An Effective and Novel Design for Aspirating Sputum With a Visual Sputum Suction System: Its Feasibility and Efficiency in a Laboratory Setting

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Abstract

BACKGROUND: Conventional sputum suction is a routine clinical practice, but complications may arise from the blind manipulation of the catheter. Recently, a visual sputum suction system (VSSS) was developed. We hypothesized that this new system would be feasible and efficient for sputum suction in a laboratory setting.

METHODS: We used 1.5% and 3.0% coagulant to simulate mucus and sputum. Conventional single-lumen and triple-lumen catheters were inserted separately into a beaker for sputum suction (15 s, 200 mmHg). Then a micro-imaging fiber was integrated into the triple-lumen catheter to create the VSSS. The single-lumen catheter and the VSSS were inserted separately into the mouth cavity, the nasal cavity, the tracheostomy tube, and the endotracheal tube of a human analogue model for further comparisons.

RESULTS: As the suction channel of the triple-lumen catheter was reduced by 46.8%, the amount of simulant it suctioned was significantly less than that suctioned by the single-lumen catheter. However, under real-time guidance, the VSSS suctioned more simulant than the conventional single-lumen catheter in a human analogue model.

CONCLUSION: Sputum suction with this new system was feasible. Because of its real-time imaging guidance, the efficiency of the VSSS procedure was greater than that of the conventional single-lumen catheter. Therefore, this system may provide a new platform for sputum suction in the future.

Key words: Visual sputum suction system; simulant; in vitro; feasibility; efficiency.

Introduction

Sputum suction is a routine clinical procedure that is crucial for keeping the airway open to reduce the incidence of respiratory tract infections. In most circumstances, conventional catheters with a
single-lumen channel are used for sputum suction. However, this procedure involves blind
manipulation of the catheter on the part of the clinician and thus depends largely on the clinician’s
skills and experience. Therefore, complications occur in some patients, especially on the mucosa lining
of the trachea. In addition, because clinicians cannot directly target sputum in the trachea, the efficiency
of the procedure may be reduced.²⁶

Recently, a visual sputum suction system (VSSS) was developed in our research group that
integrated a 0.9-mm micro-imaging fiber into a 5-mm triple-lumen catheter. The present study
investigated the feasibility of sputum suction with this triple-lumen catheter alone in a laboratory
setting. Furthermore, suctioning efficiency was evaluated in a human analogue model to provide
evidence of the applicability of this technique for clinical use. To the best of our knowledge, this is the
first study to evaluate sputum suction with the VSSS.

Methods

Materials

The VSSS

The VSSS consisted of a micro-imaging fiber (FVS-001MI, Blade Co., Beijing, China), a
triple-lumen catheter (The Plastic Research Institute, Tianjin, China), and a computer processor and
monitor (Fig. 1). The micro-imaging fiber had an image fiber bundle (0.45 mm) at its core with a
mini-optical lens at the distal end and was surrounded by 120 optical fiber luminiferous bundles. The
outside diameter (OD) of each optical fiber luminiferous bundle was 0.035 mm. Including the coating
layer and the optical fiber luminiferous bundle, the outside diameter of this micro-imaging fiber was
0.9 mm, and the distal end could bend between about 0° and 60°. The total length of the micro-imaging
fiber was 220 cm; to allow for deep suctioning, the length of the working portion was designed to be 50
cm, which provided a resolution of 6,000 pixels. Depending on the guidance of the light source, the micro-imaging fiber recorded real-time images in the trachea. The signals were processed and displayed on the screen.

The triple-lumen catheter was 50 cm in length, with an OD of 5 mm (Fig. 2). This resulted in an optical fiber channel with an internal diameter (ID) of 1.5 mm for the micro-imaging fiber, a suction channel (ID = 2.5 mm), and an oxygen supply channel (ID = 1.0 mm). The conventional catheter had an OD of 5 mm and a single-lumen channel (ID = 4.7 mm) and was commercially available (Jiangsu Yongning Medical Apparatus Instrument Co. Ltd., Jiangsu, China).

