Effect of High-Frequency Oral Airway and Chest Wall Oscillation and Conventional Chest Physical Therapy on Expectoration in Patients With Stable Cystic Fibrosis*

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Study objective: To compare the effect of high-frequency oral airway oscillation, high-frequency chest wall oscillation, and conventional chest physical therapy (CPT) on weight of expectorated sputum, pulmonary function, and oxygen saturation in outpatients with stable cystic fibrosis (CF).

Design: Prospective randomized trial.

Setting: Pediatric pulmonary division of a tertiary care center.

Patients: Fourteen outpatients with stable CF recruited from the CF center.

Interventions: Two modes of oral airway oscillation (1: frequency 8 Hz; inspiratory to expiratory [I:E] ratio 9:1; 2: frequency 14 Hz; I:E ratio 8:1), two modes of chest wall oscillation (1: frequency 3 Hz; I:E ratio 4:1; 2: frequency 16 Hz; I:E ratio 1:1, alternating with frequency 1.5 Hz, I:E ratio 6:1), and CPT (clapping, vibration, postural drainage, and encouraged coughing) were applied during the first 20 min of 4 consecutive hours.

Measurements and results: Sputum was collected on an hourly basis for a total of 6 consecutive hours. During the first and the last hour, patients collected sputum without having any treatment and underwent pulmonary function tests (PFTs). Oxygen saturation was measured at 30-min intervals during hours 1 to 6. For the first 20 min of the second to the fifth hour, patients received one of the treatments. To assess the effect of the intervention, the weight of expectorated sputum during hours 2 to 6 was averaged and expressed as percentage of the weight expectorated during the first hour (baseline). For the five treatment modalities, mean sputum dry and wet weights ranged between 122% and 185% of baseline. There was no statistically significant difference among the treatment modalities. As measured by sputum wet weight, all oscillatory devices tended to be less effective than CPT (p=0.15). As measured by dry weight, oral airway oscillation at 8 Hz with an I:E ratio of 9:1 and CPT tended to be more effective than the other treatment modalities (p=0.57). None of the treatment modalities had an effect on PFTs and oxygen saturation and all were well tolerated.

Conclusion: In outpatients with stable CF, high-frequency oscillation applied via the airway opening or via the chest wall and CPT have comparable augmenting effects on expectorated sputum weight without changing PFTs or oxygen saturation. In contrast to CPT, high-frequency oral airway and chest wall oscillations are self-administered, thereby containing health-care expenses.

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Key words: chest physical therapy; cystic fibrosis; high-frequency oscillation; mucous clearance

Abbreviations: CF=cystic fibrosis; CPT=chest physical therapy; f=frequency; FmaxE=peak expiratory flow; FmaxI=peak inspiratory flow; FRC=functional residual capacity; hayOp=Hayek Oscillator used at “optimum” settings; haySe=Hayek Oscillator used in “secretion clearance mode”; I:E=inspiratory to expiratory; MCT1=treatment with the Sensormedics MCT 1 oral airway oscillator; OCI=oscillatory clearance index; O2 sat=oxygen saturation; PFT=pulmonary function test; rhDNase=recombinant human DNase; SenB=treatment with the Sensormedics 3100B ventilator; TE=duration of expiratory airway wall displacement; Ti=duration of inspiratory radial airway wall displacement

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In subjects with normal lungs, tracheobronchial secretions are cleared by mucociliary transport. This airway clearance system fails in patients with chronic bronchitis, bronchiectasis, and cystic fibrosis (CF). Because accumulation of mucus in the lower airways may contribute to chronic infections that lead to progressive deterioration in lung function, clearing of airway secretions by chest physiotherapy (CPT) forms an integral part of the treatment of...
patients with CF. Previous studies have shown that regular CPT is able to enhance expectoration\textsuperscript{2-5} and to slow deterioration of lung function.\textsuperscript{9,10}

Recently, new methods have been developed to help clear excessive airway mucus. Among them are high-frequency oral airway oscillation and high-frequency chest wall oscillation.\textsuperscript{11-16} Previous studies have suggested that treatment with chest wall oscillation is as effective as conventional CPT in patients with CF.\textsuperscript{17-20}

