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The combination of a heat and moisture exchanger and a Booster ™: a clinical and bacteriological evaluation over 96 h

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Abstract *Objective:* To determine whether the combination with a new device (Booster ™) for active humidification improves the efficacy of a hydrophobic heat and moisture exchanger (HME). *Design and setting:* Prospective, interventional study in the ICU of a university hospital. *Patients:* Consecutive patients requiring controlled mechanical ventilation *Interventions:* Patients were ventilated with a HME, and a Booster™ was added for 96 h to the ventilatory circuit. *Measurements and results:* During the inspiration phase the following factors were measured: peak and mean airway pressures, maximal (beginning of inspiration), minimal (end of inspiration), and mean values of temperature of inspired gases, and relative and absolute humidity of inspired gases. Microbiological samples were obtained from the Booster ™, the ventilator side of the HME, and the tracheal secretions on days 1 and 4. Minimal and mean temperatures were increased as soon as the Booster ™ was used and this increase was maintained for 96 h until the Booster™ was withdrawn. Then the temperature returned to baseline values. Absolute humidity values followed the same course. There was also some indirect evidence of very little, if any, changes in the HME resistance. The ventilatory side of the HMEs remained sterile in each patient, and the Booster™ was colonized by the same bacteria as those in the tracheal secretions. *Conclusions:* Adding the Booster™ to a hydrophobic HME improved the heat and water preservation of ventilatory gas.

Keywords Active humidification · Heat and moisture exchanger · Heat and water preservation · Mechanical ventilation

Introduction

Mechanical ventilation with endotracheal intubation or tracheostomy bypasses the upper airway and the normal heat and moisture exchanging process of inspired gases. Therefore humidification and heating of gases are widely accepted and practiced in anesthetized and intensive care unit (ICU) patients [1, 2, 3, 4, 5, 6, 7]. Failure to achieve and maintain an adequate humidification may predispose patients to severe airway damages (destruction of cilia and mucus glands, decrease in surfactant and ciliary transport) and heat loss (decrease in core body temperature) [1, 2, 3, 4, 5, 6, 7]. Among the numerous devices which have been manufactured to supply heat and humidity to inspired gases, heated humidifier systems are the most widely used because of their effectiveness. However, these devices have some disadvantages: condensation of water that may be a source of infection, high maintenance costs, electrical hazards, and increased nurse workload (control of temperature, refill of water reservoir, drainage of condensed water in the circuit) [8].

The use of a modern artificial nose, or heat and moisture exchanger (HME) may provide a solution to both the problem of humidification and that of heat preservation [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Positioned between the endotracheal tube and the ventilator, the HME captures heat and moisture carried in the expiratory gases and returns collected heated and moisture to the cold, dry gases inspired by the patient. HME efficiency has been tested in several studies, but the performance of hydrophobic HMEs may be inadequate [20, 21, 22]. In addition, these humidifiers during long-term ventilation and during ventilation with elevated minute ventilation may have some limitations [23]. A device named Booster™ has recently been introduced for clinical use [24, 25, 26]. The Booster™ increases temperature and moisture levels of the medical gases delivered to the patient.

HMEs can safely be used for long-term mechanical ventilation and manufacturers' instructions are to change them after 24 h of use. However, there are no differences in tracheal tube occlusion and other mechanical or infectious complications regardless of whether hygroscopic HMEs are changed after 2 [27], 4 [28], or even 7 days of use [29]. This study was designed to determine whether the addition of a Booster™ to the ventilatory circuit affects the technical performance and the microbial colonization of a HME used for 4 consecutive days in the same patient.

