Hollow Waveguide UV Light Probe for Reduction of Ventilator Associated Pneumonia

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Abstract

Ventilator Associated Pneumonia (VAP) is the second most common nosocomial infection in pediatric intensive care units (PICUs). VAP can be contracted through inhalation of particles from the biofilm that form on the inner surface of endotracheal tubes (ETTs). A method of bacteria elimination is necessary to decrease risk of infection. The goal of this project is to use UV light technology to create a device capable of reducing the occurrence of VAP in pediatric intensive care unit patients. The power necessary to eliminate bacteria in the ETT was calculated as 0.162 W assuming each 1 cm length of tube was irradiated for 1 second. A prototype was built using a 600 μW UV LED purchased from Sensor Electronic Technology, Inc and hollow waveguides purchased from Doko Engineering. The coupled waveguide and UV LED were tested for light loss through coupling and traveling through the waveguide. The waveguide was also coupled to light coming from a collimated laser source, and it was found that the light loss of the laser was lower than that of the LED: 0.28 dB vs. 3.32 dB. This prototype was determined to be ineffective at eliminating bacteria in its current state through a bacterial test trial where the coupled LED was used to irradiate a bacterial sample for one minute. These two tests were used to determine that a UV laser would be necessary to effectively kill bacteria in an ETT. The cost for the first production device with a UV laser was estimated to be $46,880 based on both component and labor costs. This project has been successful in proving that UV irradiation is a plausible method for eliminating bacteria from ETTs and helping to prevent VAP in intubated patients.
**Introduction**

**Ventilator Associated Pneumonia**

A nosocomial infection is an infection resulting from any hospital stay whether brief or extensive. Ventilator Associated Pneumonia (VAP) is the second most common nosocomial infection in pediatric intensive care units (PICUs), representing more than 20% of all nosocomial infections identified (1). Overall, there are more than 300,000 cases of VAP reported yearly, and more than 30% of people with a critical illness develop an infection resulting in VAP (2). VAP most commonly results from prolonged mechanical ventilation with an endotracheal tube (ETT) usually exceeding 48 hours (3). Secondary outcomes of VAP include increased length of hospitalization, increased cost, and even death. The average intensive care unit stay is prolonged by an average of 8 days (5), and the time of necessary mechanical ventilation is increased by about 3.7 days (3). In 1985, the estimated cost increase due to an episode of VAP was US$5000 to US$8000 (5). More recently, it was established that the average extra hospital cost incurred by a pediatric intensive care unit patient due to VAP is $51,000 (6).

Proposed modes of infection leading to VAP include spread of bacteria from oral secretions and the gastrointestinal tract as well as inhalation of airborne bacteria (3). These infections most commonly include three main bacteria: *Pseudomonas aeruginosa, Enterobacteriaceae*, and *Staphylococcus aureus* from the VAP aspirates (4). The bacteria begin colonizing the lumen of the ETT within a few hours of intubation. The speed with which the bacteria are able to multiply and establish colonies is aided by the formation of a biofilm or layer of biologic material secreted by the bacteria to create a favorable environment for bacterial multiplication (7). Bacteria from the biofilm can easily break off from the endotracheal tube and
travel into the respiratory system causing pneumonia. This threat was identified by showing that the presence of VAP-causing bacteria on the ETT inner surface can be directly linked to the infections through cultures that indicate 70% of VAP patients have identical bacteria cultured from their ETT and tracheal secretions (7). Because many of the risk factors associated with the development of VAP are closely linked to the use of an ETT for ventilation, this project focuses on elimination of bacteria within these tubes.

Pediatric Endotracheal Tubes

The internal diameter of the ETT used for mechanical ventilation varies for each patient depending on the age and size of the patient. In pediatric intensive care units, the smallest ETTs that are used in newborns have an internal diameter of 3.0 mm and the largest tubes used for children between the age of 11 and 12 have an internal diameter of 7.0 mm (9). A device to clean these tubes has to fit within the smallest, 3.0 mm diameter tube. It also has to carry light a length of 31 cm to reach the end of the largest tubes while bending along the curve of the trachea within the tube (10).

