The influence of heat and moisture exchangers on tracheal climate in laryngectomized individuals: toward optimal pulmonary rehabilitation

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CHAPTER 5

Influence of breathing resistance of heat and moisture exchangers on tracheal climate and breathing pattern in laryngectomized individuals

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Abstract

Objective

The aim of this study was to determine the influence of breathing resistance of heat and moisture exchangers (HMEs) on endotracheal climate and breathing pattern.

Patients and methods

Endotracheal temperature and humidity and tidal volumes were measured in 11 laryngectomized patients with a regularly used HME with "standard" breathing resistance (Provox® Normal HME; R-HME), a low breathing-resistance HME (Provox® HiFlow HME; L-HME), and without HME.

Results

Both R-HME and L-HME increased end-inspiratory humidity (AHinsp): +5.8 and 4.7 mgH_2O/L, respectively; decreased end-inspiratory temperature (Tinsp): -1.6 and -1.0ºC, respectively; and prolonged the exhalation breath length to approximately 0.5 seconds. The R-HME significantly enlarged tidal volumes (0.07 L; $p < .05$).

Conclusion

Both HMEs improve tracheal climate significantly. The R-HME has better moistening properties and a small, but significant positive effect on tidal volume. Therefore, if the higher resistance is tolerated, the R-HME is the preferred pulmonary rehabilitation device. The L-HME is indicated if lower breathing-resistance is required.

Introduction

Total laryngectomy disables normal respiratory physiology stemming from the disconnection of the upper and lower airways. The most important function of the upper airways with respect to respiratory physiology – which is warming and humidification of inspired air – is lost. Lack of conditioned inspired air leads to an increase of chronic pulmonary complaints like frequent involuntary coughing, sputum production, and forced expectoration in order to clear the airways [15]. Passive humidifiers or Heat and Moisture Exchangers (HMEs) were developed to compensate for the lost upper airway function and have been found to reduce these symptoms and improve quality of life [15;25-27;86;87]. In previous clinical studies it was found that the HME most regularly prescribed in the Netherlands (Provox® Normal HME; further referred to as R-HME) increased endotracheal end-inspiratory humidity (AHinsp) with 3–6 mgH_2O/L and, because of the evaporation process of water droplets, decreased end-inspiratory temperature (Tinsp) with 1.6 °C [33;88].

Except for the warming and humidification, one of the other lost upper-airway functions is providing resistance to breathing [40]. Laryngectomized patients no longer breath against resistance during open stoma breathing. Although breathing against some resistance is thought to be beneficial for laryngectomized patients, its theoretical positive effect is not yet substantiated in clinical research. It is hypothesized that after laryngectomy, a drop in upper-airway resistance might lead to a shift of the equal pressure point (the point where the pleural pressure and the intra-thoracic pressure are balanced) toward the more peripheral and less elastic pulmonary airways [41]. Because of a decrease in transpulmonary pressure (recoil pressure), these airways might then be compressed, which leads to a reduction in circulating lung volume.

An HME that substitutes for the lost upper airway resistance would, theoretically, create positive expiratory pressure, prevent the alveoli from collapse, and lead to increased circulating lung volume [27;34]. However, breathing through an HME with a resistance close to normal upper respiratory tract (0.37 kPa.s/L) is experienced as uncomfortable, particularly during physical exertion and could possibly lead to a decreased patient compliance [45]. The R-HME, regularly prescribed in the Netherlands, provides a breathing-resistance of about 0.2 kPa. s/L, which generally is accepted by most patients and is therefore the preferred pulmonary rehabilitation device [65;87]. However, clinical experience

is that an even lower breathing-resistance (temporarily) can be desirable for laryngectomized patients. For instance, patients who start using an HME after they have become used to open-stoma breathing for a longer time period postlaryngectomy often need a couple of days or weeks to get used to breathing against at least some resistance before being able to comfortably switch to the standard-prescribed resistance version. Also when used in combination with a trachea cannula with an inherent resistance and during physical activities the use of a lower breathing resistance can be required.

Because the benefit of breathing resistance of an HME has not been proven [44] the use of low breathing-resistance HMEs would be a viable alternative, if the moistening capacity does not decrease unacceptably. The moistening capacity of passive HME devices is based on the condensation of water on the surface of porous material such as foam, paper or another substance mostly with a hygroscopic coating with a salt, such as $CaCl_2$. The larger the condensation surface (i.e., more hygroscopic material), the better the moistening capacity and vice versa [89]. An HME with the same size but with lower breathing resistance can be easily be achieved by using (the same) material with larger pores. In consequence, however, this HME will contain less (hygroscopic) material, indeed resulting in smaller moistening capacity.