The simulant coagulant

The simulant coagulant (Polyox Water Soluble Resin Coagulant NF; Dow Chemical Company, Cary, NC, USA) was a polyethylene oxide with an approximate molecular weight of 5,000,000 and a viscosity (1% solution) of 5,500–7,500 cP. The simulant coagulant was prepared by heating water to 95°C, quickly adding resin, and removing the simulant from the heat while stirring for 2 hours. We used 1.5% and 3.0% simulant in this study, as they have been shown to have properties comparable to human airway mucus and sputum.  

Study Design

We used the conventional single-lumen catheter in the control group and the VSSS (with triple-lumen catheter) in the treatment group (hereafter, “the visual group”). Three first-year interns with bachelor’s degrees participated in the study.

Evaluation of the effectiveness of sputum suction using the single-lumen catheter and the triple-lumen catheter in vitro

Simulant (150 g) with a concentration of 1.5% was contained in a 250-ml beaker. The triple-lumen
catheter was connected to the suction bottle and inserted into the beaker for suctioning for a total duration of 15 s in each trial, the negative pressure was 200 mmHg. The amount of simulant suctioned was calculated as the difference between the weights of the beaker before and after suctioning.

Following the same procedure, the amount of 1.5% simulant suctioned by the conventional single-lumen catheter was also recorded. The average of 10 measurements was considered as the weight of the simulant suctioned by the catheters under the same conditions. Similarly, the effectiveness of the suctioning was compared for the conventional single-lumen catheter and the triple-lumen catheter using 3% simulant.

Evaluation of the efficiency of sputum suction using the single-lumen catheter and the VSSS in a human analogue model

The first clinician randomly injected 20 g of 1.5% simulant into the trachea of a human analogue model (Zhonghong Teaching Equipment Co. Ltd., Shanghai, China). The second clinician used the conventional single-lumen catheter to suction the simulant following routine procedures, with a total duration of 15 s in each trial and a negative pressure of 200 mmHg. The third clinician used the VSSS with these same parameters. The maneuver was performed in a standardized manner between the second and third clinicians. The preliminary study indicated that there was no significant difference in the amount of simulant suctioned by the conventional single-lumen catheter or the VSSS alone (data not shown).

In both conditions, the suction tube was inserted separately into the trachea from the mouth cavity, the nasal cavity, the tracheostomy tube (Smiths Medical Int. Ltd., Kent, UK, ID=7.5 mm), and the endotracheal tube (Mallinckrodt Medical Co. Ltd., Co. Westmeath, Ireland, ID=7.5 mm), The amount
of simulant suctioned by the conventional single-lumen catheter or the triple-lumen catheter was calculated by the difference between the weights of the trachea before and after suctioning.

For each delivery route, 10 replications were performed, and the average amount of simulant suctioned was used as the average value. The mucus simulant collected from both the conventional single-lumen catheter and the VSSS was randomly labeled, then all the sputum was measured by the first clinician in a double-blind manner. Each procedure was evaluated by comparing the weights of the mucus simulant collected in 15 s by the conventional catheter and the VSSS.

Statistical analysis

SPSS Version 10.0 (1999, Chicago, Illinois, USA) was used for data analysis, and the data are presented here as mean ± SD. We used the two sample t-test to compare the amount of mucus simulant suctioned by the triple-lumen catheter and the conventional single-lumen catheter in vitro. We used factorial design analysis of variance to compare the amount of mucus simulant suctioned from the mouth cavity, the nasal cavity, the tracheostomy tube, or the endotracheal tube in the human analogue model by the VSSS and the conventional system. P < 0.05 was considered statistically significant.