According to earlier experiments, prerequisites for optimal transport of mucus by air-liquid interaction in a cephalad direction include airflow with an expiratory bias,\textsuperscript{11,14,16,21} which needs to be in the range of 1 to 3 L/s,\textsuperscript{16,22} and for oral airway oscillation, an oscillation frequency between 8 and 15 Hz.\textsuperscript{11,15,21} Based on these findings and on the results of preliminary studies with both an oral and a chest wall oscillator, we determined the settings for several devices that we considered optimal for mucus transport. Together with an airway oscillator at its manufacturer-provided operational mode and a manufacturer-provided secretion clearance program for the chest wall oscillator, we used our theoretically optimal treatment modes for the airway and chest wall oscillators. The aim of the study was to test if oscillations applied to the oral airway opening and to the chest wall are as effective as CPT in increasing the weight of expectorated sputum in patients with stable CF, and if treatment with the oscillatory devices is as well tolerated as CPT.

**Materials and Methods**

All patients were recruited from the CF Center at the University of Miami. A diagnosis of CF was confirmed by sweat test, and all had increased sputum production. The protocol was approved by the ethics committee, and the patients or their guardians gave written informed consent prior to being enrolled in the study.

**Selection Criteria**

**Inclusion Criteria:** Inclusion criteria were diagnosis of CF, stable condition for at least 3 weeks prior to enrollment, and age 12 years or older.

**Exclusion Criteria:** Exclusion criteria were major hemoptysis (>240 mL) within the last month, pneumothorax or chest tube placement within the last 6 months, and pregnancy. Treatment with mucoactive drugs, including recombinant human DNAse (rhDNAse), was not an exclusion criterion.

**Exit Criteria:** Exit criteria were on request by the patient or his or her guardian, on completion of the study, intolerance of the treatment, or developing one of the exclusion criteria.

**Mechanical Devices**

Three advanced mechanical oscillatory devices were used: Sensormedics 3100B Oscillatory Ventilator, the MCTI oscillator (both from Sensormedics Corporation; Yorba Linda, Calif.), and the Hayek Oscillator (Breasy Medical; Stanford, Conn.).

The 3100B oscillatory ventilator is a commercially available electronically controlled oral ventilator, using a servo-controlled piston and a compressed gas supply. It is active in both inspiratory and expiratory phases, and is capable of a wide range of adjustment, particularly for inspiratory to expiratory (I:E) ratio and frequency.

The MCTI is an oral airway oscillator using an electronically servo-controlled piston. This device was designed to aid mucus clearance. It delivers oscillations via a mouthpiece at a fixed I:E ratio of 8:1 and a variable rate and drive power.

The Hayek Oscillator is a chest cuirass ventilator designed to deliver high-frequency oscillations to the chest wall. A dual pump system generates positive and negative pressures that are conducted to the cuirass via flexible tubing. By electronic control of the pump, a range of I:E ratios, frequencies, cuirass pressures, and effective functional residual capacities (FRCs) can be set. Additionally, a programmed “secretion clearance mode” is provided. This consists of alternating applications of oscillations (16 Hz, I:E ratio 1:1, for 2 min, and 1.5 Hz, I:E ratio 6:1, pressure span \(-15/10 \text{ mm Hg for 3 min.}\)

**The Oscillatory Clearance Index**

Based on theoretical considerations and on results of previous experiments, we derived an empiric oscillatory clearance index (OCI) that includes the frequency of the oscillations (f), peak inspiratory and expiratory flows (FmaxI and FmaxE), and the duration of inspiratory and expiratory airway wall displacement (T1 and T2):

\[
\text{OCI} = \left[ \frac{f \times (F_{\text{maxI}}/T_1)}{(F_{\text{maxE}}/T_2)} \right] - f
\]

Based on this theoretical index, preliminary experiments were conducted to find out optimal settings for the oral airway and the chest wall oscillator to transport mucus in a cephalad direction.