Although the heat and moistening capacity of the lower breathing-resistance HME mostly used in daily practice (Provox® HiFlow HME, further referred to as L-HME) has been specified under standard physical and ambient conditions in laboratory settings (in accord with the ISO norm), these *in vitro* measurements may not fully represent *in vivo* behaviour. Therefore, this study aims to investigate the *in vivo* heat and moistening capacities of this lower breathing-resistance HME compared to an HME with the regularly-used breathing resistance. Secondly, the effect of both HMEs on breathing pattern and tidal volume was explored.

Patients and Methods

Subjects

In 11 laryngectomized patients, 10 men and 1 woman (median age 67 years; range 56-81 years; SD 9.1) endotracheal climate and pulmonary function data were available. All patients were regular HME users. In addition to surgery, all patients also received radiotherapy, had quit smoking and were in long-term

follow-up, on average 8.6 years postoperative (median 7.0 yrs, range 0.6–19 yrs, SD 6.2). One patient had undergone a lobectomy because of metastatic disease. The study was approved by the Protocol Review Board of the in the Netherlands Cancer Institute and written informed consent had been obtained from all patients.

HME devices

For "standard" breathing resistance, the regularly used Provox® Normal HME device (R-HME) was used. For lower breathing-resistance (L-HME), the Provox® HiFlow HME device was used. Table 5.1 shows an overview of the breathing resistance at different airflows. Manufacturer's specifications of the *in vitro* moisture loss of the R-HME and L-HME are, respectively, 23.7 mgH_2O/L and 25.4 mgH_2O/L (in accord with ISO9360-2;2001; data are available in the product's manual). Both devices use a porous foam material, which is impregnated with calcium chloride. The foam of the L-HME has more open pores (to reduce flow resistance) and thus contains less material within the same dimensions of the HME cassette, as can be seen in Figure 5.1.

Measurement protocol

The measurement protocol was identical to that used in our previous studies [88]. All patients were measured during rest breathing seated in a chair. A small hole was punched in a peristomal HME adhesive (Provox®, Atos Medical, Hörby, Sweden), through which the distal tip of the sample catheter of the Airway Climate Explorer (ACE; described in Chapter 2) was inserted. The catheter tip was positioned approximately 1 cm in the cranial end of the trachea. Each measurement session included at least three 10-minutes breathing periods (observations), in a randomized sequence: 1 observation with open stoma breathing (without HME), 1 observation with the R-HME and one with the L-HME. All measurements were performed at room climate conditions.

Breathing measurements

The breathing frequency was monitored with respiratory inductive plethysmography (Respitrace QDC, Viasys Healthcare, Houten, The Netherlands). During 2 minutes after each 10-minute observation period, airflow was measured with a calibrated spirometer flowhead (flowhead MLT300L, Adinstruments, Oxfordshire, UK) placed on the peristomal adhesive by use of an airtight attachment with a cardboard tube (Figure 5.2). During the

measurements both R-HME and L-HME were left on the peristomal adhesive after the 10-minute observation so that spirometric results of breathing with R-HME, L-HME and without HME could be compared.

Table 5.1 Breathing resistance of the HMEs used in this study. The pressure drop (Pa) at 30 and 60 L/min were measured according to ISO9360-2;2001. Also the pressure drops of the *squared* flow [90] are shown. The other values are derivatives.

	flow at 30 L/min (0.5 L/s)			**flow at 60 L/min (1.0 L/s)**		
	Pa	**kPa.s/L**	**Pa.s²/L²**	**Pa**	**kPa.s/L**	**Pa.s²/L²**
Provox® Normal HME (R-HME)	89	0.18	356	207	0.21	207
Provox® HiFlow HME (L-HME)	66	0.13	264	172	0.17	172

