Performance of a new recuperative Heat and Moisture Exchange Mask

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B – the assembly of data for the research undertaken
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Abstract

Aim of the study: The purpose of this work is to show the possibility to use a recuperative design of a heat and moisture exchange face mask (HME). Such HME are used as cold weather face masks for Arctic expeditions and conditioning of air for long-term intubated patients. Common regenerative HME have the disadvantage of increasing airway resistance and airway volume (dead space). In recuperative devices, the separation of inspired and expired airflow could reduce dead space and resistance.
Materials and methods: Prototype HMEs were built using two concentric ducts of aluminium or cotton. A valve ensures that expired and inspired air are led through either the inner or the outer tube. The inner tube's wall transmits heat and water. The HMEs were tested in a simulated Arctic environment using a breathing simulator and characterized in terms of heat and moisture exchange efficiency. The new design was also tested at room temperature in order to simulate the conditions of long-term intubation. To compare the results, the relative difference in temperature (Performance Coefficient PC) between the expired and the inspired air was calculated.
Results: During the experiments, the ambient temperature was −37°C and therefore the absolute water content was about zero. The recuperative HME conditioned the air to 21°C and 10.7 mg/l water (61% relative humidity), giving a PC of 82%. At room temperature the recuperative mask showed a PC of 62%.
Conclusion: The recuperative HME shows great potential. It might be of use in clinical conditions and Arctic expeditions.

Keywords: heat exchanger mask, cold weather mask, heat and moisture exchanger mask, recuperative HME

Introduction

The effect of heat and moisture exchange face masks for cold weather conditions has been studied [1,2] and their benefit is documented. It is well known, that survival in very cold conditions critically depends on adequate clothing [3], which minimizes the effect of heat loss. Such heat loss is a significant risk factor for a wide range of work in cold environment e.g. cold production facilities in food industry (some of which with −55°C), construction and maintaining jobs in the Arctic or at high altitude (e.g. dam and hydropower projects in Tibet or the construction of the new European telescope at 5,600 m on Cajnator Plateau, Chile, just to give some actual examples), research camps in Antarctica, expedition climbing or alpine rescue operations. For the latter Küpper et al showed that depending on the

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model used for calculation ("mean" or "worst case") 11.6% rsp. of all operations are performed under conditions corresponding to cold class 4 of DIN 33403.5 which is in the range of −18° to −30°C. 0.5% rsp. 13.7% of all operations fulfil the conditions of cold class 5 which describes temperatures of less than −30°C. As Küpper et al. stated there is no perfect protective clothing for such operations due to the temperature differences on scene compared to the interior of the helicopter when transferring patients to hospitals in the valleys. They also reported that sometimes rescue teams are blocked by bad weather, e.g. a team had to stay more than 13 hours at about 4,000 m on Hörnli Ridge / Matterhorn in a terrific storm [4].

However, the respiratory heat loss cannot be addressed by clothing. The inspired air is warmed and saturated with water in the airways and the lungs. By exhaling that air, a certain amount of energy and water is lost with every breath. The amount of energy loss depends on the environmental conditions and increases with the temperature difference. Cain et. al. (1990) found, that the respiratory loss at an ambient temperature of −40°C is in the range of 25-100 Watts, depending on the degree of physical work [5]. This is 20-30% of the metabolic rate. In addition, there are hints that cold air temperatures during training can cause asthmalike chronic airway disease in athletes [6].

The interaction is more complex when high breathing volume is involved: such volumes of cold air cause cooling of the upper airways and thereby they shift the condensation point towards the upper, or even central trachea. Then the water vapor of the expired air will condense within the body which is an effective saving mechanism of body fluid. By this the loss of water in a cold environment increases less with minute volume than it would do in warmer conditions. It should be mentioned that breathing is only one among other factors which cause water loss in a cold environment, for example cold-induced diuresis.