**Determining the Optimal OCI With the Oral Airway Oscillator**

Using the Sensormedics Oscillatory Ventilator 3100B, we calculated the OCI for different settings. The oral airway oscillations were applied to the airway opening via a mouthpiece. Airflow was measured with a pneumotachograph (Rudolph 4813; Kansas City, Mo) at the airway opening, and change in neck circumference as a measure of radial airway wall displacement was measured with a respiratory inductive plethysmograph, modified to remove the low-pass filter (Respitrak; Non-Invasive Monitoring Systems; Miami Beach, Fla). To prevent oscillations of the cheeks, a clamping device applied constant pressure to the cheeks. An occlusive noseclip was also fitted. Measurements were taken with subjects comfortably seated while breath-holding at FRC position for 5 to 10 s. The data were recorded with a model 78D poligraph (Grass Instruments; Quincy, Mass) and manually analyzed.

Twelve normal adults and six adult patients with COPD, whose conditions were diagnosed according to the American Thoracic Society guidelines,\textsuperscript{23} were examined. In normal subjects, the highest OCI of 61 was attained with a frequency of 12 Hz and an I:E ratio of 9:1. In COPD patients, the highest OCI reached was 28 with a frequency of 8 Hz and an I:E ratio of 9:1.\textsuperscript{24}

**Determining the Optimal OCI by High-frequency Chest Wall Compression**

Chest wall compressions were applied with the Hayek Oscillator. The airflow at the airway opening was measured with the
pneumotachograph, attached to a mouthpiece, and radial airway wall displacement was measured with respiratory inductive plethysmography by attaching a band around the midchest. A noseclip and the cheek stabilization device were fitted. Measurements were taken with subjects comfortably seated while breath-hold¬ ing at FRC position for 5 to 10 s. The data were directly fed into a personal computer via an analog to digital converter board and analyzed using custom-made software.

The OCl was determined for multiple machine settings in 10 normal adults and 5 patients with COPD. To reach airflows in the range of 2 L/s, we had to set the chamber pressures of the cuirass at −10 and +10 mm Hg during inspiration and expiration, respectively. Due to limitations of the hardware, at frequencies above 4 Hz, I:E ratios higher than 4:1 could not be attained. The highest OCl reached was 12 in normal subjects and 7 in COPD patients with an I:E ratio of 4:1, a frequency of 3 Hz, and cuirass pressures of ±10 mm Hg.

Based on these results and assuming that all our patients had chronic airflow obstruction, we chose as study settings the ones that resulted in the highest device-specific OCl in COPD patients.

Randomization

The study contained five treatment arms. One treatment mode was applied per study day (in the afternoon), with a minimal interval of 2 days between study days. Randomization was performed with a computer-generated randomization table.

Treatment Arms

1. “SenB”: High-frequency oral airway oscillations with the Sensormedics Oscillatory Ventilator 3100B were applied at an I:E ratio of 9:1, a frequency of 8 Hz, and a positive end-expiratory pressure of up to 4 mm Hg if tolerated. The power (oscillatory tidal volume) was increased to the extent that vibrations could be felt through the chest wall. The cheek compression device and a noseclip were used during treatments. In 5-min intervals, the patients were positioned supine, then left and right lateral decubitus, and again supine (total of 20 min).

2. “MCT1”: Treatment with the Sensormedics MCT1 oral airway oscillator was given at an I:E ratio of 8:1 and a frequency of 14 Hz. The positive end-expiratory pressure was increased with an expiratory valve to an extent that patients felt some expiratory resistance but were still able to breathe comfortably. The power setting, cheek support, noseclip, and body positioning were similar to SenB.

3. “HayOp”: High-frequency chest wall compression with the Hayek Oscillator was carried out at an I:E ratio of 4:1 and a frequency of 3 Hz. The cuirass pressure was set to −10 mm Hg during inspiration and +10 mm Hg during expiration. Due to the bulky cuirass, comfortable lateral positions were not possible. Therefore, the patients remained in supine position during treatments. The patients’ cheeks were not supported and no noseclip was fitted.