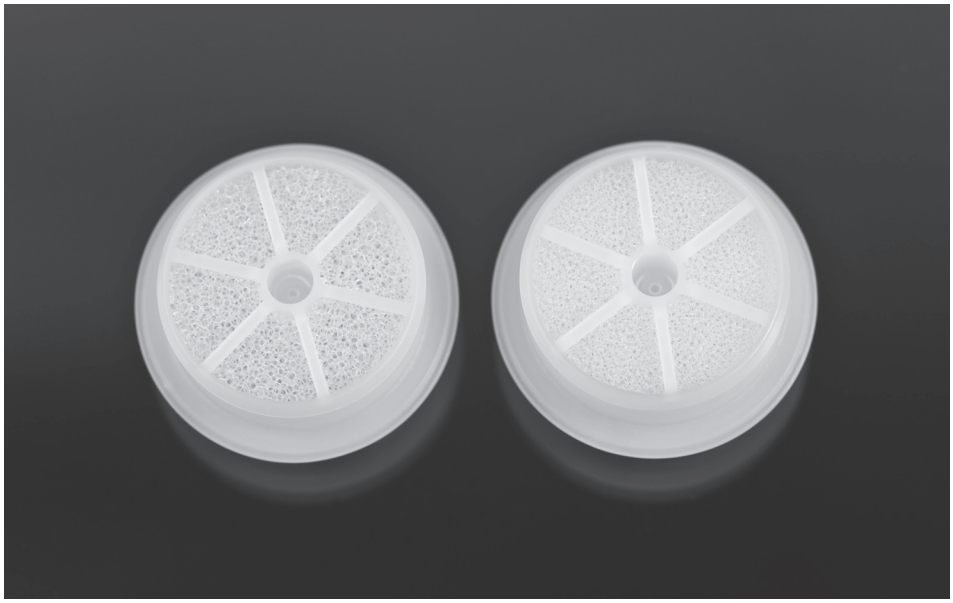

Figure 5.1 The "standard" breathing-resistance Provox® Normal HME (R-HME; right) and low breathing-resistance Provox® HiFlow HME (L-HME; left). Within the same HME cassette, the foam of the L-HME has more open pores and thus contains less material.

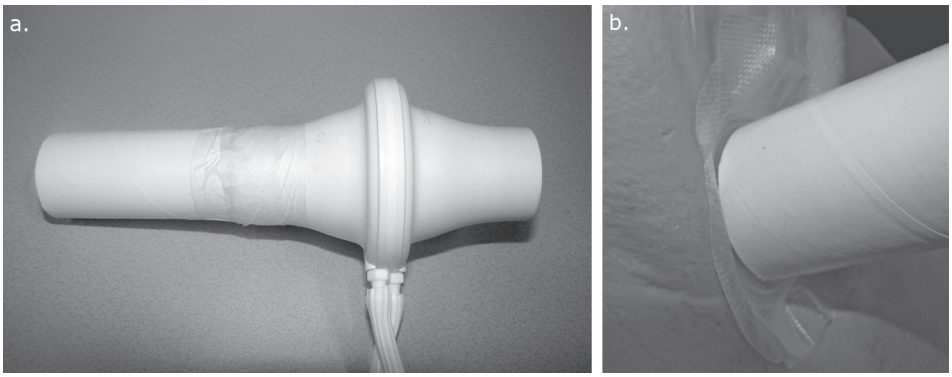

Figure 5.2 Airflow was measured with a calibrated spirometer flowhead (a) placed on the peristomal adhesive by use of an airtight attachment with a cardboard tube (b). Spirometric measurements with R-HME and L-HME did not influence the airtight construction.

Data collection

All data have been checked on sufficient quality prior to analysis since measurement errors can occur, particularly in humidity measurements (see Chapter 3). Good-quality measurements for both temperature and humidity were available in 11 patients. End-inspiratory and end-expiratory parameters of this data set were analysed in conjunction with the more extended data set which we used in our previous study for consistency and increased statistical power (see Chapter 3 and 5).

Data processing, modelling and analysis

Data processing and analysis is described in detail in Chapter 3. In summary, from each observation, two 2-minutes episodes (minutes 6,7 and 9,10) of each observation were used for analysis. Breaths from each episode were identified using a peak detection algorithm ('peaks' – Splus). The time between 2 end-exhalations was defined as the full breath length (FBL), and the time between end-exhalation and end-inhalation as the inhalation breath length (IBL). The difference between FBL and IBL is the exhalation breath length (EBL). The midpoints of the inhalation and exhalation periods were used to approximate the IBL, EBL and FBL. We used five linear mixed effect models for the analysis of IBL, EBL, FBL, Tinsp and Texp. As a result of the dependence of AHinsp on IBL (in contrast to Tinsp), a non-linear exponential-decay mixed effects model was used to analyse both AHinsp and AHexp simultaneously.