Current Methods of VAP Prevention

There are a number of procedures and protocols in place to attempt to reduce the occurrence of VAP in hospitalized patients including regular mouth cleaning, avoidance of re-intubation, suction of oropharyngeal secretions, limitations on patient transport throughout the hospital, and modifications of the ETT itself (7). The first ETT modification used to prevent bacterial colonization of the tube is coating the inside and sometimes the outside of the tube with an antimicrobial agent. This agent should be a broad-spectrum antimicrobial to cover a variety of pathogens and induce as little bacterial resistance as possible (7). One coating used is a layer
of silver ions meant to interact with the thiol groups on bacterial proteins and cause inactivation (11). The use of silver-coated ETTs has been confirmed to significantly reduce the incidence of VAP by preventing bacterial colonization. In a randomized clinical trial by Kellef et.al., the rate of confirmed VAP cases was 4.8% in a group receiving the silver-coated endotracheal tubes and 7.5% in the patient group receiving the uncoated tubes (12). The safety of the silver-coated tubes was established by comparing adverse events between the two groups (coated and uncoated) and finding no statistically significant difference in the number of these events (12).

While the benefits of the use of the silver-coated ETTs are undeniable, this improvement accounts for a relative risk reduction of 35.9% (12). Another study found that the silver coated endotracheal tubes began accumulating VAP-causing bacteria after 72 hours of ventilation (13). This suggests that patients requiring extended mechanical ventilation past 72 hours will still be at high risk of developing VAP. An additional method of bacteria elimination is necessary to improve risk reduction.

_Ultraviolet Technology for Elimination of Bacteria_

Ultraviolet (UV) light is useful in killing bacteria. High intensity UV light of 200 to 300 nm falls within the high UV-C range (100-280 nm) and low UV-B range (280-315 nm) and causes effective inactivation of bacteria (14,15). UV light attacks the bacterial DNA preventing it from replicating. The double bond in pyrimidine bases absorbs the light causing the bond to open and react with neighboring molecules. The open pyrimidine base may form a direct covalent bond with another pyrimidine base if the two bases are next to each other (16). UV light can be harmful to humans because the same mechanism can disrupt the DNA of skin cells. UV-C light is less harmful to humans because it cannot penetrate the dead layer of human skin.
This wavelength of light is also blocked by opaque surfaces (15). Threshold Limit Values (TLV) are published by the American Conference of Governmental Industrial Hygienists (ACGIH) of 250 mJ/cm² at 180 nm and 3.1 mJ/cm² at 275 nm (15).

Project and Device Goals

The overall goal of this project is to use UV light technology to create a device capable of reducing the occurrence of VAP in pediatric intensive care unit patients. The project goals for the device include:

1. Effectively killing bacteria on the inner wall of the endotracheal tube
2. Achieving an appropriate device size in order to be used with ETTs down to 3 mm in diameter and up to 31 cm in length
3. Achieving sufficient flexibility in the part of the device inserted into the tube in order to bend and travel down the entire length

Ideally, a device that meets these criteria should also be made reusable and easily sterilized to help reduce cost of care.

Methods

Selecting an Appropriate Wavelength for Elimination of Bacteria

Before beginning the search for a source of UV light, the optimal wavelength for elimination of bacteria was determined. In a study by Wang et.al. in 2005, E. coli bacteria was used to represent a broad spectrum of gram-negative bacteria (14). The bacteria were irradiated with pulsed UV light of wavelengths ranging from 230-300 nm. Figure 1 shows the results of this study and indicates that the most efficient wavelength for eliminating E. coli is 270 nm (14).
Therefore, under the assumption that E. coli is representative of gram negative, VAP causing bacteria, the device design includes a UV light source with a main wavelength of 270nm.

**Amount of Power Required to Kill Bacteria**

In order to determine the amount of power necessary in a potential UV light source, the power required to effectively eliminate bacteria was calculated. The dose of UV light to kill representative E. coli was approximated using Figure 2 and the curve representing 270 nm light for elimination of 99%, 75%, and 50% of bacteria.

