Background. Adequate humidification of inspired gas with active or passive humidifiers is a standard of care for tracheotomized patients. In this study, a comparison is made between the tracheal climate after tracheobronchial humidification either with molecular water (via a vaporizing humidifier) or particulate water (via spray) in spontaneously breathing tracheotomized patients.

Methods. We performed a randomized, 2-way crossover study on 10 tracheotomized patients. Tracheal humidity and temperature were measured prior to and after use of a vaporizing humidifier and aerosol spray, respectively.

Results. After use of both the vaporizing humidifier and the aerosol spray, the end-inspiratory total water content and water gradient in the upper trachea increased significantly, compared with baseline values before application. After end of use of the vaporizing humidifier, the total water content and the water gradient decreased significantly faster than after application of the aerosol spray.

Conclusions. Delivery of both molecular and particulate water significantly increases the tracheal climate and conditioning in the tracheal airways. Because the tracheal humidity remained on a higher level after aerosol spray, we speculate that particulate water may be efficient on tracheal humidification for longer. However, the positive effect on tracheal humidity after prolonged application of the aerosol spray remains to be proven.

Keywords: tracheotomy; humidification; respiratory pathophysiology; air conditioning

In patients with a tracheal opening, the normal heat and moisture exchanging process of inhaled air in the upper airway system is bypassed. A continuous loss of heat and moisture occurs and can lead to serious damage of the tracheobronchial mucosa. It has therefore long been considered desirable to provide warm and humid inspired air to patients with an artificial airway (tracheostomy tube or endotracheal tube), and various methods to achieve this have been proposed. Also, complications after tracheotomy, such as tube occlusion by crusts and formation of crust within the tracheal airways, may be prevented by the use of different vaporizers, nebulizers, or passive humidifiers.

Whereas numerous studies on heat and moisture exchange and thermoregulation in the lower airways during anesthesia have been performed, only scant data on clinical parameters of humidification in tracheotomized patients are currently available.

When the upper respiratory tract is bypassed, the inspiratory air being delivered to the lower respiratory tract has to be as close to physiologic levels as possible. However, the optimal form of
delivered water (ie, aerosol or particulate form, vapor or molecular form) of inspired gas administered to tracheotomized patients has not been well established and is still a matter of controversy.17,19,20

Tracheotomees and laryngectomees often suffer from dry tracheal mucosa and tracheal crusting when staying or working in a dry environment or in air-conditioned rooms. An external supply of humidity is frequently not available in these situations, but an artificial way of adding moisture to the tracheal airways might reduce clinical symptoms of crusting of the tracheobronchial airways and increase breathing comfort. A portable and commercially available tracheal nebulizer for this purpose is currently not available.

This study was therefore done (1) to examine if a portable tracheal nebulizer is appropriate to supply humidity in particulate form to the lower airways and (2) to compare the influence of two forms of water delivery to the lower airways in patients after tracheotomy. The increase in tracheal temperature and humidity after humidification was the primary outcome variable. Secondary outcome variables included a symptom score and an endoscopic score of the tracheobronchial mucosa.

PATIENTS AND METHODS

Subjects. In this study, 10 patients after either tracheotomy because of completely obstructing malignancies of the larynx (n = 2) or total laryngectomy (n = 8) were studied (Table 1). The inclusion criteria were existence of a permanent or temporary tracheal opening for at least 6 weeks and age >18 years. The study was approved by the Ethics Committee of the University of Ulm, Germany, and informed consent was obtained from all patients.

Experimental Protocol. A randomized, 2-way crossover study design comparing the effects of molecular and particulate water on the tracheal climate was chosen. First, the patients were brought to the laboratory. Following an equilibration period at an ambient temperature of 22.4°C (range, 20.3–24.1°C) and a relative humidity of 41% (range, 33–48%), the tracheostomy tube was removed and each patient was instructed to breathe calmly through the tracheal opening for 15 minutes. The study patients received either delivery of molecular water in a vapor stream (32°C and approximately 100% relative humidity; 30 μL H₂O/L₉; inhalation device Davos, Heimomed, Kerpen, Germany; Figure 1) for 20 minutes or delivery of particulate water in an aerosol stream via pump spray (26°C and 90% relative humidity; 300 μL H₂O/L₉; spray flacon, Aesculap, Tuttlingen, Germany; Figure 2) on day 1. On day 2, the other method of airway humidification was performed and measurement of tracheal conditioning was repeated in the same manner. A time interval of 24 hours between the individual exposures was kept to minimize possible carry over effects.

Tracheal Conditioning. Evaluation of tracheal conditioning was performed similarly to measurements of nasal and tracheal conditioning and has been described in detail previously.21,22 In brief, a thermocouple and a suction probe that was connected to a relative humidity sensor outside the body were placed into the upper part of the trachea. The thermocouple measured the temperature within the tracheal lumen close to the tip of the suction probe. Relative humidity was detected at the end of the suction probe in the air that was sampled in the trachea. To minimize errors due to any slight condensation within the suction system.