AHinsp can be determined from the equation (see also Chapter 3), where A_1 is the asymptotic minima, A_2 is the initial humidity value (AHexp), A_3 is the decay rate and IBL is the inhalation breath length. A_1, A_2, A_3 and IBL are all dependent on HME type. A_1 is linearly related to H_r with co-efficient β (= 0.94).

Since larger IBL implicates lower AHinsp, the HME effect (i.e., the difference with and without HME) or the difference between 2 different HMEs can be calculated in two different ways (see also Figure 3.4b):

1. the clinical relevant HME effect: AHinsp is calculated at type specific IBL
2. the pure HME effect: AHinsp is calculated at the same IBL in order to exclude the enhanced moistening effect caused by a shorter IBL The choice of the IBL is somewhat arbitrary (for consistently with previous work, we used IBL = 1.1 s) [33].

The difference between the estimate of clinical Tinsp and AHinsp obtained with either of the HMEs and without an HME was tested with *t* tests using the estimates of the residual standard errors (SEs) at the clinical Tinsp and AHinsp (differing by HME type) and the degrees of freedom estimate obtained if a standard linear mixed effects model was used.

The statistical analysis was conducted using Splus v6.2 pro software.

Calculation of Relative Humidity

Relative humidity (RH) values were calculated from the observed end-inspiratory and end-expiratory absolute humidity (AHinsp and AHexp) and temperature (Tinsp and Texp) values using an approximation for the saturation humidity with an accuracy > 0.5% [33].

Analysis of spirometric results

Within each breathing episode, a 60-second time period of tidal breathing (without very deep inhalations and exhalations) was selected for analysis. Tidal volume (Vt) and breathing frequency (*f*) were calculated using the Spirometry Extension v2.0 software for Chart 5 5.4.1 software program (ADInstruments Ltd, Oxfordshire, UK). Before calculation, a drift correction was applied for the spirometer flowhead. In the Volume Chart Extension, the algorithm for Vt includes a correction for the difference in volume between inhalation and expiration resulting from differences in temperature and humidity with a

fixed volume ratio of 1.05. Also a volume correction for the dead space of the flowhead and the cardboard tube was applied (in total 110 ml). The additional dead space of the HME (approximately 5 ml) was too small to influence tidal volumes. Theoretically, warm and humid air has a larger volume expansion that requires an additional correction [91]. However, for the differences between with R-HME, L-HME and without HME in this study, this correction < 1% and therefore neglected.

The results of the spirometric parameters per measurement were collected in a separate database using SPSS v15.0 (SPSS Inc., Chicago, IL). Because the means of Vt were non-normally distributed and the breathing frequency *f* had occasional outliers, both parameters were tested with the nonparametric Wilcoxon-rank test of 2 related samples.

Room conditions
The median room environment temperature was 23.7 ºC (range 22.6– 27.8 ºC, SD 1.1), the median room absolute humidity was 6.4 mgH_2O/L (range 5.9–10.0 mgH_2O/L, SD 1.3) and the median room relative humidity was 30.0% (range 22.6–46.2%, SD 6.3).

Results

Effect of HME on temperature and humidity
The model estimates of the end-inspiratory and end-expiratory endotracheal temperature and humidity of the R-HME, L-HME, and open stoma breathing (without HME) are shown in Table 5.2.

Tinsp without HME was 28.5 °C. Both during breathing with R-HME and with L-HME, Tinsp decreased slightly but significantly (-1.6 °C and -1.0 °C, respectively; $p < .0001$). All end-expiratory temperature values were similar (see also Figure 5.3).

The end-inspiratory and end-expiratory humidity values plotted against IBL and the estimated model fits are given as an example of one measurement in Figure 5.4. The presence of the R-HME and L-HME increased AHinsp with respectively 5.8 mgH_2O/L ($p < .0001$) and 4.7 mgH_2O/L ($p < .0001$), which is the clinical HME effect at type specific IBL. The difference in AHinsp between both HMEs was 1.1 mgH_2O/L ($p < .0001$). When the enhanced moistening

effect caused by the decreased IBL is excluded (pure HME effect; IBL = 1.1 s), the HME effect is somewhat smaller for both R-HME and L-HME (4.9 mgH_2O/L and 3.8 mgH_2O/L, respectively). Both HMEs increase the maximum absolute humidity with 0.7 mgH_2O/L ($p < .0001$).