Materials and methods

Fourteen consecutive patients were included in a prospective, interventional study; patients' clinical characteristics are presented in Table 1. With institutional approval and informed consent obtained from the closest relative, we studied tracheally intubated, mechanically ventilated patients sedated with sufentanil (0.3 µg/kg per hour) and midazolam (0.06 mg/kg per hour). All patients were on controlled mechanical ventilation; the reason for mechanical ventilation was acute respiratory failure in six and coma after head trauma in the other eight. We planned to replace the HME after 96 h of continuous use unless a serious clinical event occurred (endotracheal tube occlusion, HME obstruction). The hydrophobic HME tested in the present study was the Thermovent HEPA+ (SimsPortex, Hythe, UK). Technical characteristics of the HME are as follows: deadspace 100 ml, moisture output 29.6 mgH_2O/l (tidal volume 500 ml, 15 bpm), resistance to flow (24 h) 1.7 hPa (cmH_2O) at 60 l/min; gas leakage less than 1 ml/min (70 hPa cmH_2O). The HME was placed between the Y-piece and the connecting tube and positioned above the patient's head to avoid mucus deposition on the filter membranes. The Booster™ was added to the ventilatory circuit. This device consists of a ceramic heating element fed by an electrical energy source, a water input port, a Gore-Tex membrane, and an aluminum grid which vaporizes water from a conventional giving set. The Gore-Tex membrane only allows water vapor into the airway. The device is positioned between the HME and the endotracheal tube (Fig. 1).

To be included in the study the patients had to require controlled mechanical ventilation for 4 days or more. Patients were not included in the study if they were hypothermic (body temperature <35°C) or had a bronchopleural fistula. The ventilatory circuit consisted of inspiratory and expiratory lines connected by a Y-piece. The ventilator used was a Purittan Bennett 7200. Respiratory rates, tidal volumes, fractional inspiratory oxygen and positive end-expiratory pressure were adjusted to maintain arterial carbon dioxide pressure around 10.5 kPa (80 mmHg) and arterial carbon dioxide pressure 5.5 kPa (40 mmHg). Temperature and relative humidity were obtained using the Gibeck Humidity Sensor System [30]. The system consists of an extremely fast reacting humidity sensor and a fast reacting temperature sensor, both integrated in an angled connector (15 M–15 F ISO, Gibeck, Sweden) placed in the breathing circuit between the endotracheal tube and the HME or the T-tube. The method used by the Humidity Sensor System is based on the capacitive sensor principle [30]. A very thin layer of hygroscopic polymer compound is placed in between two conductive layers to make up a condensator. This condensator is placed in an oscillator system, the frequency of which is a function of the condensator capacity. The Humidity Sensor System capacity changes as the hygroscopic polymer withdraws water molecules from air or gives water molecules back to air. The rate of transportation of water molecules to and from the Humidity Sensor System is highly dependent on the sensors "free" surface areas. A largely open sensor, with a very open conductive layer attracts and dissipates water molecules faster than a more covered surface area. This type of sensor is used in the Humidity Sensor system. The specifications of the Humidity Sensor System are the following.

- Relative humidity: range 0–120%, accuracy ±4%; sampling time: 21 times/s
- Temperature: range 0–100°C, rise time <150 ms (90% of °C difference), fall time <150 m (90% of °C difference), accuracy: ±1°C, sampling time: 21 times/s

Table 1 Clinical characteristics of the study patients

Sex: M/F	9/5
Age (years)	39±18
Simplified Acute Physiology Score II	42±+15
Glasgow Coma Score	8±5
Duration of ventilation (days)	28±11
ICU length of stay (days)	36±15
Pulmonary atelectasis[a]	None
Tracheal tube occlusion[a]	None

[a] During the study period

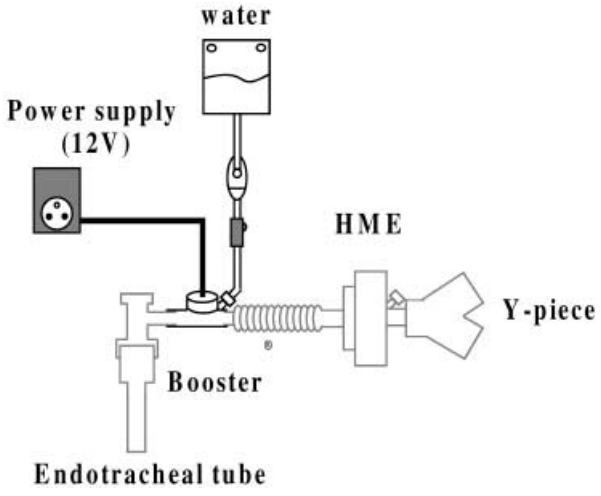

Fig. 1 The Booster™ is positioned between the HME and the endotracheal tube

Table 2 Ventilatory parameters

	Baseline	24 h	48 h	96 h
Tidal volume (ml)	658±101	690±101	664±143	698±132
Respiratory rate (b/min)	15.6±4.4	15.3±3.1	17.8±6.0	22.5±8.2*
Minute volume (l/min)	10.2±3.0	10.6±2.8	11.6±3.5	15.4±5.5*
Peak airway pressure (cmH_2O)	30.0±7.4	33.2±8.9	32.2±9.8	26.3±9.2
Mean airway pressure (cmH_2O)	8.9±2.7	9.8±2.9	10.2±2.7	9.5±3.1