4. “HaySe”: High-frequency chest wall compression with the Hayek Oscillator was performed using the program settings provided by the manufacturer for secretion clearance. It consisted of vibrations at 16 Hz during 2 min (16 Hz, I:E ratio 1:1) alternating with chest wall oscillations during 3 min (1.5 Hz, I:E ratio 6:1, pressure span of −13 to 13 mm Hg) during inspiration and expiration, respectively. Patients remained in a supine position while receiving treatments; the cheeks were not supported, and no noseclip was fitted.

5. “CPT”: Conventional CPT consisted of postural drainage (head-down tilt 30°), clapping, external vibration with a standard electrical chest wall percussor (frequency 40 Hz), and encouraged coughing.

Protocol

All patients were allowed to continue treatment with their medications, except for inhaled β2-adrenergic agonists, which were not permitted 4 h prior to and during the treatments. During the time of enrollment, patients received only the study treatments, unless the interval between treatments was >5 days.

On study days, the patients arrived at the laboratory around noon. Baseline pulmonary function tests (PFTs) were performed with measurement of FVC and FEV1. Oxygen saturation (O2 sat) was measured with a pulse oximeter (Minolta Pulse Ox-7; Catalyst Research, Div of Mine Safety Appliances Co; Pittsburgh, Pa) every 30 min starting on arrival and ending 1 h after the last treatment. Patients coughed and expectorated sputum ad libi¬ tum, except for CPT, where they were encouraged to cough in regular intervals. They were instructed to swallow all saliva before coughing. The sputum was collected on an hourly basis in preweighed and labeled sputum cups.

After 1 h of sputum collection (baseline sputum weight), patients were randomized to one of the five treatment protocols. For 4 consecutive hours, the patients underwent treatment for 20 min followed by 40 min of sputum collection. Thereafter, sputum was collected for 1 more hour.

Data Analysis

The wet and dry weights for all sputum collections were measured. Sputa were dried by heating in a commercial micro¬ wave oven until all water had evaporated. Some sputum samples were considerably contaminated with saliva and the sputum had to be manually separated with the help of a pair of tweeze¬ ers before weighing.

To assess the effect of the treatments on the weight of expectorated sputum, the sputum weights from hours 2 to 6 were averaged and expressed as percentage of the baseline sputum weight.

To assess any change in O2 sat, the mean O2 sat during and after treatments was expressed as percentage change from baseline.

To assess the effects of the treatments on PFTs, the percentage change in FVC and FEV1 after each treatment and between study entry and exit was calculated.

Statistics

Because the data were not normally distributed and the treatment effects had different variances, data were analyzed using nonparametric tests. Friedman analysis of variance was used to test for differences in mean baseline sputum weights, for differences in treatment effects among the various treatments, for differences in treatment-related change in PFT results, and treatment-related change in O2 sat. The Wilcoxon Matched Pairs Test was used to test for changes in PFT results before and after treatments, between study entry and exit, and for change in O2 sat between study entry and exit. The Mann-Whitney U Test was used to test for differences in treatment effect between patients who were and were not receiving rhDNAse. Calculations were made using a personal computer and software (STATISTICA; StatSoft Inc; Tulsa, Okla). Significance was accepted when p<0.05. Sample size estimations for a type I error of 5% and a type II error of 20% were made using tables provided by Kastenbaum et al.25 Data in tables, text, figures, and legends are presented as mean±SEM unless otherwise indicated.
RESULTS

Study Population

Fifteen patients were enrolled in the study. Due to transportation problems, one patient requested to exit after the first treatment. Fourteen patients completed the study and were available for evaluation. The characteristics of the study population are shown in Table 1. One patient had normal PFT results, four were mildly obstructed, five were moderately obstructed, and four were severely obstructed. Except for three patients, all used bronchodilators (either inhaled β₂-agonists and/or ipratropium bromide). Eleven regularly inhaled rhDNase.

Weight of Expectorated Sputum

Wet Sputum: The mean baseline sputum weights for the various treatments ranged between 4.3±1.2 g and 7.6±3.1 g. There was no significant difference among them.

The increase in the weight of expectorated sputum (average of hours 2 to 6 as percent of baseline) ranged between 123±16% and 168±24% for the five treatment modalities (Fig 1). No treatment proved to be significantly more effective than the others.

There was no difference between patients who inhaled rhDNase (n=11) and those who did not (n=3) (Table 2).