Calculations were made assuming: (1.) E. coli is representative of the properties of VAP causing bacteria, (2.) the ETT is perfectly cylindrical and a height (h) of 1 cm of tube may be exposed to the UV light at a time, and (3.) each 1 cm segment of tube is exposed for 1 second. At 270 nm, about 5 mJ/cm² of UV light is necessary to eliminate 99% of the bacteria present (Figure 2).

\[
\text{Surface Area Exposed (SA)} = \text{Circumference} \times \text{height} \quad \text{Eq. 1}
\]

\[
\text{Energy to Kill Bacteria} = \text{SA} \times \text{Dose Needed} \quad \text{Eq. 2}
\]

\[
\text{Power} = \frac{\text{Energy}}{\text{Time}} \quad \text{Eq. 3}
\]

**Hollow Waveguide Technology for Transmission of UV Light**

Research was conducted to determine the optimal way to transmit 270 nm wavelength UV light down an ETT by way of a flexible device. Silica-based glass fibers are traditional optical fibers that have a core and outer coating made of fused silica. These types of fibers are not sufficient for transmitting UV light because the imperfections in the glass cause scattering.
losses at low wavelengths. Although special silica fibers have been made to counteract this effect, they have increased attenuation the more UV laser pulses that are transmitted in the fiber due to photon absorption by the silica glass (17). Other types of fibers were researched to find a better way to transmit UV light in a fiber that is flexible and does not lose the majority of the light power from the UV light source. Correspondence was made with Dr. James A. Harrington at Rutgers University who suggested contacting Dr. Yuji Matsuura at Doko Engineering in Sendai, Japan. Doko Engineering manufactures hollow waveguides for UV light. These fibers were chosen as a solution that would be able to bend down the ETTs and transmit high powered light to the end of the hollow waveguide without the majority of the power being lost in the bending of the waveguide (17).

The hollow waveguides are made up of a hollow glass tube as the main structure. This glass layer is indicated by number 2 in Figure 3 and has thin walls and a small bore size. Deposited on the inside of the glass tube as indicated by number 3 in Figure 3 is a thin aluminum film that creates a smooth surface and has the highest reflection coefficient for UV light of metals. The surface roughness of the aluminum is less than 50 nm in root mean square value. The low surface roughness creates very little light loss due to scattering as well as low attenuation of the light that is transmitted down the waveguide (17).

*Ultraviolet Light Sources*

Ideally, with an estimated transmission percent of 6.8% and a required bactericidal power of 0.011 W for a 7 mm diameter tube and 99% effectiveness, the device would require a light source with a minimum power of about 0.162 W minimum. The options for sources of UV light include lasers and LEDs.
1. UV Lasers: In the studies involving hollow waveguides, excimer lasers were used to couple UV light to the waveguides. Excimer lasers come in a variety of wavelengths depending on the active gas that is used within the laser. Argon fluoride excimer lasers have an output wavelength of 193 nm, krypton fluoride excimer lasers have an output wavelength of 248 nm, and xenon chloride excimer lasers have a wavelength of 308 nm (19). The average power output (W) from the laser is the energy of each pulse (mJ) multiplied by the repetition rate (Hz) divided by 1000 (19). Changing the pulse rate and energy of each pulse will produce a different power output of the laser. Lasers are an ideal source because they produce more power to transmit through the hollow waveguide. Increased power will allow exposure time to be decreased because the bacteria will experience a larger dose of UV light and be eliminated more quickly. Another advantage of UV lasers is that the light is collimated which will allow the light to be more easily coupled into the hollow waveguide and result in less light loss.

2. UV LEDs: Due to the economic limitations of this project, purchasing a UV laser is not possible. A second option to allow testing of coupling into the hollow waveguides, estimate a light budget, and determine anti-bacterial properties of the chosen wavelength is a 270 nm UV LED. The UV LED ordered is a UVTOP270 from Sensor Electronic Technology Inc. The LED is equipped with a ball lens capable of focusing the output light to a point of diameter 1.5 mm (Figure 4) and has an output optical power range of 360- 600 μW. At the maximum power of 600 μW and an estimated transmission of only 5.2%, the expected light output is 31.2 μW. This is not enough power to expect elimination of 99% of bacteria, but it should be sufficient to show set up and prove the concept.
Predicted Light Loss Budget

Light loss estimates were made based on a study by Matsuura et.al. on a 1 m long, 1 mm bore hollow waveguide using 8 mJ ArF-excimer laser with repetition rate of 200 Hz (17). The study found a transmission loss of 1-4 dB due to the large absorption coefficient of ozone. This loss was reduced to less than 1 dB by using a flow of 50 mL/min of nitrogen. Up to 0.6 dB of light were lost due to the process and accuracy of coupling between the light source and the fiber. Attenuation losses result in a reduction of 0.2 dB/m and were calculated in Table 1 for the device waveguide of 31 cm. Figure 5 shows the relationship between curvature of the waveguide and loss due to bending. The waveguide used in this device will be expected to bend relatively sharply and will therefore lose a significant amount of light power due to bending.