To address the problems of cooling and loss of water, a variety of face masks have been developed and tested [1,2]. Most of the commercially available masks use an integrated air filter, which serves as a regenerative heat exchanger. The filter is positioned in the combined airway of both the exhaled and the inspired air. During the breathing cycle, the air filter is intermittently warmed and cooled by the air flow, thereby cyclically storing and releasing the heat and moisture contained in the exhaled air. Depending on the adsorptive properties of the filter material, heat and moisture are transferred to the inspired air. An important disadvantage of such a system is the increase of dead space and resistance [7]. It is easy to imagine, that a very dense and big filter would improve the efficiency in terms of heat and moisture transfer. However, dead space and airflow resistance would be modified as well.

The aim of this work is to develop a prototype heat and moisture exchange system that does not depend on breathing through an air filter. Instead, expired and inspired air are guided through different, concentric ducts which are separated by a heat and water conducting membrane. This type of device (rHME) reduces the disadvantages of conventional HMEs. The recuperative design potentially optimizes HME efficiency without increasing dead space and airflow resistance. Such a mask could be of use during expeditions or work in very cold or high regions, where water and energy loss is of great interest.

In clinical practice, conditioning of respiratory gas is crucial to prevent lung damage of long-term intubated patients [8]. If the resistance and dead volume of conventional HME's would possibly harm the patient, actively Heated Humidifiers (HH) can be used, but they are expensive and inconvenient to use [9].

However, the conventional HMEs are not as effective and have some contraindications, most of them referring to dead space and resistance [7,8]. These restrictions might not apply for the new rHMEs with low airflow resistance and dead space.

This paper introduces a prototype recuperative HME. It was tested for its potential in a simulated Arctic environment using an artificial lung to produce ventilation and water-saturated exhaled air at a temperature of 34 °C. The mask was also tested at 21°C to establish its potential in clinical long term intubation.

Materials and methods

Design of the prototype

The exchanger consists of a 170 cm long 50 mm diameter plastic tube with a concentrically positioned 30 mm diameter inner tube, thus creating two ducts that are separated by the inner tube wall. The heat exchanger, consisting of a thin, thermally conductive membrane like aluminium foil or cotton tissue, can be placed as a section of the inner tube by plug connections. The expired air is guided through the inner tube, thereby warming and moistening its wall. The inspired air is guided through the space between inner and outer tube taking up the heat and, if permeable to water, moisture from the wall of the inner tube during passage. To prevent exhaled air from being drawn back into the outer tube during inspiration, the exhaust end of the inner tube extends 30 cm beyond the entrance to the outer tube. As a result, heat and moisture is transferred to the inspired air without any direct contact to the expired air (no increase of dead space). All heat exchangers have a length of 50 cm (Fig. 1).