Results

Evaluation of the effectiveness of sputum suction using the single-lumen catheter and triple-lumen catheter in vitro

We used a triple-lumen catheter to deliver the micro-imaging fiber into the suction catheter without interfering with the suction or compromising the oxygen supply. Although their ODs were the same, the ID of the suction channel of the triple-lumen catheter was 46.8% less than that of the conventional single-lumen catheter. Because of the reduced size of the suction channel, the amounts of both the 1.5%
and 3.0% simulant suctioned by the triple-lumen catheter were significantly lower than those suctioned by the conventional single-lumen catheter (Table 1) (P < 0.0001).

**Evaluation of the efficiency of sputum suction using the conventional single-lumen catheter and VSSS in a human analogue model**

We used a human analogue model to simulate the complicated anatomy of the human airway and to evaluate the use of the VSSS within the airway. As shown in Table 2, the VSSS was able to suction the 1.5% and 3% simulant from the mouth cavity, the nasal cavity, the tracheostomy tube, and the endotracheal tube. The VSSS was able to suction more simulant than the conventional single-lumen catheter (the mouth cavity, P<0.0001; the nasal cavity, P<0.0001; the tracheostomy tube, P=0.0053; and the endotracheal tube, P< 0.0001).

**Discussion**

**Summary of the main findings**

The main results of the study are as follows. (1) A VSSS consisting of a micro-imaging fiber (OD = 0.9 mm) integrated into a triple-lumen catheter was developed. (2) Both the triple-lumen and single-lumen catheters were able to suction simulant with properties equivalent to those of mucus and sputum. (3) Because the sputum suction channel of the triple-lumen catheter was reduced by 46.8% compared to that of the conventional single-lumen catheter, the amount of simulant suctioned by the triple-lumen catheter was significantly less than that suctioned by the single-lumen catheter under the same conditions. (4) As the ODs of both the single-lumen and triple-lumen catheters were the same (5 mm), these catheters could be inserted into the airway of a human analogue model from the mouth cavity, the nasal cavity, the tracheostomy tube, or the endotracheal tube. (5) Under real-time imaging
guidance, the VSSS collected more simulant than the conventional single-lumen catheter.

A comparison of the VSSS and the conventional single-lumen catheter

Sputum suction with a conventional single-lumen catheter is routine in clinical practice. However, as operators are not able to directly see what they are doing, this procedure depends largely on the experience of the clinician. This blind operation may increase the incidence of unnecessary damage to the trachea wall or decrease the effectiveness of the suctioning process. Moreover, the visual guidance supplied by the VSSS enables the operator to estimate the amount and location of residual sputum after suctioning.

To address these limitations, we developed the VSSS (Figs. 1 and 2), which we evaluated for the first time in a laboratory setting in this study. Because of rapid progress in optical fiber technology, micro-imaging fibers as small as 0.9 mm are available. This micro-imaging fiber can be inserted into a conventional single-lumen catheter to guide sputum suction. To further manage the oxygen supply and avoid disturbing the suctioning function, we used a triple-lumen catheter. Because both catheters had the same OD (5 mm), the suction channel of this triple-lumen catheter was 46.8% less than that of the single-lumen catheter.

This study indicates that the ID of the suction channel plays an important role in the efficiency of sputum suction (Table 1). Under the same conditions, less sputum was suctioned by the triple-lumen catheter than the single-lumen catheter because of the reduced ID of the suction channel.

Although the beaker experiment suggested that the effectiveness of sputum suction using the triple-lumen catheter was significantly less than that of the conventional catheter (Table 1), the human analogue model experiment indicated that the triple-lumen catheter integrated with the micro-imaging fiber was more efficient than the single-lumen catheter (Table 2). The reason for this may be
attributable to the real-time imaging guidance.

Sputum is randomly distributed within the airway, and to be as thorough as possible, conventional blind suction sometimes targets areas of the trachea without sputum. This procedure may be less efficient and may cause unnecessary damage to the trachea. In contrast, targeted sputum suction with imaging guidance can help operators locate sputum as quickly as possible.