Further assumptions were necessary to estimate the light loss when the UV LED was used as the light source. A coupling loss triple that of the coupling loss for a laser was used in order to indicate difficulties associated with coupling an uncollimated light source to the hollow waveguides.

An overview of the expected light loss for both the design utilizing a laser and the design utilizing the UV LED can be seen as a comparison in Table 1. The estimates made in Table 1 are extreme in order to make a conservative guess for the total percent output of UV light. The reduction in power was determined by Equation 4 below. The output power found in each line of Table 1 was used as the input power for the subsequent line.

\[
\text{Light Loss (dB)} = 10 \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)
\]  
Eq. 4
Table 1. Estimate of Percent of Original Light Power that is Output from the Waveguide

<table>
<thead>
<tr>
<th>Source of Loss</th>
<th>Assumptions with 270 nm Laser</th>
<th>% Light Output from 100% Initial Power Input</th>
<th>Assumptions with LED</th>
<th>% Light Output from 100% Initial Power Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Loss</td>
<td>4.0 dB loss</td>
<td>39.8%</td>
<td>4.0 dB loss</td>
<td>39.8%</td>
</tr>
<tr>
<td>Coupling Loss between Laser and fiber</td>
<td>0.6 dB loss</td>
<td>34.7%</td>
<td>Assume 1.8 dB loss</td>
<td>26.3%</td>
</tr>
<tr>
<td>Attenuation Loss</td>
<td>0.2 dB/m * 0.34m = 0.068 dB loss</td>
<td>34.2%</td>
<td>0.2 dB/m * 0.34m = 0.068 dB loss</td>
<td>25.9%</td>
</tr>
<tr>
<td>Loss Due to Curvature</td>
<td>7 dB loss with 16.7 cm radius of curvature</td>
<td>6.8%</td>
<td>7 dB loss with 16.7 cm radius of curvature</td>
<td>5.2%</td>
</tr>
<tr>
<td>Total Percent Output or Total Light Loss in dB</td>
<td>11.67 dB</td>
<td>6.8%</td>
<td>12.87 dB</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

The light loss data from a study by Yuji Matsuura and Mitsunobu Miyagi was produced using an ArF-excimer laser of 193 nm (18). Since the device will have a larger wavelength, less light is expected to be lost due to absorption. Also, the source that was used in the experiment had a rectangular beam shape which is more difficult to couple than a circular beam. By using light sources with circular beams, loss due to this mismatch can be avoided in the design of this device. Further, the most allowable curvature to obtain the maximum loss that may occur for a particular waveguide diameter was assumed. The loss due to curvature was established using a waveguide wrapped in a full circle. Since the waveguide used for this device will be shorter and only make a partial bend around a circle, the total power output can be expected to be greater in a marketable device. As seen in Table 1, approximately 6.8% of the original power is output with
a laser light source and approximately 5.2% of the original power is output with a UV LED as the source.

*Calculation of ETT Irradiation Time Necessary to Kill Bacteria*

An estimate of the relationship between the ETT inner diameter and the duration of irradiation necessary to eliminate 99% of the bacteria in the inside of the tube was completed under the following assumptions: (1.) the ETT is perfectly cylindrical, (2.) the tube may be irradiated in 31, 1 cm segments, and (3.) the light lost due to coupling and attenuation is equal to the percentages calculated in Table 1 above. A comparison was made between the UV LED with a maximum power of 600 μW and a representative UV laser of wavelength 266 nm and a maximum of 15 μJ pulsed energy (1-100 kHz) from CrystaLaser. The maximum repetition rate of 100 kHz was used in calculations.