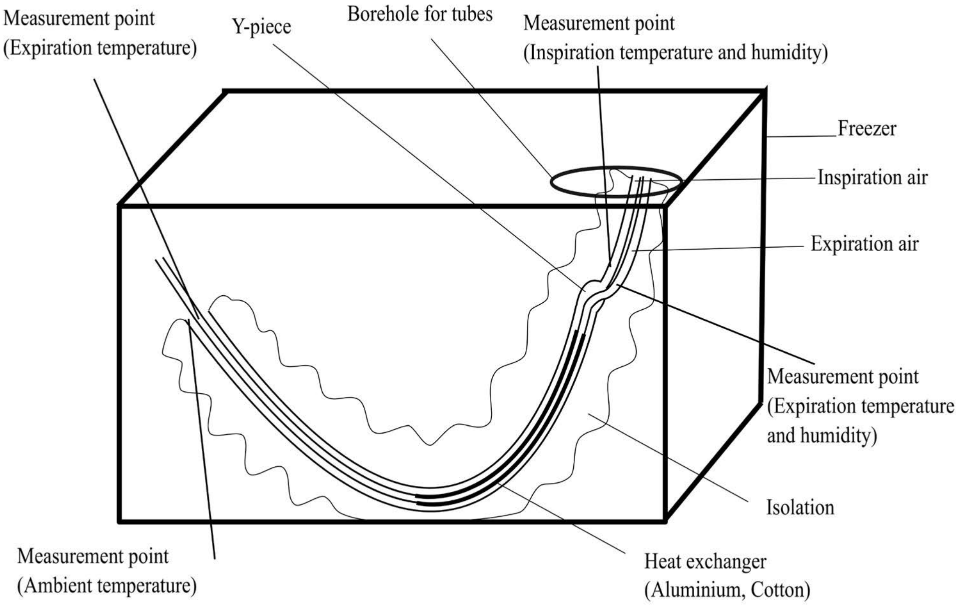

Fig. 1. The device consists of two concentric tubes. The expired air passes through the heat and moisture exchanger which is plugged in as a section of the inner tube. The system is placed into a deep freezer to simulate a very cold environment. Temperature is measured at different points, as seen above

Integration of the rHME into a face mask would require a valve mechanism to separate inhaled and exhaled air. In order to simplify the testing set-up, the exchanger was directly connected to a breathing simulator with distinct ducts for the incoming and outgoing air.

Experimental set-up

Breathing simulator

A piston pump with a tidal volume of 0.5 l and a frequency of 15 strokes per minute produced a ventilation of 7.5 l/min. The air was cyclically directed to the inhale and exhale air ducts by manually driven valves. A counter-current heat exchanger and humidifier was installed between the manually driven exhale valve and the rHME exhale tube. Pilot studies completed with the breathing simulator at −40°C ambient temperature showed that the inhaled air temperature would be in the range of 10-20°C. Consequently, a thermostat on the counter-current heat exchanger was adjusted so that the air entering the exhale tube of the rHME would be water-saturated at 34°C to match conditions identified by Cain et. al. [5].

Simulation of an Arctic environment

The efficiency of the heat exchange process was tested by placing the prototype into a 239 l volume deep freezer at a temperature held around −40 °C (Fig. 1). The heat exchanger was shielded against heat loss with a 5 cm layer of cotton wool in order to minimize direct heat loss through the outer tube wall. The hose connections with the breathing simulator on the outside of the deep freezer were heat insulated in the same way.

Data collection and data analysis

Airflow resistance of the exhale duct was measured using a U-tube manometer, referenced to the surrounding pressure and attached to the connector at the entrance of the exhale duct. Air temperature and water saturation were monitored with electronic lab thermometers (IP65 certified lab thermometer LT-102, TFA, Reicholzheim, Germany [Range: −40–+70°C, Accuracy: ±1°C, Resolution: 0.1°C]) and hygrometers (remote sensor Hygrometer, Trixie, Tarp, Germany [Range: 20-100%, Accuracy ±2.5%, Resolution: 1%]) and recorded manually in intervals of 5 minutes. The sensors for the exhaled air were placed directly at the entrance point into the inner tube. The parameters of the inspiratory air were taken at the exit connector of the heat exchanger (outer air duct) (Fig. 1). These data define the thermal and hygrometric state of the inspired and expired air and are used to determine the efficiency of the heat and moisture exchange process. The calculations were made using the average values of the series. The performance coefficient (*PC*) is calculated as proposed by Johnson at al. [1].

$$PC\,(\%) = (Tin - Ta) / (Tex - Ta) \cdot 100$$

Tin (°C) – inspired air temperature
Tex (°C) – expired air temperature
Ta (°C) – ambient air temperature

Performance of the breathing simulator

The “exhaled air” output of the breathing simulator was tested for stability with respect to temperature and water saturation. In the experiment the water temperature in the counter-current device was set to 34°C. With a pumped air volume of 7.5 l/min the outgoing air exhibited perfect equilibration with the thermostated water. The temperature was constant at 34°C within ±1°C and the relative water saturation was about 94% ±3% over the whole period of time.

Aluminium as heat exchanging material

The performance of the prototype recuperative heat exchanger was tested using aluminium tubing of 0.1 mm and 1.0 mm thickness as heat exchange membrane. Two series of experiments were run. The first two experiments were run with 0.1 mm aluminium foils starting with the heat exchanger placed in the deep freezer and precooled overnight to –39°C. The second series with a 1.00 mm aluminium tube was not precooled to focus on the characteristics in the steady state. The breathing air was taken and released through the heat exchanger at 7.5 l/min.