Table 1. Characteristics for 10 patients.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>65 (46–74)</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>10/0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>90 (63–103)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178 (168–188)</td>
</tr>
<tr>
<td>Time after tracheotomy (months)</td>
<td>13 (3–42)</td>
</tr>
</tbody>
</table>

FIGURE 1. The tracheotomized patient receives delivery of molecular water in a vapor stream (inhalation device Davos) for 20 minutes.
and the sensor box, a heat map was wrapped around the sensor box and warming of the suction system was achieved. The suction tube outside the trachea was also warmed, whereas the tip of the suction system within the trachea was without active heating. Temperature and relative humidity in the tracheal air-stream were obtained during respiration at quiet breathing for 2 minutes. Signals of this device were compared to temperature and relative humidity signals that were simultaneously recorded directly in front of the patient's tracheal opening. Data on relative humidity and temperature obtained simultaneously in front of the tracheal opening and in the tracheal lumen were used for calculation of the total water content of the air in the trachea and the water gradient across the upper tracheal airway, analogous to calculation processes of other working groups.23

The water gradient was defined as the difference of the total water gradient measured in the tracheal airway using sensor 2 minus the total water gradient detected in front of the tracheal opening using sensor 1. The phase of inspiration and expiration was continuously detected using a stressesensitive belt around the thorax of each patient.

Before exposure, baseline values of tracheal conditioning were obtained. At the end of exposure, tracheal conditioning measurement was repeated after 0, 2, 4, and 6 minutes.

Symptom Score. Tracheobronchial symptom scores were assessed before and after exposure to both molecular and particulate water. The patients were asked to answer whether the symptom evaluated was present or not before and after first 10 minutes after water delivery. Symptoms included coughing, tracheobronchial irritation, hypersecretion, dryness, and need for suctioning.

Endoscopic Score. Rigid or flexible tracheobronchoscopy was performed before and after water delivery whether the clinical signs evaluated were present or not before and after the first 10 minutes after water delivery. Clinical signs of irritation of the tracheobronchial mucosa were mucosal swelling, edema, redness, and amount of secretions.

Statistical Analysis. Absolute values of tracheal temperature, total water content, and water gradient at various detection times are calculated and shown. Results are presented as a median ± 95% confidence interval. Intergroup and intra-group comparisons were performed using non-parametric tests: Wilcoxon and Friedman’s tests where appropriate.24 Significant differences were determined using the 2-sided Fisher’s exact test for categorical data. Significance was accepted at the 95% confidence level (p ≤ .05).

RESULTS

Baseline values of tracheal temperature, total water content, and water gradient before inhalation and spray application did not differ significantly (Table 2). After both inhalation and spray

<table>
<thead>
<tr>
<th></th>
<th>Baseline = pre-INH</th>
<th>Baseline = pre-SPR</th>
<th>INH0 = post-INH</th>
<th>SPR0 = post-SPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP (°C)</td>
<td>27.1 (26.6–29.4)</td>
<td>27.3 (26.4–29.3)*</td>
<td>27.9 (25.1–29.3)§</td>
<td>26.8 (25.2–29.3)†</td>
</tr>
<tr>
<td>TWC (mg/L)</td>
<td>13.5 (11.3–18.8)</td>
<td>13.3 (10.3–18.6)*</td>
<td>16.6 (11.4–21.2)§</td>
<td>15.7 (13.3–20.7)§</td>
</tr>
<tr>
<td>WG (mg/L)</td>
<td>5.7 (3.5–9.7)</td>
<td>5.5 (2.9–9.3)*</td>
<td>8.2 (4.1–12.4)§</td>
<td>7.9 (4.7–11.9)§</td>
</tr>
</tbody>
</table>

Abbreviations: pre-INH, before inhalation; pre-SPR, before application of spray; post-INH, after inhalation; post-SPR, after application of spray; TEMP, end-inspiratory temperature in the trachea; TWC, end-inspiratory total water content in the trachea; WG, end-inspiratory water gradient across the upper tracheal airway.

*p > .05, baseline (pre-) INH vs. baseline (pre-) SPR.
†p > .05, baseline vs. post-INH; baseline vs. post-SPR.
‡p > .05, post-INH vs. post-SPR.
§p < .05, baseline vs. post-INH; baseline vs. post-SPR.
application, the total water content and water gradient in the upper trachea increased significantly compared with baseline values before humidification. The temperature did not change significantly after inhalation and spray application. Values of temperature, total water content, and water gradient immediately after inhalation did not differ significantly from those immediately after spray application (Table 2).

After both inhalation and spray application, the end-inspiratory tracheal temperature did not change significantly at each measurement time (see Figure 3). The temperature values after inhalation did not differ from those after spray application.