*Coupled UV Laser to Sample Waveguide*

To couple the UV fiber, the fiber was threaded down a support that was attached to a magnetic optical table. The UV LED source was then placed at the appropriate distance and position away from fiber so that focal length of the LED light was within the acceptance angle of the fiber. The LED was positioned on a breadboard and clamped into place on the optical table. Successful coupling was visualized by placing a piece of cardboard at the other end of the fiber so that the light could be seen on the cardboard if the light was successfully coupled. To measure the intensity of the light spot size on the cardboard, a camera was positioned at a constant distance away from the setup and the image was analyzed in MATLAB to determine power. The design setup can be seen in Figure 6.
Measured Light Loss by reduction in Power

To measure the loss in light power through coupling and traveling down the waveguide two representative models were employed. The first was a UV LED which was equipped with a ball lens for focusing its light into the hollow waveguide. The second model was a PHR-803T laser with a wavelength of 405 nm. For this model a separate lens system was set up as shown in Figure 7. For each model the light intensity incident to the waveguide and light intensity exiting the waveguide were measured using a 12 megapixel camera. Light intensity was converted to power using Equation 5 where \( r \) represents distance to the camera, \( I \) represents integrated intensity from each pixel, and \( P \) represents power. Intra-model values for power were compared to determine light loss.

\[
P = I \times 4\pi r^2
\]

Eq. 5

Measured Reduction in Bacteria from UV LED and Waveguide System

The amount of bacteria elimination was measured by comparing a control plate to a plate of bacteria that had been exposed to UV light from the LED and coupled waveguide system. A 1 \( \mu \)L spot of an overnight bacterial suspension containing Staphylococcus aureus bacteria was placed on the center of two agar plates. After allowing the colonies to grow for 24 hours the 1 \( \mu \)L spot of Staphylococcus aureus bacteria on the test plate was exposed to the coupled UV LED light as shown in Figure 8 for 1 minute.
Results and Discussion

Power Necessary to Kill Bacteria

The power necessary to eliminate bacteria increases as the inner diameter of the ETT increases because a greater amount of surface area must be irradiated in each 1 cm segment of the tube (Figure 9). It should be noted that the total surface area of each irradiated segment may be increased or decreased in a final design based on the scattering or reflecting system chosen and the amount of tube irradiated simultaneously.

Irradiation Time

The amount of time the ETT must be exposed to the UV light should be kept to a minimum to avoid depriving the patient of ventilation for extended periods of time. Figure 7 shows the estimated irradiation times as a function of the ETT size for both a representative UV laser and the UVTOP270 LED purchased. In order to eliminate 99% of bacteria after light loss and attenuation, the laser requires an irradiation time of less than 7 seconds for all ETT diameters. The LED however, requires time on the order of hours to be as effective as the laser. The estimates provided do not account for different lengths of tubes, so it is likely the irradiation time for smaller tubes which are shorter than 31 cm, will be shorter than the time shown in Figure 10. Irradiation time may be adjusted by changing the pulse rate of the laser, and may be further reduced by irradiating the tube in multiple, shorter bouts that are more tolerable to patients.
**Light Intensity**

The input and output light intensity for the UV LED condition are shown in Figure 11. The light loss for the UV LED calculated from Figure 11 was higher than that for the laser model: 3.32 dB vs. 0.28 dB. This is the expected result as the UV LED’s light contained much higher incident light angles. This result adds to the evidence that a UV laser is needed for a production device.

**Elimination of Bacteria**

The experiment to test whether the hollow waveguide with coupled UV LED was an effective method for killing bacteria did not yield a noticeable reduction in bacteria. Figure 12 displays a comparison between the plate that received UV light treatment and the control. Both plates appear the same and show no decrease in bacteria due to the current device setup. The UV LED was proposed as a source that may not be powerful enough to kill bacteria. The amount of light lost due to coupling this source and the initial low power of the source show that the UV LED from Sensor Electronic Technology Inc is not a sufficient light source to kill bacteria. A source such as a laser that can be purchased with a higher power and is collimated for easier coupling is the next step in developing a device that can deliver enough light to eliminate bacteria on the sides of an ETT.

**Safety Issues**

Ultraviolet light (UV) has the potential to be harmful to the tissue of the trachea. The use of UV radiation destroys the DNA of cells causing them to lose the ability to regulate replication and is linked to the development of cancer. The antibacterial properties are due to the DNA absorption of UV light which causes crosslinking between nearby pyrimidine nucleoside bases.
Too much UV light exposure could produce this effect in the trachea tissue of patients. Although the use of UV light is necessary to kill bacteria and prevent VAP, precautions have to be taken in order to protect trachea. Silver coated ETTs must be used if it is found that the regular silicone tubes expose the tracheal tissue to harmful doses of UV light. The trained physician or nurse must secure the device to the entrance of the ETT before turning on the UV light source. This will keep the UV light within the tube to protect both the physician or nurse and the patient.