The end-inspiratory relative humidity (RH) without HME was 60% and was increased to 89% (R- HME) and to 82% (L-HME), calculated at type specific IBL. At end expiration, endotracheal relative humidity was about 90% in all observations (without HME 87%; R-HME 90%; L-HME 89%).

Table 5.2 Overview of the model estimates of the breath length, temperature and absolute humidity R-HME, L-HME and open stoma breathing (without HME). Room humidity H_r = 6.4 mgH_2O/L.

	Without HME	**R-HME**	**L-HME**	**Difference R-HME** minus **Without HME**	**Difference L-HME** minus **Without HME**	**Difference R-HME** minus **L-HME**
Breaths (s)						
IBL	1.35	1.05	1.06	- 0.30**	- 0.29**	- 0.01
EBL	2.19	2.61	2.69	+ 0.42**	+ 0.49**	- 0.08
FBL	3.55	3.65	3.75	+ 0.11	+ 0.20*	- 0.09
Temperature (°C)						
Tinsp	28.5	26.9	27.5	- 1.60**	- 1.0**	- 0.6**
Texp	34.4	34.4	34.5	0.0	+ 0.10	- 0.10
Absolute humidity (mgH_2O/L)						
A_1	9.7	12.6	12.3	+ 2.6**	+ 2.9**	+ 0.3
AHinsp (type specific IBL)	17.0	22.8	21.7	+ 5.8**	+ 4.7**	+ 1.1**
AHexp (IBL =1.1 s)	17.7	22.6	21.5	+ 4.9**	+ 3.8**	+ 1.1 **
A_2 (AHexp)	33.5	34.2	34.2	+ 0.7*	+ 0.7*	+ 0.0
A_3 (reaction time) in seconds	0.51	0.80	0.68	+ 0.29	+ 0.17	+ 0.12

** p value < .01; ** p value < .0001*

Breathing pattern

The IBL, both with and without HME, was statistically significant different: the IBL values with R-HME and L-HME were 1.05 and 1.06 s, respectively, compared to 1.35 s without HME ($p < .0001$). The difference in EBL, both with and without HME, was statistically significant, but no difference in EBL

Table 5.3 Spirometric results of tidal volume Vt (L) and breathing frequency *f* (breaths per minute) of breathing with R-HME, L-HME and without HME.

Spirometry tidal breathing N = 12	**without HME** Median (SD)	**R-HME** Median (SD)	**L-HME** Median (SD)	**Difference R-HME** minus **without HME** p-value	**Difference L-HME** minus **without HME** p-value	**Difference R-HME** minus **L-HME** p-value
Vt (L)	0.42 (0.1)	0.49 (0.1)	0.45 (0.1)	0.01*	0.15	0.29
f (breaths per minute)	18.5 (3.0)	18.7 (2.6)	18.2 (2.4)	0.84	0.33	0.27