In this study, the efficiency of sputum suction was determined by the weight of sputum suctioned; the suctioning time was not directly compared. However, it is possible that the greater efficiency of the VSSS may help to reduce the amount of time needed for suctioning. Future studies should use animal models to evaluate the potential benefits in terms of reducing the risk for hypoxemia-related complications due to a long procedure.7, 10

In addition, the VSSS catheter can be inserted into the airway more smoothly because the operator can visualize key anatomical structures, such as the epiglottis, the trachea wall, and the carina (Fig. 3); this will reduce the incidence of lesions to the airway. Future research should use animal models or clinical trials to determine whether this system has additional safety benefits.

A comparison of the VSSS and the bronchofiberscope

Bronchofiberscopes of different diameters have been used as an alternative for sputum suction in clinical practice.11, 12 The commonly used 5-mm bronchofiberscope is equivalent to the triple-lumen catheter, and thus the VSSS represents an alternative to the bronchofiberscope.

Rapid progress in optical fiber technology reduced the diameter of the micro-imaging fiber to 0.9 mm. Although optical imaging fiber bundles had previously been used in fiberoptic ductoscopy to diagnose nipple discharge,13 the working length of the fiber was only 8.4 cm. In order to enable deep suctioning within the trachea, we extended the optical fiber to 50 cm. To the best of our knowledge, this...
is the first report to demonstrate the application of imaging guidance for sputum suction using an optical fiber of such length.

The image resolution of the micro-imaging fiber was 6000 pixels, which was about one fifth less than that of the bronchofiberscope.\(^\text{14}\) However, the primary purpose of this study was to use the micro-imaging fiber to guide sputum suction, not for diagnosis, and the quality of the images acquired by the VSSS was sufficient for this purpose (Video 1, online supplementary material).

In China, only clinicians and respiratory therapists are allowed to use the bronchofiberscope; moreover, repeated sterilization is necessary within different patients, which limits the application of this technique for routine clinical practice and repeated suctioning. In contrast, sterilization involves simply changing the triple-lumen catheter. Also, as the basic procedure for sputum suction using the VSSS is similar to the conventional method, respiratory therapists are able to perform this procedure competently, which may help to further popularize this new method.

**Implications for Clinical Practice**

In this study, a micro-imaging fiber was inserted into a triple-lumen catheter to guide sputum suction. In addition to its use in sputum suction, this micro-imaging fiber has the potential to be integrated into the nasogastric tube, urethral catheter, or rubber drainage tube. Therefore, this technique has the potential to change and improve many clinical practices.

**Limitations**

Although the VSSS has many potential benefits, this prototype system is still in its infancy. Further optimization in terms of catheter design and manipulation and resolution of the micro-imaging fiber should take place according to the results of subsequent studies. Moreover, because of the external
diameter of the catheter, this system is not suitable for suctioning sputum in smaller endotracheal tubes (e.g., those of neonates and pediatric patients).

Future studies should investigate the efficiency and efficacy of the VSSS in animal models to further evaluate the safety of this technique. An application for a clinical trial is also pending. Studies of this system in real patients will provide the most meaningful information on the feasibility, efficiency, and safety of this technique; the perspectives of patients; the acceptance of the technique among clinicians; and the financial benefits of this system.

Conclusions

This new system is feasible for sputum suction in a laboratory setting. Although the efficiency of the suctioning was reduced compared to that of a triple-lumen catheter in vitro, this drawback can be compensated for by the targeted sputum suction using real-time imaging guidance. Therefore, this system may provide a new platform for sputum suction in the future.
REFERENCES