Hypoxia or lack of oxygen may become a problem for the patient if the ETT is obstructed by this device for too long. For the duration of device use, the patient will not be actively ventilated and the ventilator will be detached. This time period should be kept to a minimum by either utilizing a UV light source powerful enough to eliminate bacteria in an acceptable time frame or using the device in sequential, short bouts that add to a large enough bactericidal dose of UV light.

Finally, the hollow waveguides are glass, and though they are flexible, if they are bent too sharply or subjected to other significant force, the glass may break. To avoid breaking, the device should be inserted slowly. A protective sheath should always be present to protect the patient from glass in the event of a break.

Economic Considerations

The device discussed will ultimately be designed to prevent cases of VAP in patients in the PICU. The device has the potential save millions of dollars in medical care if it is widely implemented and can be manufactured reasonably well with a higher powered light source such as a laser. These cost savings could become more imperative in the near future as insurance
companies may reevaluate the costs they are willing to cover. Since the ETT sterilizer was envisioned as a device for the children’s hospital, the cost variables for the use of the device in pediatrics will be discussed. The device however, will be adaptable for use in adult patients as well because adult ETTs are made only slightly larger than the largest pediatric ETT.

Every year in the United States 230,000 children are admitted to PICUs (20). Of those children 30-64% percent require mechanical ventilation as part of their care (21). Those children on mechanical ventilation have a 5% chance of developing VAP (22). Tragically, 20% of the children who develop VAP die each year, which corresponds to 690 child victims per year in the US (22). On average, an increased hospital stay of 8 days and an increased cost of approximately $51,000 result from each case of VAP in the PICU (6). Using the lowest estimate for number of children requiring mechanical ventilation, it can be projected that VAP in PICUs accounts for $175,950,000 in medical costs per year in the United States. If the device was capable of stopping even 50% of VAP cases per year that amounts to nearly 80 million dollars saved. The calculation for this estimate is shown below as Equation 6.

<table>
<thead>
<tr>
<th>(230,000 children admitted to PICUs annually)</th>
<th>* (30% of PICU cases require mechanical ventilation)</th>
<th>* (5% of mechanical ventilation cases develop VAP)</th>
<th>* ($51,000 additional cost per case of VAP)</th>
<th>= $175.95 Million</th>
</tr>
</thead>
</table>

Equation 6: Justification for Cost of VAP per year

The cost required to develop a prototype device has been small, largely because many parts were received for free or used sample versions of parts that would be necessary on the full size device. The hollow waveguide pieces that were received from Doko Engineering of Japan were given as samples. Two sources of UV light were used for experimentation: the blue wide light spectrum laser and the UV LED. The laser was borrowed from a personal collection to
show coupling principles and would be ineffective at killing bacteria. The UV LED was purchased for $275 from Sensor Electronics Technologies. Theoretically, if given a long enough exposure time, it is capable of killing bacteria but does not have sufficient power to allow for quick application in a clinical setting. For coupling, lenses were borrowed from the student optics lab at Vanderbilt University, but using these lenses made the device stationary. The last cost associated with the prototype would be developmental costs. The hours for this project were freely given by all parties but if they were purchased the prices would be a total of $4800. Those hours are estimated to be four students working 12 hours a month for six months on the project at $15 an hour and two advisors working 2 hours a month for 6 months at $100 an hour. The breakdown of all costs is listed in Table 2. Also in Table 2, the final prototype cost was estimated to be $5075, which includes the cost of development.

**Table 2: Cost of Prototype Device**

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost per Item</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV LED</td>
<td>1</td>
<td>$275</td>
<td>$275</td>
</tr>
<tr>
<td>Student work hours</td>
<td>288</td>
<td>$15</td>
<td>$4320</td>
</tr>
<tr>
<td>Advisor work hours</td>
<td>48</td>
<td>$100</td>
<td>$480</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>-</td>
<td>-</td>
<td><strong>$5075</strong></td>
</tr>
</tbody>
</table>

For a production model, many of the device components would need to be upgraded. A high powered UV laser would be necessary to kill bacteria effectively without blocking the airway for a large amount of time. The cost of one of these lasers is a minimum of approximately $10,000. Full length waveguide fibers would also be necessary, and each of which adds $200 to the cost of the device. For the lenses and other apparatus needed to focus the
laser and scatter the light at the end we estimate a cost of $200. In addition to these material costs
production hours will be necessary as well as the developmental time needed to make the device
functional. This development time was estimated by taking the amount of time necessary to
create our current prototype and multiplying by four to allow for a two year development time.
An estimate for all costs in the process of producing the first finished device is below in Table 3
with a total of $46,880.