Cotton tissue as heat and water exchanging membrane

The possibility of counter-current transfer of heat and humidity from the exhaled air to the inhaled air was studied using a very densely weaved, fine cotton fabric (175 g/m^2) which is airtight at low pressure, especially when wetted with water. The cotton fabric heat exchange membrane was tested following a similar scheme as described with the aluminium foil exchanger. One series of three experiments was conducted at –37 °C to explore the performance at very low temperatures; a second series of two experiments was conducted at room temperature in order to test the suitability of the new technical concept to condition the air for long term intubated patients. The humidity of the room was 49% (47%, 51%), the temperature 21°C (20.1°C, 21.7°C). As the room was big enough, those parameters were not influenced by the experiments. In both cases the heat exchanger was not precooled.

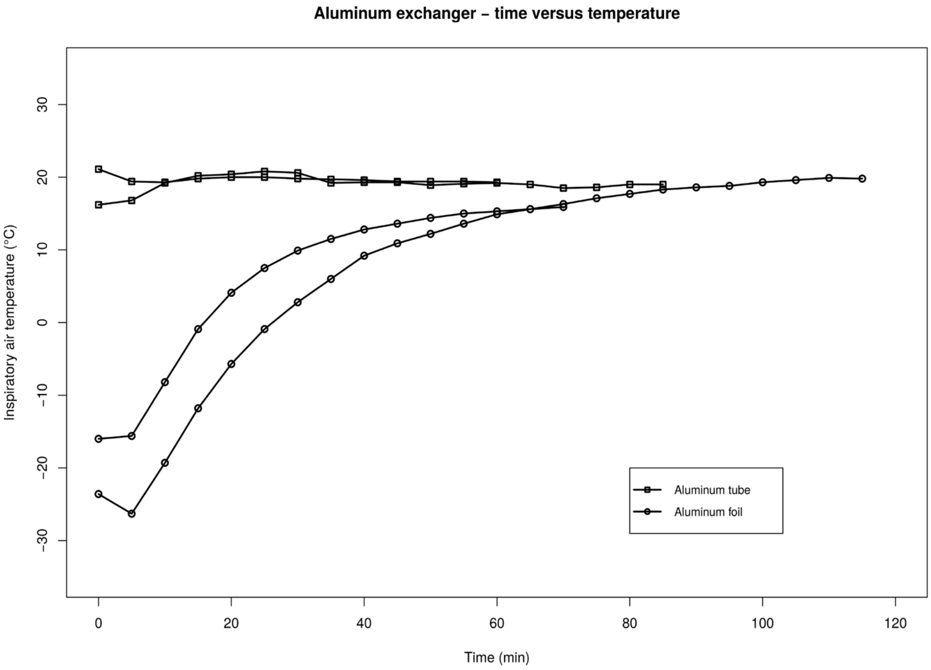

Fig. 2. The different slope of the lines for Aluminium 1 mm to Aluminium 0.1 mm derives from the fact, that the 1 mm Aluminium heat exchanger was not precooled to focus on the equilibrium. As shown, the temperatures achieved are identical

Results

Aluminium foils as heat exchanging material

As shown in Figure 2, the temperature of the air leaving the heat exchanger started at –20 °C (–16°C, –23.6°C) and increased over the first 50 minutes of breathing, than levels off after 80 minutes at 19°C (15.9°C, 19.8°C). The curves reflect the heat of the expired air warming up the heat exchanger until a stationary state is reached after 80 minutes. In the second series, the heat exchanger was not precooled before starting the experiments. As seen in Fig. 2, upper curves, no heat is lost for thermal equilibration. The inspired air leaves the heat exchanger at a constant temperature of 19°C (19°C, 19.3°C) right from the beginning.