Immediately after end of both inhalation and spray application, the total water content was significantly higher than the baseline values before humidification. Six minutes after end of inhalation, the total water content decreased to values similar to the baseline total water content before inhalation, whereas the total water content after spray application only slightly decreased and did not reach the baseline total water content after 6 minutes (see Figure 4).

The same was observed for the water gradient after inhalation and spray application. Six minutes after end of spray application, the water gradient did not reach the baseline water gradient, whereas after inhalation the water gradient decreased to the baseline water gradient before humidification (see Figure 5).

No significant changes in the tracheobronchial symptoms and no significant differences in endoscopic scoring before and after both types of water delivery were observed (data not shown).

DISCUSSION

Respiratory problems, such as excessive sputum production, coughing, crusting, and recurrent tracheobronchitis, after tracheotomy are frequently observed. Supply of humidity may sometimes be beneficial for tracheotomized patients during a day (eg, while staying in a dry environment or in air-conditioned rooms).

Therefore, the aim of this study was to evaluate 2 forms of water delivery to the lower airways in patients with tracheal opening. One type of humidity supply was “optimal” humidity in molecu-
lar form at normal conditions of air entering the tracheobronchial region. The other type of humidification was particulate form between ambient and tracheobronchial condition.

After use of both a vaporizing humidifier (molecular form) and an aerosol spray (particulate form), the end-inspiratory total water content and water gradient in the upper trachea increased significantly compared with baseline values before application of humidity. After end of use of the vaporizing humidifier, the total water content and the water gradient decreased significantly faster than after application of the aerosol spray.

In the present study, a 20-minute period of use of the vaporizing humidifier was investigated. This short period plus the time of adaptation prior to the measurements was chosen because humidification of the lower airways in front of the airways reliably functions without clinically relevant delay time. The second form of humidity delivery via aerosol spray was chosen for 2 reasons. First, a reduced amount of heat and total amount of humidity via aerosol spray was delivered, allowing to compare a reduced humidity delivery with the optimal humidity entering the lower airways in normal airways. Second, humidity delivery via spray could offer a new and easy form of humidification for tracheostomees or laryngectomees independent of an apparatus such as a vaporizer, which is not always available and applicable during a day. Based on the spray flacon used in this study, flacons with short tracheal catheters similar to intratracheal catheters applied for intracheal drug delivery are imaginable for post-tracheotomy care.

The tracheal temperature and humidity values before use of the vaporizing humidifier and aerosol spray measured in our study are similar to the values from previous studies. We, therefore, conclude that the experimental setup for tracheal temperature and humidity detection used in our study proved to be suitable to be used in a clinical trial in tracheotomized patients.

In the present study, increase in airway humidity after humidification was not significantly different between the 2 forms of humidity delivery after short delivery time. However, relevant differences of impact of water in molecular or particulate form on the respiratory mucosa are known and may be of clinical importance in the application in tracheotomized patients when humidity is delivered for a longer time. Aerosols (water volume, 10–500 mg/L) that deposit in the tracheobronchial airways provide water that can be evaporated to condition subsequent breaths. However, little heat energy, depending on its temperature, is transferred to the mucosa. Water that is not evaporated through the breathing circuit will have to be absorbed by the respiratory epithelium, thus consuming energy the epithelium has to provide. In case the absorption rate is lower than the deposition rate, water can accumulate on the respiratory epithelium and obstruction of small peripheral segments of the bronchial airways might occur. In contrast, the water volume in a vapor stream is 20 to 50 mg/L, with only minimal risk of overhumidification of smaller airways. When the temperature of the vapor is considerably above the body core temperature, however, an increased risk of thermal injury of the respiratory mucosa exists.

Since the water content of the respired air is increased after delivery of both molecular and particulate water, a higher amount of water can be transferred to the tracheal mucosa, with possible impact on mucosal functions (eg, mucociliary clearance). Because the time of delivery of both particulate and molecular water was short, no negative effect on the mucociliary function and no disturbance of the ion-associated and osmotically driven water transport of the tracheobronchial mucosa was assumed. Williams et al suggested that the mucociliary transport is the most sensitive indicator of appropriate humidity and therefore is optimized when inspired air reaches 37°C and 100% relative humidity. In the present study, no clinical signs of tracheobronchial irritation or subjective complaints after both forms of humidity supply were found. We, therefore, suggest that there is some evidence that an increase in humidity after short-time delivery of both molecular and particulate water is beneficial for the integrity of the tracheal mucosa and mucosal function because the optimum temperature and humidity of the trachea may be considered to be that of the lower tracheobronchial part of the airways.

In conclusion, the results of the present study support the fact that humidification via both vaporizing humidifier and aerosol spray is effective in tracheotomized patients even after a short period of use. Because the tracheal humidity remained on a higher level after aerosol spray, we speculate that particulate water may be efficient on tracheal humidification for longer. However, the feasible impact of delivery of both molecular and particulate water on the energy balance of the tracheal mucosa after prolonged application
remains to be proven and will be investigated by our working group with the equipment presented in this study.

REFERENCES