Table 3: Cost of first Production Device

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost per Item</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Laser</td>
<td>1</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Hollow Waveguide</td>
<td>1</td>
<td>$200</td>
<td>$200</td>
</tr>
<tr>
<td>Lenses and Scatter System</td>
<td>1</td>
<td>$200</td>
<td>$200</td>
</tr>
<tr>
<td>Student work hours</td>
<td>1152</td>
<td>$15</td>
<td>$17,280</td>
</tr>
<tr>
<td>Advisor work hours</td>
<td>192</td>
<td>$100</td>
<td>$19,200</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>-</td>
<td>-</td>
<td><strong>$46,880</strong></td>
</tr>
</tbody>
</table>

Conclusions

A promising strategy for killing VAP-causing bacteria in pediatric ETTs has been
determined to be irradiating the inside of the tube with UV light. We have identified a hollow
waveguide fiber which is capable of transmitting UV light down an ETT with a minimum loss in
power and is capable of fitting down the smallest ETT in use in PICUs. The necessary power of
the light exiting the waveguide within the ETT was determined as well as the amount of power
lost through coupling and due to the waveguide itself. A relationship between the amount of
power exiting the waveguide and the necessary duration of irradiation necessary to kill the bacteria was established. The concept has been proven to be viable through experiments and extensive research, and the device has been determined to be economically beneficial.

**Future Work**

This year’s progress has given this project and design a good base from which to continue. However, there is still a large amount of future development to be completed. The funding was not available this year to buy a UV wavelength laser which is necessary to achieve the light intensity needed to make the device usable. Once the laser is purchased, it will need to be coupled to a new waveguide in a stable and mobile fashion. The new waveguide should be purchased from Doko Engineering Inc. located in Sendai, Japan. They hold the US patent for the waveguides and are currently the only distributor of this particular product. An important aspect in the next version of the device is the light scattering system located at the end of the waveguide. The system needs to be designed and adapted to fit on the end of the hollow waveguides without causing another large amount of light loss and without hindering the ability of the waveguide to travel down the ETT. Additional improvements also include the addition of a nitrogen gas stream on the inside of the waveguide to eliminate the absorption of the UV light by ozone and research into the most effective procedure for device use. The ETT should not be obstructed nor should the patient be kept off of the ventilator for more than about 15 seconds at the time. Therefore, it may be necessary to use multiple 15 second procedures to insert and remove the waveguide from the ETT. A schematic of the envisioned future device can be seen in Figure 13. Finally, because the waveguides have a limited flexibility, research may be completed to determine if placing the child’s head in the sniffing position described by Adnet et.al. is beneficial. The study found that by tilting the patient’s head back, the mouth axis, the pharyngeal
axis, and the laryngeal axis are better aligned as shown in Figure 14. This will hopefully reduce the amount the waveguides are expected to bend.

Once all of the previous steps have been taken, the device needs to be tested against the bacteria lining the walls of actual endotracheal tubes. This can be done by swabbing the inside of the endotracheal tubes before and after irradiation with our device. These swabs would then be cultured to determine colony counts and the efficacy of the device thus measured. Once the device is determined to be effective enough for clinical use a manufacturing partner needs to be identified and approached to build these devices. Once the manufacturing has taken place the devices need to be brought to the FDA for approval, a process which could take between months and years. For this approval all previous steps need to be well documented. After FDA approval the device can be marketed to hospitals around the country. At that point the device will prove its effectiveness by saving lives.

Ethical Concerns

The patient may become very uncomfortable during the procedure. It is important that the insertion of the sterilization device take the shortest time possible to minimize the patient’s discomfort from disruption of oxygen flow. The patient’s breathing will be temporarily impaired when the wand is inserted in the trachea.
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