*p<0.0001 vs. baseline, 24, and 48 h

- Computer specifications needed: IBM or compatible computer, MS-DOS version 2 or higher, hard disc, >512 kb RAM, VGA screen, RS 232 connection with nine pins (9600 baudrate, 8 databits, 1 stopbit, no parity), 3.5ö-in. disc station with 1.44-MB format.

Each sensor was calibrated over saturated NaCl and LiCl solutions before use. The calibration procedure (Swedish National Testing and Research Institute, Energiteknik Department, Borås, Sweden) was as follows. The humidity calibration was performed at +20°C and +40°C. Corrections for relative humidity measurements were between ±0.0 and ±2.2% relative humidity at +20°C and between –1.7 and 1.3% relative humidity at +40°C. For each calibration eight sets of measurements were performed. Five levels of temperature were used for the temperature calibration and for each level, eight sets of measurements were performed. Temperature corrections were the following: 19.7°C, ±0.0°C; 25.3°C, –0.07°C; 30.3°C, –0.07°C; 35.2°C, –0.17°C; 40.3°C, –0.26°C.

The humidity and the temperature sensors were connected to a computer interface which transformed the signals into a computer-readable signal of the ASCII type. The signs were transformed into graphs and values by an IBM-compatible computer and a specially designed computer program. The program transformed temperature and relative humidity into absolute humidity (calculation formula):

$$AH = \frac{\left(3.939 + 0.5019 \times T + 0.00004615 \times T^2 + 0.0004188 \times T^3\right) \times RH}{100}$$

where T=temperature (in °C); RH=relative humidity (in percentage). All values were displayed as graphs in which each separate value could be read. The computer program made it possible to compare different graphs on the computer screen as well as calculate average values of all parameters from any part of the graph.

The following factors were measured: temperature, relative humidity and calculated absolute humidity of gases during the inspiration phase. Each parameter was obtained at the beginning (maximal temperature) and end (minimal temperature) of inspiration and averaged over the whole inspiration phase (mean temperature). For each patient values were averaged over three consecutive ventilatory cycles. Measurements were performed after 1 h use of the HME; then the Booster™ was introduced, and after stabilization a new set of measurements was made. Measurements were then made daily at 09:00 a.m. A last set of measurements were made on day 4, 1 h after the BoosterZZZ; was withdrawn.

At the same periods total respiratory heat loss of breathed gases were computed by summing the algebraic values of the convective or sensible heat exchanges (Wcv) and the evaporative, latent, or insensible heat exchange (WEV):

$$Wcv = V \rho Cp (T_{ex} - T_{insp}) \quad WEV = V \lambda (AH_{exp} - AH_{insp})$$

where V=minute ventilation; ρ=volumetric mass of the ventilatory gas (N_2=1.25 g/l, O_2=1.43 g/l); CP=specific heat of the inspired and expired gases (N_2=0.2487 cal/g per 1°C, O_2=0.2198 cal/g per 1°C); T_{ex}=temperature of expired gas; T_{insp}=temperature of inspired gas; λ=latent heat of water evaporation (585 cal/g H_2O); AH_{exp}=absolute humidity of expired gas calculated from T_{ex} with the hypothesis that expired gases were fully saturated in water vapor (relative humidity: 100%); AH_{insp}=absolute humidity of inspired gas [31].

Tracheal tube occlusion was suspected on the basis of an unexplained rise in peak pressure without evidence of HME obstruction and inability to insert a suction catheter through the previously patent tube. Obstruction of the HME was suspected by a sudden increase in airway pressure and confirmed by normalization of airway pressure after HME removal and by visual inspection of the HME. Episodes of pulmonary atelectasis were prospectively recorded from chest radiography. Airway pressure (peak and mean pressures) were prospectively collected every 8 h and averaged.