Dry Sputum: The mean baseline sputum weights for the treatments ranged between 0.14±0.04 g and 0.41±0.08 g. There was no significant difference among them.

The increase in the weight of expectorated sputum ranged between 122±26% and 185±23% (Fig 1). No treatment proved to be significantly more effective than the others.

Patients using and patients not using rhDNase had similar increases in weight of expectorated sputum for any treatment modality (Table 3).

PFTs and O₂ Sat

FVC, FEV₁, and O₂ sat showed no significant change after any of the five treatment modalities (Figs 2 and 3) and between study entry and exit.

Complications

Three patients developed streaky hemoptysis during the treatments (one patient during treatment with SenB, one during HayOp, and one during MCT1) that resolved spontaneously without interrupting treatments.

Patient Tolerance and Comments

Seven patients stated that the oral airway oscillators were uncomfortable. Two patients felt that the treatments with the chest wall oscillators were most comfortable, two preferred all the mechanical devices over CPT, while two patients preferred CPT.

DISCUSSION

The results of our study show that high-frequency oral airway oscillation, high-frequency chest wall oscillation, and conventional CPT have comparable augmenting effects on the weight of expectorated sputum in patients with stable CF. By comparing weight of expectorated sputum during treatment with a preceding baseline period, day-to-day variation in sputum expectoration was taken into account.

The reason to analyze wet and dry sputum weights was that some patients had difficulties delivering lower airway secretions without contamination with saliva. Although we were able to manually separate lower airway secretions from saliva with a pair of tweezers, contamination with saliva was not eliminated entirely. Due to its high water content, saliva adds considerable weight to the samples. By evaporating the water, an important part of this confounding factor is eliminated. The fact that for almost all treatments the relative increase in weight of expectorated sputum was greater for the dried samples is in keeping with our assumption. Dry weights might therefore better represent lower airway secretions than wet weights. However, this question cannot be answered by this study and further experiments are needed to clarify the issue.

Table 1—Patient Characteristics*

<table>
<thead>
<tr>
<th>Patient No./Age, yr/sex (F/M)</th>
<th>BMI</th>
<th>FVC, % Pred</th>
<th>FEV₁, % Pred</th>
<th>Bsl O₂ sat, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/25/F</td>
<td>19.5</td>
<td>42</td>
<td>29</td>
<td>96</td>
</tr>
<tr>
<td>2/34/M</td>
<td>27</td>
<td>100</td>
<td>83</td>
<td>97</td>
</tr>
<tr>
<td>3/20/F</td>
<td>17.6</td>
<td>63</td>
<td>47</td>
<td>97</td>
</tr>
<tr>
<td>4/14/F</td>
<td>19.6</td>
<td>62</td>
<td>37</td>
<td>96</td>
</tr>
<tr>
<td>5/17/F</td>
<td>19</td>
<td>85</td>
<td>70</td>
<td>96</td>
</tr>
<tr>
<td>6/17/F</td>
<td>20.5</td>
<td>90</td>
<td>74</td>
<td>97</td>
</tr>
<tr>
<td>7/16/M</td>
<td>22</td>
<td>85</td>
<td>67</td>
<td>95</td>
</tr>
<tr>
<td>8/16/M</td>
<td>23.4</td>
<td>96</td>
<td>82</td>
<td>96</td>
</tr>
<tr>
<td>9/18/M</td>
<td>25.1</td>
<td>82</td>
<td>72</td>
<td>95</td>
</tr>
<tr>
<td>10/29/M</td>
<td>17.4</td>
<td>56</td>
<td>35</td>
<td>95</td>
</tr>
<tr>
<td>11/14/M</td>
<td>21.7</td>
<td>59</td>
<td>54</td>
<td>96</td>
</tr>
<tr>
<td>12/15/M</td>
<td>16.1</td>
<td>64</td>
<td>48</td>
<td>97</td>
</tr>
<tr>
<td>13/27/M</td>
<td>16.7</td>
<td>50</td>
<td>33</td>
<td>95</td>
</tr>
<tr>
<td>14/12/F</td>
<td>18.9</td>
<td>101</td>
<td>80</td>
<td>96</td>
</tr>
</tbody>
</table>

Mean±SD 20.3±3.2 73.9±19.5 55.5±20.6 96±0.8 19.4±6.3 (6F/8M)

*F/M=Female/male; BMI=body mass index; FVC % pred=percent of predicted FVC; FEV₁ % pred=percent of predicted FEV₁; Bsl=baseline; O₂ sat %=percent of arterial O₂ sat.

