanically ventilated patients. The measurement system was in agreement with the ISO draft standard and was capable of measuring dynamic variation of water and heat exchange over the range of a clinically used ventilator setting. Conclusion: The experimental set-up described is reliable for evaluating HMEs and can also be used for future clinical evaluation of HMEs. The main advantages of this set-up over those described previously are: (i) measurements of dynamic variations of water and heat exchange; (ii) on-line measurements of expiratory, as well as inspiratory resistance.

Key words Humidity · Heat and Moisture exchangers · Mechanical ventilation · Mass spectrometry · Temperature · Resistance

Introduction

The heat and humidity exchange functions of the nose and upper airways are bypassed during endotracheal intubation and tracheostomy. Use of dry medical gases for mechanical ventilation increase the water and heat loss from the lower airways, which can produce serious airway damage and worsen pulmonary function [1-5]. Heated humidifiers (HHs) or heat-moisture exchangers (HMEs) are therefore used to both heat and humidify the air before being delivered to the patient. HHs, however, have some disadvantages such as the potential to deliver excessive heat with the consequent problem of thermal injury and of acting as a reservoir for bacterial growth resulting in nosocomial infections [6].

The HME filter is a simple solution to the problems of humidification of inspired gases and contamination of ventilatory circuits. HMEs are passive devices which absorb the expiratory moisture and heat, and return it partially to the patient at the next inspiration [7, 8]. However, previous publications have reported some drawbacks of
the use HMEs such as inadequate humidification and heating efficiency, high resistance to airflow, clogging by sputum and endotracheal tube occlusion [8–12]. Nonetheless, continued developments of the HMEs have improved their heating and humidification efficiency, decreased their resistance to airflow and improved their qualities as a bacterial-viral filter [8, 13–15]. A variety of HMEs are available with different physical properties and various experimental set-up models have been developed to evaluate these properties [7–10, 13–22]. The International Organization for Standardization (ISO) has released a draft standard for testing HMEs [18]. This draft standard specifies the minimum requirements of a patient model and measurement system to test HMEs. An ideal experimental set-up should not only imitate the respiratory properties of mechanically ventilated patients but also be able to record dynamic variations of humidity, temperature and resistance to calculate more accurately the performance characteristics of HMEs in time.

The present study concerns the design and validation of an experimental set-up to test HMEs in accordance with the technical standards of the ISO and with the ability to measure dynamic variations of humidity, temperature and resistance.

The aims of the study are: (i) to construct a patient model which imitates a mechanically ventilated patient in terms of compliance, resistance, expiratory temperature and humidity output; (ii) to measure dynamic variations of flow, pressure, pressure difference, temperature and humidity continuously, thereby allowing intra- and inter-breath interpretation of the results; (iii) to calculate inspiratory and expiratory flow-weighted mean values of humidity and temperature to assess the performance characteristics of the HME (efficiency of humidification and heating); (iv) to determine the intrinsic properties of the experimental test system with a commonly used ventilator setting and to validate the set-up during long-term measurements with a commonly used HME.

**Materials and methods**

**The experimental set-up**

The experimental set-up includes a patient model, measurement systems and a ventilator.

The patient model consisted of a 1 l training thorax (Ubungs-thorax, M 13333, Dräger, Germany), a HH (Conchatherm 3, Kendall Company Limited, London, UK), standard ventilatory tubing, two one-way valves, connectors and an incubator (Intensivpflege Incubator 6500, Drägerwerk AG, Lübeck, Germany) as shown in Fig. 1. A calibration bag with a capacity of 650 ml was used during high tidal volume settings to prevent changes in compliance and pressure of the patient model. The output of the patient model was adjusted to produce 100% relative humidity at 34.5 ± 1.0 °C. The incubator was kept at 36.0 ± 0.5 °C to prevent condensation.

A heated flowmeter (Fleisch No. 2, Sensormedics, Bilthoven, The Netherlands), located between the training thorax and the HH, connected to a pneumotachograph (Type 17212, Godart-Statham, Bilthoven, The Netherlands) was used for flow measurements. The flow measurement system was linear between 0–100 l/min, and used to measure the inspiratory and expiratory flow ($V_i$ and $V_e$).

Two sampling ports were used to introduce the temperature probes, humidity sampling capillary and pressure lines; one sampling port was located between the patient model and HME ("P" site), and the other was located between the HME and Y-piece of the ventilatory tubing ("V" site). Two differential pressure transducers (Hewlett-Packard model 270, HP International, CA) and two signal conditioners (Hewlett-Packard model 8805 B carrier amplifier, HP International, CA) were used to measure the pressure in the ventilation circuit at the "V" site ($P_v$) and the pressure difference between the "P" and "V" site ($P_{AV}$). The response time and ranges of the pressure transducers were 5 ms and $-40$ to $40$ cmH$_2$O, respectively.

Two precalibrated, small bead NTC thermistors (Fenwal Electronics, American Power Devices, MA) and a two channel temperature module (Temperature module 78204 B, Hewlett-Packard, HP International, CA) were used for temperature measurements at the "P" and "V" sites. The accuracy of the temperature module was ±0.2 °C. The 0–90% step response times of the thermistors in flowing air were 200 and 300 ms respectively. The temperature probes were calibrated between 20–40 °C with a mercury thermometer.

A quadropole mass spectrometer (MGA 3000, Case, Biggin Hill, UK) was used to measure partial water vapour pressures at the "P" and "V" sites. A transparent, unheated, constricted tip capillary was used for humidity measurements (sampling flow: 40 ml/min). The delay time of the mass spectrometer was 460 ms with a 10–90% step response time of 600 ms.

The barometric pressure was measured by a barometer (Fues barometer, Berlin, Germany) before each measurement and used for calibration of the mass spectrometer.

Bottled helium with a dew point of $-30$ °C (0.038 kPa or 0.34 mg/l humidity) and a vapour generator (Type WG-600 water vapour generator, The Analytical Development Co. Ltd., UK) were used to calibrate the mass spectrometer.

All signals (flow, pressure, pressure difference, temperature and humidity) were amplified (Medium gain differential input DC am-