Bacterial colonization was assessed on days 1 and 4 during the study. At study inclusion (day 1) tracheal secretions were obtained as well as swabs (about 1 cm^2) from the ventilator side of the HME. Similar bacteriological samplings were performed on day 4. On day 4 a swab was obtained from the Gore-Tex membrane of the Booster™. Quantitative surveillance cultures were obtained by plating samples onto cysteine lactose electrolyte deficient agar and incubating them for 48 h. Colonies were quantified and the genus identified.

Patients were evaluated each day during and after the study period for the occurrence of ventilator-associated pneumonia. Diagnosis of ventilator-associated pneumonia was based on all of the following: body temperature higher than 38.2°C or lower than 36.5°C, purulent sputum, white blood all count higher than 0,000/mm^3, new or progressive infiltrates on chest radiography, and significant growth (>10^4/ml) of a pathogen on a bronchoalveolar lavage sample [32].

No tracheal tube occlusion was observed during the study period. Peak airway pressure and mean airway pressure were used as indirect indicators of humidifying activity. As shown in Table 2, no significant change was observed in either ventilatory parameters between days 1 and 4. There was a significant increase in minute ventilation due to an increase in respiratory rate (Table 2). Results are presented as mean ±SD. Normal distribution of data was checked for each tested parameters. The χ^2 test was used to test quantitative data. Intragroup comparisons were performed using analysis of variance. A p value lower than 0.05 was considered significant.

Results

The technical performance of the combination Booster™ and HME is presented in Figs. 2 and 3. After 1 h of ventilation with the Booster™ we observed significant increases in temperature of inspired gas at the end of inspiration and in mean temperature recorded over the whole inspiration phase (Fig. 2). With the use of the Booster™, absolute humidity was significantly increased (Fig. 3) at end of inspiration and when averaged over the inspiration phase. Values of relative humidity were not affected by the use of Booster™and ranged between 88% and 100%.

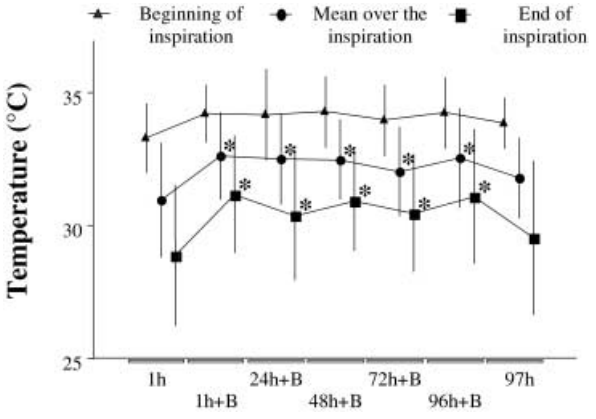

Fig. 2 Variations in temperature of inspired gases when the HME was used for 97 h. *B* Booster™. *p<0.02 vs. 1 h

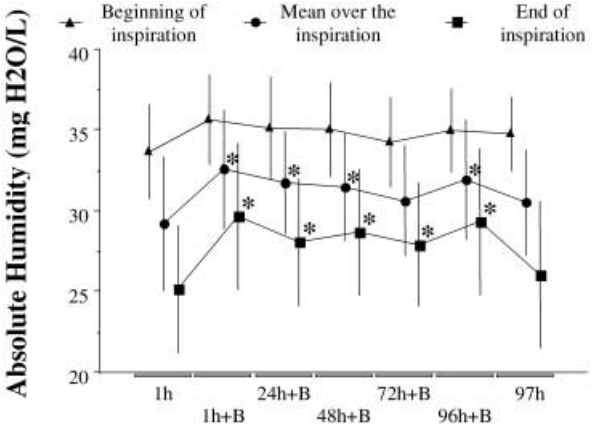

Fig. 3 Variations in absolute humidity of inspired gases when the HME was used for 97 h. *B* Booster™. *p<0.05 vs. 1 h

No significant changes were observed over time in either temperature, relative humidity, or absolute humidity of inspired gases when the combination Booster™plus HME was used for 96 h. It was not until the Booster™ was withdrawn that temperature and humidity returned to baseline values (Figs. 2, 3).