Clinical Investigations

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An increased weight of expectorated sputum may or may not reflect a reduction in the amount of lower airway secretions, the ultimate goal of the treatment modalities we tested. We cannot rule out that oscillations and CPT induce secretion of lower airway mucus, and if so, the increased weight of expectorated sputum reflects the secretory effect of the treatment. A complicated method such as radioaerosol clearance would be needed to test this possibility. However, the difficulty to obtain informed consent from parents and guardians (due to prejudice and fear of harmful effects from radioaerosols in adolescents) precluded the use of this method. We therefore used sputum weight as our quantitative end point as has been used in several previous studies involving CPT.\textsuperscript{2,3,5,6,17}

### Table 2—Effect of Treatments on Wet Weight of Expectorated Sputum\textsuperscript{*}

<table>
<thead>
<tr>
<th>Treatment</th>
<th>rhDNase</th>
<th>Mean±SEM, %</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airway</td>
<td>+</td>
<td>144.9 ± 29.1</td>
<td>0.59</td>
</tr>
<tr>
<td>8 Hz, 9:1\textsuperscript{1}</td>
<td>-</td>
<td>153.8 ± 98.7</td>
<td></td>
</tr>
<tr>
<td>Airway</td>
<td>+</td>
<td>129.5 ± 20.1</td>
<td>0.31</td>
</tr>
<tr>
<td>14 Hz, 8:1\textsuperscript{1}</td>
<td>-</td>
<td>97.7 ± 17.9</td>
<td></td>
</tr>
<tr>
<td>Chest wall</td>
<td>+</td>
<td>137.0 ± 44.6</td>
<td>0.48</td>
</tr>
<tr>
<td>3 Hz, 4:1\textsuperscript{1}</td>
<td>-</td>
<td>120.5 ± 33.9</td>
<td></td>
</tr>
<tr>
<td>Chest wall</td>
<td>+</td>
<td>115.5 ± 19.8</td>
<td>0.94</td>
</tr>
<tr>
<td>16 Hz, 1:1\textsuperscript{1}</td>
<td>-</td>
<td>196.2 ± 131.5</td>
<td></td>
</tr>
<tr>
<td>1.5 Hz, 6:1\textsuperscript{1}</td>
<td>+</td>
<td>186.7 ± 27.7</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\textsuperscript{*}Comparing the group that inhaled rhDNase (n=11) with the one not receiving (n=3) this medication did not reveal any significant difference for any treatment.

\textsuperscript{1}I:E ratio.

### Table 3—Effect of Treatments on Dry Weight of Expectorated Sputum\textsuperscript{*}

<table>
<thead>
<tr>
<th>Treatment</th>
<th>rhDNase</th>
<th>Mean±SEM, %</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airway</td>
<td>+</td>
<td>189.7 ± 48.9</td>
<td>0.59</td>
</tr>
<tr>
<td>8 Hz, 9:1\textsuperscript{1}</td>
<td>-</td>
<td>136.9 ± 59.6</td>
<td></td>
</tr>
<tr>
<td>Airway</td>
<td>+</td>
<td>141.3 ± 30.0</td>
<td>0.07</td>
</tr>
<tr>
<td>14 Hz, 8:1\textsuperscript{1}</td>
<td>-</td>
<td>50.7 ± 12.9</td>
<td></td>
</tr>
<tr>
<td>Chest wall</td>
<td>+</td>
<td>164.9 ± 32.6</td>
<td>0.48</td>
</tr>
<tr>
<td>3 Hz, 4:1\textsuperscript{1}</td>
<td>-</td>
<td>113.4 ± 36.0</td>
<td></td>
</tr>
<tr>
<td>Chest wall</td>
<td>+</td>
<td>126.3 ± 28.1</td>
<td>0.82</td>
</tr>
<tr>
<td>16 Hz, 1:1\textsuperscript{1}</td>
<td>-</td>
<td>209.1 ± 146.5</td>
<td></td>
</tr>
<tr>
<td>1.5 Hz, 6:1\textsuperscript{1}</td>
<td>+</td>
<td>193.2 ± 23.3</td>
<td>0.59</td>
</tr>
</tbody>
</table>