* *statistical significant (p < .05)*

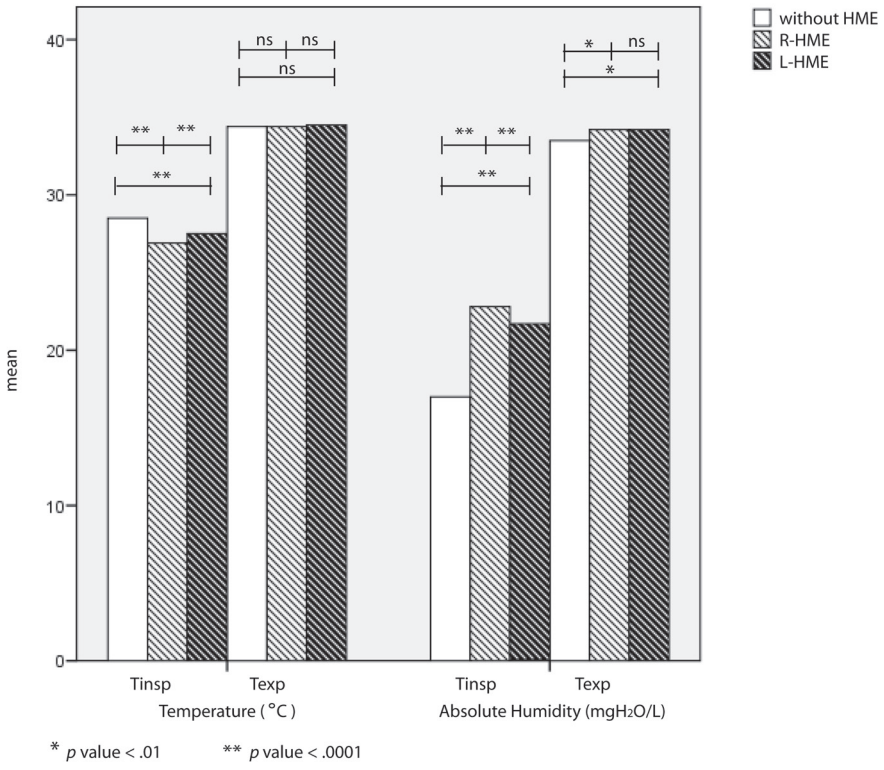

Figure 5.3 The model estimates of Tinsp, Texp, AHinsp and AHexp and of R-HME, L-HME, and without HME are shown.

was found between both HMEs (Table 5.2). The FBLs of breathing with R-HME, L-HME and without HME were similar and correspond to breathing frequencies of, respectively, 16.9, 16.0 and 16.4 breaths per minute. The results of the spirometric measurements (Table 5.3) showed somewhat higher breathing frequencies (respectively, 18.7, 18.2 and 18.5 breaths per minute). The tidal volume (Vt) was, slightly, but significantly, larger with R-HME than without HME (0.47 L versus 0.42 L; $p < .05$). The increase in Vt induced by the L-HME was smaller and did not reach statistical significance.

Discussion

Humidity and temperature at end-inspiration

Both the HME with the standard breathing resistance (Provox® Normal HME; R-HME) and the HME with the lower breathing-resistance (Provox® HiFlow HME; L-HME) cause the end-inspiratory absolute humidity (AHinsp) to increase significantly with respectively 5.8 and 4.7 mgH_2O/L. Although the R- HME is thus about 25% more effective in preserving water than the L-HME, both HME devices can be considered clinically effective moisture exchangers. As anticipated, the L-HME provides a smaller increase in humidity, since it contains less (hygroscopic) material because of the larger pores in the foam within the same cassette dimensions to achieve a lower breathing resistance. During inspiration, the moistening capacity of passive HME devices is based on the evaporation of the water on the surface of foam inside the HME. Because vaporization is a heat-consuming process, heat is absorbed from the environment, which cools the inspired air and the foam of the HME. If the foam of the HME is constructed with larger pores it will have less surface, less water can be vaporized, and less heat is required for vaporization. Indeed we find that the end-inspiratory temperature values decrease less with the L-HME than with the R-HME.

Inhalation and exhalation breath length

The breathing frequency with R-HME, L-HME and without HME was similar and on average 16.4 breaths per minute. Noticeably, the breathing frequencies measured with the spirometer were somewhat higher (about 18.5 breaths per minute). Probably the patients were more alert and active during the short spirometric acquisition than during the long ACE measurements when patients were sometimes breathing very slowly while they almost fell asleep,

and sometimes breathing with very deep inhalations and exhalations (having sighs).

When compared with open-stoma breathing, breathing with HME leads to a prolonged EBL. The increase in EBL in the presence of a higher breathing resistance (with HME) is reminiscent of the effect of pursed-lip breathing (PLB), which is a commonly employed method of breathing through pursed lips in order to achieve a prolongation of expiration. This pattern of respiration is used spontaneously by some patients with chronic airway obstruction (COPD) and is thought by many (mainly COPD) patients to reduce the subjective feeling of dyspnoea. PLB has been shown to decrease expiratory flow rate, enlarge tidal volumes, improve arterial oxygenation and reduce CO_2 levels [74;75;77;78]. This positive effect on pulmonary parameters is thought to be mainly attributed to enlarged transpulmonary pressures, reducing the tendency for alveoli to collapse [74-76]. This theory has also been introduced in the discussion of the possible benefits of the breathing resistance provided by an HME in laryngectomized patients [27;34;41]. Interestingly, in the present study we have found that breathing through the R-HME not only leads to prolonged expiration, but also to slight but significantly increased tidal volumes. For the L-HME, a (smaller, nonsignificant) trend toward increased tidal volumes was observed, suggesting a similarity between the effect of an HME and PLB, although on a smaller scale.