Total respiratory heat loss and convective heat exchange were not affected either by the introduction of the Booster™, the use of HME for 96 h, or the withdrawal of the Booster™ (Fig. 4). Evaporative heat loss was significantly lower when the Booster™ was in use (Fig. 4).

Of the 14 patients 2 had no tracheal colonization at study inclusion (Table 3) and 4 on day 4. The ventilator side of the HME was always sterile on day 4. Four patients (21%) developed pneumonia (Table 3). This corresponds to the incidence of nosocomial pneumonia observed in the unit in 1999 (crude incidence: 27%; 24/1000 days of mechanical ventilation) for the 942 patients admitted during this period.

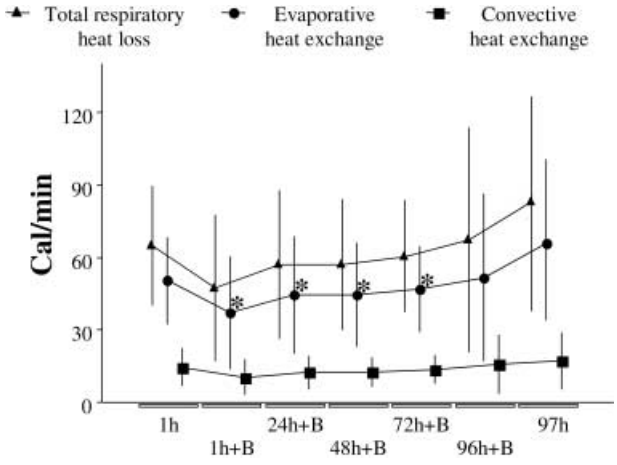

Fig. 4 Variations in total respiratory heat loss of inspired gases when the HME was used for 97 h. *B* Booster™. *: p<0.04 vs. 1 h

Discussion

This study demonstrates that the combination of Booster™ and HME (a) is more effective on inspired gas temperature and absolute humidity than the HME used alone, and (b) can be used continuously for 96 h without alterations in the technical performance of the combination and without contamination of the ventilator side of the HME. It has already been shown that HMEs used alone can preserve efficiently heat and humidity of inspired gas when used for 48 or 96 h rather than 24 h [28, 33]. The present study in a small group of ICU patients indicates that a similar trend is observed when combining an HME the Booster™ system.

The optimal humidity of the inspired gas of ICU patients has not been well evaluated, and the minimal acceptable level is still the matter of controversy. Under normal circumstances it can be assumed that the upper tracheal temperature ranges between 30°C and 33°C, and that relative humidity is 95%, providing a water content of 30 mgH_2O/l [6, 7, 34, 35, 36]. In our opinion, in patients who receive mechanical ventilation 95–100% relative humidity should be adequate for inspired gases with an absolute humidity of 25–30 mgH_2O/l. During this study the technical performance of the combination of Booster™ and HME was not significantly altered when used for 96 h instead of 24 h. No patient had absolute humidity less than 22 mgH_2O/l. Larger studies should be undertaken to determine the clinical relevance of our findings, particularly using an HME with a better performance.

The present study also evaluated the efficiency of the HME after 96 h of use by calculating total, evaporative, and convective respiratory heat loss [33]. There was significantly less evaporative heat loss with the Booster™. More heat is extracted from the respiratory tract during inhalation for the conditioning of inspired air. One con-

Table 3 Bacteriological evaluation (*NG* no growth)