\textsuperscript{*}Comparing the group that inhaled rhDNase (n=11) with the one not receiving (n=3) this medication revealed no significant difference for any treatment.

\textsuperscript{1}I:E ratio.
The OCI was created based on theoretical considerations and on results of previous experiments which demonstrated that through air-liquid interaction, mucus is transported within the airways.\textsuperscript{26-29} Airway wall radial displacement may help disengage the secretions from the airway wall and thereby enhance the effect of air-liquid interaction on mucus movement.\textsuperscript{28,30} For mucus transport in a cephalad direction, an expiratory bias flow is mandatory.\textsuperscript{11,14,15,21} In the OCI (OCI = \([f_{\text{Hz}}] \times \frac{(F_{\text{max}}/T_i)}{(F_{\text{max}}/T_i) - f}\)), frequency, inspiratory and expiratory flows, and time of inspiratory and expiratory airway wall displacement are arranged to obtain a higher index for better movement of mucus in a cephalad direction. Thus, the higher the f, the higher the expiratory flow, the lower the inspiratory flow, the faster the inward displacement of the airway wall during expiration, and the slower the outward displacement during inspiration, the higher becomes the index. Without any bias flow and with equal times of inspiratory and expiratory airway wall displacement, the OCI equals zero.

In our preliminary experiments, we systematically tested multiple settings for the chest wall and the oral airway oscillator to reach the highest OCI.\textsuperscript{24} This led to the settings in SenB and HayOp. However, for MCT1, HaySe, and CPT, we did not calculate the OCIs. This study, therefore, was not designed to validate the OCI. The fact that SenB, which resulted in much higher OCIs than HayOp, tended to perform better than HayOp, and both “optimized” treatments (SenB and HayOp) tended to be superior than the manufacturer-provided settings (which were not optimized according to our theoretical considerations), might be a hint that the OCI is of some value. However, the differences between all the treatments were minor and not statistically significant. Further experiments are clearly needed to find out if the OCI is a valid index.

Estimations of required sample sizes revealed that at least 300 patients are needed to achieve a power of 80\% with a type I error of 5\% for differences in means and variances that lie in the range of our study. Because we did not know the expected effects of the various treatments on sputum weight, sample size calculations could not be done in advance. The high variability between patients and the small differences between treatments resulted in the need of a large sample size for reasonable type I and II errors. In light of the many possible advantages of self-treatment, which is feasible with the oscillatory devices, the small differences between the treatment modalities might lose their importance, especially if compliance can be improved.

Comparing expectorated sputum weight in patients using and patients not using rhDNAse failed to reveal a significant difference. Almost all patients in our study were receiving rhDNAse, which complicates statistical comparison. However, our findings are in keeping with the work of Laube et al.\textsuperscript{31} which
did not achieve an increase in mucociliary clearance or improvement of airflow obstruction for patients inhaling rhDNase when compared with placebo.

Our results are consistent with findings of previous experiments, which showed that high-frequency chest wall oscillation is at least as effective as CPT in patients with CF who are in stable condition\textsuperscript{20,32,33} or suffer from acute exacerbation.\textsuperscript{17,18,32} To our knowledge, this is the first study that included oral airway oscillation. The results indicate that the increase in sputum weight by airway oscillations approximates the CPT-induced increase.

CPT has been shown to improve or to slow deterioration of pulmonary function in patients with CF.\textsuperscript{9,10,34-37} Short-term improvements in PFT results are thought to be caused by relief of mucus-related obstruction.\textsuperscript{34} The absence of short-term improvement in PFT results in our study can be explained by the fact that the patients were in clinically stable condition and did not manifest mucus plugging. Our finding is also consistent with the report of Wilmott and coworkers\textsuperscript{38} who did not find any beneficial effects of CPT on PFT results in patients with CF who had an acute exacerbation.