Figure 1. The visual sputum suction system for sputum suction in a human analogue model. The arrow shows the red point as the distal end tip of the micro-imaging fiber in the trachea.
Figure 2. The visual sputum suction system. A micro-imaging fiber was inserted into a triple-lumen catheter. The outer diameter (OD) of the triple-lumen catheter was equivalent to that of a conventional single-lumen catheter. Details concerning the tip and size of the catheters are in the top right corner. A: micro-imaging fiber (OD = 0.9 mm), B: triple-lumen catheter (OD = 5.0 mm), I: imaging channel (internal diameter [ID] = 1.50 mm), II: suction channel (ID = 2.50 mm), III: oxygen supply channel (ID = 1.0 mm), C: conventional catheter (OD = 5.0 mm) with a single lumen (ID = 4.7 mm).
Figure 3. Real-time imaging guidance using the visual sputum suction system in a human analogue model. The images show the anatomical structure of the trachea wall (A); simulant in the trachea (B); the carina, the RB, the LB (C); and the RB (D). RB: right bronchus, LB: left bronchus.
Table 1. The weight of simulant suctioned by a conventional single-lumen catheter (Control group) and a triple-lumen catheter (Visual group) in vitro with 15 s and 200 mmHg (mean ± SD, g). C_r is the concentration of the simulant. We used 1.5% and 3.0% simulant to simulate mucus and sputum in the human airway. * The amount of simulant suctioned in the visual group was significantly different from that suctioned in the control group.
Table 2. The weight of simulant suctioned by a conventional single-lumen catheter (Control group) and a triple-lumen catheter (Visual group) in a human analogue model with 15 s and 200 mmHg (mean ± SD, g). C, is the concentration of the simulant. We used 1.5% and 3.0% simulant to simulate mucus and sputum in the human airway. * The amount of simulant suctioned in the visual group was significantly different from that suctioned in the control group.
Video 1. Real-time imaging guidance using the visual sputum suction system (VSSS) in a human
analogue model. The video shows the VSSS entering the trachea from the tracheostomy tube, the carina
and the entrance of the right and left bronchi, and the VSSS reaching the left bronchus.
<table>
<thead>
<tr>
<th>$C_s$</th>
<th>1.5%</th>
<th>3.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control group</td>
<td>$46.75 \pm 1.22g$</td>
<td>$53.97 \pm 2.18g$</td>
</tr>
<tr>
<td>Visual group</td>
<td>$35.42 \pm 1.56g^*$</td>
<td>$42.81 \pm 2.31g^*$</td>
</tr>
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Values are mean ± SD.

$C_s$ is the concentration of the simulant.

* The amount of simulant suctioned in the visual group was significantly different from that suctioned in the control group.
<table>
<thead>
<tr>
<th>C_s</th>
<th>Visual group (n=10)</th>
<th>Control group (n=10)</th>
<th>Visual group (n=10)</th>
<th>Control group (n=10)</th>
</tr>
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<tbody>
<tr>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Mouth Cavity</td>
<td>11.74±1.50g*</td>
<td>9.80±1.00g</td>
<td>11.94±0.48g*</td>
<td>9.03±1.07g</td>
</tr>
<tr>
<td>Nasal Cavity</td>
<td>10.46±1.03g*</td>
<td>9.33±0.78g</td>
<td>9.96±1.00g</td>
<td>8.29±0.64g</td>
</tr>
<tr>
<td>TT</td>
<td>11.61±0.92g*</td>
<td>10.41±0.94g</td>
<td>11.09±1.05g*</td>
<td>10.55±0.68g</td>
</tr>
<tr>
<td>ET</td>
<td>11.04±1.03g*</td>
<td>9.34±0.72g</td>
<td>11.18±0.93g*</td>
<td>8.21±1.07g</td>
</tr>
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</table>

| 3.0%      |                     |                       |                     |                      |

C_s is the concentration of the simulant.

* The amount of simulant suctioned in the visual group was significantly different from that suctioned in the control group.
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Real-time imaging guidance using the visual sputum suction system in a human analogue model. The image shows the carina, the RB, the LB. RB: right bronchus, LB: left bronchus.
Real-time imaging guidance using the visual sputum suction system in a human analogue model. The image shows the RB. RB: right bronchus.