The results of this experiment show that the –39 °C (–36.7°C, –40.9°C) cold air in the deep freezer is passively warmed up by 58°C in the prototype heat exchanger, reaching 19°C before entering the (simulated) human airway. Based on the difference between body temperature and the –39°C cold environment, this result implies, that 79% of the energy needed for warming up the air can be passively extracted from the thermal energy of the expired air.

The thickness of the aluminium foil separating the flow of incoming and outgoing air has no influence on the heat transfer efficiency, as the same temperature of 19°C (15.9°C, 19.8°C) is reached in the stationary state. The relative humidity of the inhaled air is near 0%, as the heat exchanging aluminium foil is impervious to water, thereby blocking moisture transfer.

Cotton tissue as heat and water exchanging membrane

As seen in Fig. 3, the heat transfer properties of the cotton membrane closely resemble the results obtained with the aluminium foils when tested at –37°C. Again, the incoming air is passively heated from –37°C (–35.4°C, –37.9°C) to 21°C (20.3°C, 21.8°C) . Based upon the difference between exhaled air temperature and the simulated –37°C cold environment of 71°C, 82% of the temperature interval is covered by the heat exchange with the expired air. In addition to the thermal energy, moisture is also transferred due to the water permeability of the cotton-membrane. The relative humidity of the air was 61% (60%, 62%) at 21°C (20.3°C, 21.8°C) at the outlet of the heat and moisture exchanger, corresponding to 30% absolute water recovery (calculated with the Magnus equation).

The plots of the experiments with cotton membrane at room temperature (21°C (19.7°C, 21.5°C) are displayed in Fig 3.The curves approach a stationary state in the vicinity of 29°C (28.8 °C, 29.5°C) at 77% (76%, 78%) relative humidity. The PC in this series is 62%.

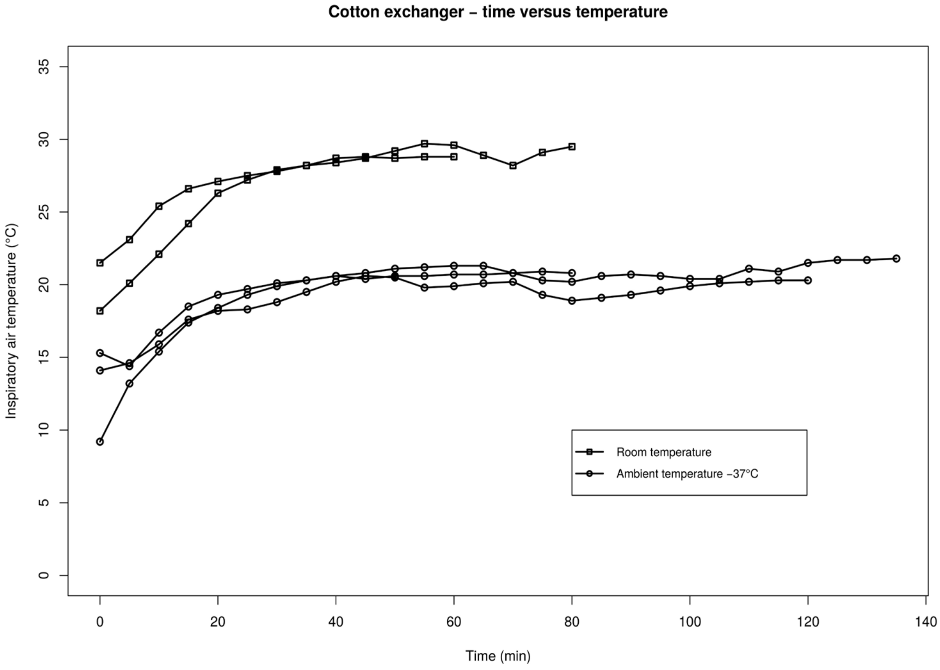

Fig. 3. Upper curves: At room temperature, the cotton membrane heat and moisture exchanger shows great performance, reaching almost 30°C. Lower curves: The performance in terms of temperature is similar to Aluminium. However, the cotton membrane additionally transfers a great amount of moisture to the inspiratory air

Measured with an U-tube manometer, the resistance of the cotton membrane heat exchanger was 2 mm/(L/s) water column, which even at this early stage of development is very similar to conventional HME [7].