Patient no.	Day 1	Day 4			Pneumonia	
	Tracheal secretions	Booster™	HME (ventilator side)	Tracheal secretions	Onset[a]	Bacteria (>10^4 cfu/ml)
1	*Haemophilus influenzae; Streptococcus pneumoniae*	NG	NG	NG	J2	*Haemophilus influenzae*, *Streptococcus pneumoniae*
2	*Staphylococcus aureus*, *Streptococcus pneumoniae*	*Staphylococcus aureus*, *Haemophilus influenzae*	NG	*Staphylococcus aureus*, group C streptococcus		
3	NG	NG	NG	*Haemophilus influenzae*		
4	*Branhamella catarrhalis*, *Haemophilus influenzae*	Group G streptococcus, *Haemophilus influenzae*	NG	*Haemophilus influenzae*	J5	*Haemophilus influenzae*
5	*Staphylococcus aureus*, group B streptococcus	*Klebsiella pneumoniae*	NG	*Staphylococcus aureus*, *Klebsiella pneumoniae*		*Staphylococcus aureus*, group B streptococcus
6	*Staphylococcus aureus*	NG	NG	*Staphylococcus aureus*		
7	*Staphylococcus aureus*, *Corynebacterium*	NG	NG	NG		
8	NG	*Escherichia coli*	NG	*Escherichia coli*		
9	*Streptococcus vulgaris*, alpha streptococcus	*Klebsiella pneumoniae*	NG	NG		
10	*Staphylococcus aureus*	*Staphylococcus aureus*	NG	*Staphylococcus aureus*		
11	*Candida albicans*, alpha streptococcus	*Staphylococcus epidermidis*	NG	*Enterobacter cloacae*	J4	*Enterobacter cloacae*
12	Alpha streptococcus, group D streptococcus	NG	NG			
13	*Candida albicans*	NG	NG	*Candida tropicalis*		
14	Alpha streptococcus	*Streptococcus viridans*, *Staphylococcus epidermidis*	NG	Group F streptococcus, *Staphylococcus epidermidis*		

[a] From the day when the HME was introduced in the ventilatory circuit

cern with high respiratory heat loss is that it may be responsible for abnormal viscosity of bronchial secretions and subsequent atelectasis or endotracheal tube obstruction. No such complication was observed in the present study. Total respiratory heat loss did not change when the same hydrophobic HME was used for 96 h in combination with the Booster™ system, suggesting that heat extraction from the respiratory phase during inspiration was not altered by the prolonged use of the HME.

The present study did not directly evaluate expiratory resistance of the HMEs. Small changes in this parameter may cause a significant dynamic lung hyperinflation, increased work of breathing, and patient distress and discomfort [37]. In the present study there is some indirect evidence of very little if any change in HME resistance over the 96 h study period since no modifications were observed in peak and mean airway pressures, with identical or increased tidal and minute volumes in the study patients. However, this important problem needs to be evaluated in further studies.

With conventional heated humidifiers (HH) there is substantial condensation of water in the ventilatory circuit. This may cause ventilator malfunction and increase bacteriological contamination. Indeed, 60–80% of venti-

lator tubings are contaminated after 24 h of use with HH [8]. Theoretically HH set to produce a relative humidity of 100% at 37°C in the inspired air causes about 18 mg/h water condensation in the ventilatory circuit [8]. A common way to overcome this problem is to set the HH at lower temperatures (30–33°C) at the Y piece. This also reduces absolute humidity.

Using the same HME for a prolonged period of time may the cause of a deterioration in the bacterial filtration properties of the filter and subsequent ventilatory circuit colonization and ventilator associated pneumonia [28, 29, 38, 39]. We therefore also studied the properties of bacterial filtration of the combination Booster™ and HME. At the beginning of the study 12 patients had a positive culture, at a significant bacteriological count, of their tracheal secretions. After 96 h of mechanical ventilation with the same HME only 10 patients still had bacterial colonization of their bronchial tree. All cultures of the ventilator sides of the HME were sterile. Thus despite 96 h of use of the same HME bacterial colonization was not increased in the study patients, and the ventilator side of the HME did not become colonized by the patients' bronchial flora. These results are comparable to those of a previous study by Djedaini et al. [39]. The Booster™ was designed to reduce the problem of water condensation. In the present study the Booster™ was very well tolerated, and condensation in the tubing was not present. There was no need to drain circuits or to change machine filter. In addition, with the Booster™ the technical performance of the HME used was significantly improved in terms of heat and water preservation of ventilatory gas. Our results agree with those of two studies that evaluated similar devices [24, 26]. Such devices may have some potential drawbacks. They cannot be used in patients with copious secretions. The Booster™ adds 9 ml dead space, and this can have a negative impact on ventilation in spontaneously breathing patients.

In conclusion, the present study strongly suggests that a prolonged use (96 instead of 24 h) does not affect the technical performance of a combination of Booster™ plus hydrophobic HME in terms of conditioning of inspiratory gases. The bacteriological properties of the HME were not affected by its prolonged use, and the ventilator sides of the filters remained sterile at the end of the study period despite a significant bacterial colonization of the patients' bronchial secretions. Other large clinical trials should be undertaken to confirm the safety of extending the duration of use of the combination Booster™ and HME.

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