In contrast though to the effect of PLB, the clinical effects of HME-induced breathing resistance in laryngectomized patients have not been demonstrated, for either the short or the long term. McRae et al [43] were the first to study the possible short-term impact of an HME on transcutaneous oxygenation ($tcpO_2$). They found an increase in $tcpO_2$ of 10.5 mgHg (1.4 kPa) in 20 laryngectomized patients after breathing with a high-resistance HME (about 0.32 kPa.s/L) for 4 hours. Our research group repeated the experiment with a similar HME (0.37 kPa.s/L), but included a control group without HME. An increase (with and without HME) was found in $tcpO_2$ of about 0.5 kPa in both groups without a significant difference between the groups [44]. It was presumed that the results of McRae et al arise from the spurious effect of an undetected upward signal drift of the transcutaneous electrode [92]. Considering the long term effects, Jones et al [27] reported an increase of 8.6 kPa $tcpO_2$ after 6 months of HME breathing, which differed significantly from the increase that was found

in control measurements (6.7 kPa). Although the authors suggested that this increase is primarily related to the breathing resistance of an HME, it may also be hypothesized to be the result of a generally improved mucosa condition arising from increased endotracheal temperature and humidity in the HME group [65].

Even though the effects of breathing against resistance in laryn-gectomized patients are qualitatively similar to PLB (increased tidal volumes, prolonged EBL), it is not surprising that the expected increase in arterial oxygenation was not observed by Zuur et al [92]. PBL achieves much higher expiratory pressures than those caused by HME breathing. Consequently, a larger increase in tidal volumes can be reached. For example, increases of 0.2–4 L in tidal volume resulting from PLB have been reported in patients with COPD [78]. This is substantially larger than the minor increase of 0.07 L, which we observed. Consequently, even if the arterial oxygenation would measurably increase, the amount is not likely to be clinically very relevant.

Considering the limited benefit of HME resistance on arterial oxygenation the impact of HME resistance on patient comfort and compliance must be considered [27;45]. In previous studies, earlier versions of the present R-HME (the Free vent HME) with a breathing resistance of 0.1–0.2 kPa.s/L (166 $Pa.s^2/L^2$) [50;90] were assessed [65;86]. Patients included in that study had never used an HME before enrolment. Although some patients reported an increased breathing resistance, none of them experienced uncomfortable breathing with this HME, except for a few patients reporting that they sometimes removed the filter during the first days of the study period [65;86]. Our clinical experience is that the present R-HME (0.2 kPa.s/L) is generally accepted as comfortable during rest breathing in almost all patients. Ackerstaff et al [25] investigated the clinical experience with the R-HME and L-HME in a cohort of 81 patients. In this patient group, 21% preferred the R-HME, 43% the L-HME and 36% alternated between the 2 HME devices, while only 2 patients (2.5%) experienced uncomfortable breathing. Jones et al [27;45] previously found that an HME with a higher breathing resistance (0.32 kPa.s/L) was tolerated in most of the patients (80%) during rest-breathing, whereas during exercise, 50% of these patients experienced this same breathing resistance as uncomfortable. The proportion of laryngectomized patients experiencing uncomfortable breathing decreased to 6% if the breathing resistance of the HME device was cut in

half (0.12 kPa.s/L) [27;45]. Obviously, increased exercise intensity requires an increase in airflow. In healthy individuals, with normal functioning upper airways, a drop of 30% in nose-breathing resistance was shown during intensive physical exercise [93]. The L-HME with its 25% lower resistance compared to the R-HME offers laryngectomized patients an alternative choice during physical exercise. Additionally, the L-HME can also be advised when patients experience the breathing resistance of the R-HME as uncomfortable, when patients start using an HME for the first time after a period without HME breathing, or when the HME is used in combination with a trachea cannula, which gives an inherent additional airflow resistance. Compliance in all these patients groups may be improved by the choice for a lower-resistance HME.

Conclusions

Both HMEs increase endotracheal humidity (compared with open-stoma breathing) and decrease end-inspiratory temperature. The lower-resistance HiFlow HME (L-HME) is constructed with less material (with larger pores) to achieve a 25% lower breathing resistance, and, consequently, is a 25% less effective humidifier. Because of the significantly better water-preserving capacities of the standard- resistance Normal HME (R-HME), such an HME is the better choice for regular daily use. In circumstances when a lower breathing-resistance HME provides more comfort for example during physical activities, the L-HME still appears to be an acceptable alternative, also because it potentially increases compliance. Additionally, both the R-HME and the L-HME prolong exhalation breath length, and the R-HME even causes a small but significant increase in tidal volume.