Discussion

Masks were in use since the stone age not only for ritual purposes but also for protection (e.g. the Inuit and other Arctic people use them until today). They are also well known in mountaineers and workers in cold environments for decades. However, until recently masks were exclusively used to protect the face's skin from freezing. This is also true for modern military missions and research which focuses on skin protection by balaclavas but not protection from hypothermia by heat loss by (increased) breathing [10]. So far the European regulations for health and safety for work in cold environment include exclusively clothing and head gear, but no aspect of thermal heat loss by breathing [11,12]. First attempts to reduce the body's energy loss were made in the 1960's and 70's, but all these constructions needed additional equipment for heating or increased the resistance significantly [13]. The present-day systems for optimizing the body's temperature balance by "recycling" the heat loss due to breathing are limited due to technical problems: The systems are either too large, need additional equipment (heaters), or increase the resistance.

This study about rHME established the feasibility of this technique. The experiments were conducted in a simulated, Arctic environment using a breathing simulator. The freezer was found to provide a constant temperature of –39°C ± 2°C over extended periods of time. The temperature of the water saturated expiratory air remained constant at 34°C within ± 1°C. With a respiratory volume of 7.5 l/min, these values constitute one boundary condition for the heat exchange device, determining an amount of thermal energy that can be transferred on the inspired air. To assess the amount of thermal energy which is actually transferred, the temperature and the relative humidity of the fresh air leaving the heat and moisture exchanger must be known.

The common method, to place the sensors for temperature and humidity into the joint between heat exchanger and breathing simulator, thus recording these parameters continually during the movement of expired and inspired air, has some serious measuring difficulties: The inspired and expired air flows intermittently in alternating direction around the sensors, with temperature and humidity oscillating synchronously to the breathing cycle over a wide range of temperature (–40°C to 34°C). Although those oscillations can be recorded with thermocouples and high resolution data acquisition systems, thermal energy by condensation and freezing of water on the surface of the sensors distorts the results [14]. In order to obviate these difficulties, the temperature and humidity of the inspiratory and expiratory air has been measured, each in its separated compartment (Fig. 1). By this way, only the unidirectional flow of the inspired, respectively expired air is measured with standard remote sensors. This technique is also applicable with air filter based heat exchangers by using a valve driven system to sample the inspired and expired air in separate ducts.

To compare the performance of the new recuperative with conventional, regenerative HMEs, the performance coefficient as defined by Johnson was used. In this type of score, the difference of the temperatures measured in the inspired and expired air to the ambient temperature is determined and their proportion was calculated. According to the data presented in Fig. 2 and 3, the performance coefficient was about 80% in both cases. These results of the new recuperative design compare well with the performance coefficients observed with conventional air filter based regenerative exchangers [1].

However, the performance coefficient as calculated from the temperature intervals does not truly reflect the proportion of thermal energy recovered from the expired air. This is evident, considering the classification of the aluminium foil and the cotton-membrane as equally effective with a performance coefficient of 80%, although moisture is additionally exchanged by the cotton-membrane, in contrast to the water impermeable aluminium foil. An alternative approach to rate the efficiency of heat and moisture exchange devices could be based on the ratio of the thermal energy recovered from the expired air, including the latent energy released in the process of water condensation. The amount of thermal energy ΔQ released by a given volume of air containing moisture after cooling is calculated according to:

$$\Delta Q = \text{air mass} \cdot c_{\text{air}} \cdot \Delta\text{temperature} + \Delta w_{\text{vap}} \cdot \Delta \text{w}_{\text{mass}}$$

With the specific heat capacity of air $c_{\text{air}} = 1.25$ kJ/(m³ · K) and the specific enthalpy of evaporation of water $\Delta w_{\text{vap}} = 2.4$ kJ/g and considering equal mass for the inhaled and exhaled air, the fraction of the recovered heat reduces to the following formula:

$$PC_{\text{new}}(\%) = [1.25(Tin - Ta) + 2.4 \cdot Win] / [1.25(Tex - Ta) + 2.4(Wex)] \cdot 100$$