Our patients were in a stable condition and this may explain the observed lack of detectable treatment-induced changes in $O_2$ sat. Patients with acute exacerbations may behave differently. McDonnel and coworkers\textsuperscript{39} observed acute deteriorations in $O_2$ sat by CPT in their hospitalized patients with acute exacerbation. Connors and coworkers\textsuperscript{40} were able to show that among patients with acute nonsurgical lung disease, patients with excessive airway secretions maintained their $O_2$ sat, while patients without hypersecretion experienced oxygen desaturation. Another possible explanation why $O_2$ sat failed to change in our patients may have been their normal baseline values. Small changes in arterial oxygen tension may have been missed given the sigmoid shape of the oxygen-hemoglobin dissociation curve.

High-frequency chest wall oscillation is able to improve oxygenation and ventilation in patients with normal lungs,\textsuperscript{41,42} in patients with respiratory failure,\textsuperscript{43} and in patients with COPD.\textsuperscript{44-46} These effects have been attributed to improved interregional and intraregional gas mixing.\textsuperscript{47-52} These beneficial actions would not have been reflected by our $O_2$ sat measurement which was made after, not during, the treatment period.

High-frequency oral airway and chest wall oscillations were both well tolerated. No patient developed bronchospasm. Three patients with a history of

**Figure 3.** Effect of treatments on $O_2$ sat. Mean changes from baseline expressed as percent change from baseline (mean±SEM) are depicted for all treatments. There were no significant differences among the treatments.
hemoptysis developed trace amounts of blood in the spumon in two or three samples while receiving treatment (two while receiving oral airway oscillation and one while receiving chest wall oscillation). All these episodes resolved spontaneously without interrupting treatment. Arens and coworkers'17 made similar observations. They treated 25 CF patients with acute exacerbations three times per day over at least 14 days with high-frequency chest oscillation. Only two patients developed mild hemoptysis that stopped after interrupting the treatments for 24 h. Warwick and Hansen18 applied chest wall oscillation to 16 CF patients over 7 to 26 months one to four times per day without observing any adverse effects. It therefore seems that these new treatment modalities are safe.

Overall, our patients did not show a preference for any of the treatments. However, they did not have the option to self-administer treatments at home. Informal polls have shown that patients like the independence from caregivers during treatments that the newer devices offer, and therefore tend to prefer chest wall oscillation over conventional CPT.19 Minor uncomfortable side effects like drying of the mucous membranes during oral airway oscillation are readily relivable by humidification.

Many patients do not like conventional CPT because it is uncomfortable and time consuming. These inconveniences inherent in conventional CPT contribute to the low compliance rates that are reported to be in the range of 26 to 47%.53-57 It is conceivable that compliance can be improved by the availability of simple, effective, and easy-to-use devices that allow independent treatment at home. Devices to apply oral airway and chest wall oscillation fit these criteria. Considering their effectiveness and their potential to reduce health-care costs by permitting self-administration, 38 they appear to represent a useful alternative to conventional CPT.

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REFERENCES
7 Sutton PP. Respiratory physical therapy. Semin Respir Med 1984; 5:353-56
23 American Thoracic Society. Standards for the diagnosis and care of patients with chronic obstructive pulmonary disease (COPD) and asthma. Am Rev Respir Dis 1987; 136:223-44
27 Kim CS, Greene MA, Sankaran S, et al. Mucus transport in


34 Cochrane GM, Webber BA, Clarke SW. Effects of sputum on pulmonary function. BMJ 1977; 2:1181-83


36 Pryor JA. An evaluation of the forced expiration technique as an adjunct to postural drainage. Physiotherapy 1979; 65: 304-07


54 Davids LM, Heneley LD. Investigation into the compliance with physiotherapy regimens in cystic fibrosis. S Afr J Physiother 1990; 46:7-10


58 Klous D, Boyle M, Hazelwood A. Chest, vest, and CF: better care for patients. Adv Mgrs Respir Care 1993; 2:45-50