Tin (°C) – inspiratory air temperature
Ta (°C) – ambient air temperature
Tex (°C) – expiratory air temperature
Win (g/m³) – absolute water content inspiratory air (g/m³)
Wex (g/m³) – absolute water content expiratory air (g/m³)

Taking this into account, a different rating follows: With aluminium the thermal energy recovery is about 41%, whereas the water permissive cotton membrane shows 56% recovery. The superiority of the cotton membrane relates exclusively to the higher moisture content (61% r.h. versus 0% r. h.) as the temperature of the air leaving the heat and moisture exchanger is around 20°C in both cases. These results probably picture the physiological need more precise, than the comparison of temperatures alone.

Testing the cotton membrane based heat and moisture exchanger at 21°C ambient temperature, the breathing air was warmed up to 29°C with 77% relative humidity. These values suggest that the recuperative design may also be useful in long term intubated patients.

With these results demonstrating the equivalence of the membrane based recuperative, with the air filter based regenerative design, the question of possible benefits of the new method is to be posed.

The main advantage of rHMEs is related to the clear separation of the expired air from the inspired air by guidance through spatially separated ducts. The inner volume of the exchange device does not increase the airway dead volume, as there is no reversal of flow direction, neither in the duct for the expired air nor in the duct for the inspired air. Due to this property, the design of the heat and moisture exchangers along the recuperative method is freed from the restriction to keep the inner volume of the device as small as possible. Considering this aspect, optimizations are conceivable for outdoor applications in very cold regions, where heat and water loss is of interest. For example, it offers the possibility to use long ducts and place expiratory air outside the tent while sleeping or cooking, thus avoiding water to condense inside the tent. This would lead to an ice barrier which increases toxic carbon oxides by minimizing gas exchange. Several case reports of incidents during high altitude expeditions were published [15,16]. In contrast to tents the risk of icing within the exchanger may be reduced by adequate design features.

Such features should be of advantage for a wide range of possible usage when employees work in very cold (cold class 4 DIN 33403.5) or extreme cold conditions (class 5 DIN 33403.5). Examples were given above. It is difficult to estimate the total reduction of energy loss since this is not only affected by the environmental temperature but also by the minute breathing volume which is unknown for most types of work. However, the following situations may be estimated carefully: An employee in the cold section of a yeast plant works at −40°C for 8 hours a day (it may be assumed that he will spend the rest of the day in a comfortable environment). During the shift he will work at a metabolic rate comparable to walk a 5% slope with 3 km/h. Cain et. al. identified a respiratory heat loss of 72 watts for this condition which corresponds to 2074 kJ during the shift. According to our data he could reduce his daily energy loss by more than 1000 kJ [5].

But there might be other fields of use: The currently used HME masks for intubated patients have contraindications resulting from the increase of dead space and airflow resistance [8]. Such HMEs have an integrated filter, preventing infectious material from entering the ventilator. In conventional masks, this filter must not increase dead space too much so it has to be very small, therefore increasing the resistance to considerably high values of up to 13 mm/l/s water column [7]. In the rHME, the filter would not be in a combined airway, so it could be much larger and therefore lower in resistance and additionally it would be used in an unidirectional flow. In this way, germs in the expiratory air cannot colonise in the filter and be drawn back into the lung during inspiration. As the rHME adds no additional dead space and its air flow resistance can be adjusted to very low values, the contraindications of currently used HME masks might be relieved, thereby offering an alternative to the expensive Heated Humidifiers.

Conclusions

The study has proven that rHMEs have the potential to save 41% to 56% of energy loss in extreme cold conditions. Because of their small dead volume and resistance they could be of benefit for work in extreme cold conditions, on expeditions to the Arctic or at extreme altitude. Furthermore they may be a benefit for intubated patients in intensive care units.

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