Use of the Carbon Dioxide Laser for Tracheobronchial Lesions in Children

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Importance: Obstructing tracheobronchial diseases in children can be treated by a variety of techniques. The nonfiberoptic delivery of the carbon dioxide laser coupled to a rigid bronchoscope has rarely been described for this purpose and has unique advantages over other treatment methods.

Objectives: To report the indications, safety, efficacy, and limitations of the carbon dioxide laser delivered through a rigid bronchoscope for tracheobronchial lesions in the pediatric population.

Design: Case series of patients undergoing treatment for tracheobronchial lesions at a single institution from December 2, 2001, through December 14, 2011.


Participants: Seventeen patients aged 3 months to 17 years with endotracheal and endobronchial disease.

Intervention: Carbon dioxide laser treatment through a rigid bronchoscope.

Main Outcome Measures: Reduction in tumor burden or improvement of ventilation.

Results: A total of 234 laser bronchoscopies were performed on 17 patients. Mean operative time was 29 (range, 2-89) minutes. Blood loss and complications were minimal. Sixteen patients received carbon dioxide laser delivered through a rigid bronchoscope with a proximal coupler or flexible fiber. The most common indication was tracheobronchial granulation tissue (n=10), followed by prolapsed cartilage causing tracheal obstruction (n=3), recurrent respiratory papillomatosis (n=2), and granular cell tumor (n=1). Of these patients, 15 (94%) underwent successful treatment. One patient was treated electively with the Nd:YAG laser owing to a vascular malformation.

Conclusions and Relevance: The carbon dioxide laser delivered through a rigid bronchoscope is a suitable tool for managing nonvascular endotracheal and endobronchial lesions in the pediatric population. Its unique wavelength properties offer a safe, effective alternative to other lasers and open resection.

MANAGEMENT OF ENDO-TRACHEAL AND ENDO-BRONCHIAL LESIONS IN CHILDREN IS A CHALLENGING CLINICAL PROBLEM because the smaller pediatric anatomy requires precision and preservation of underlying structures. Bronchoscopy is essential in determining the lesion type and exact location in the airway.

The rigid bronchoscope consists of an open metal tube through which ventilation is maintained for airway control. In comparison, the flexible bronchoscope is thinner and longer and contains fiberoptic bundles capable of light and image transmission. Ventilation cannot take place through a flexible bronchoscope but must be accomplished alongside it. In children, rigid and flexible bronchoscopy are usually performed under general anesthesia. Channels for suctioning and instrumentation are often present in both endoscopes; however, the channel diameter in the flexible bronchoscope is significantly smaller.

More than 40 years have passed since Polayni et al reported the first endoscopic application of the carbon dioxide laser. Since the addition of a coaxial helium-neon beam, visualization of the laser path allowed its use in a wide variety of diseases. Although the carbon dioxide laser has gained international acceptance in laryngeal applications, its ability to perform beyond the immediate subglottic airway has yet to gain wide acceptance. Moreover, current literature on the status of the carbon dioxide laser in the distal pediatric airway is sparse. To our knowledge, the last report on bronchoscopic carbon dioxide laser treatment for children with tracheobronchial disease was more than a decade ago. In this retro-
pective case series, we present our 10-year experience with the carbon dioxide laser coupled to a rigid bronchoscope for the treatment of endotracheal and endobronchial disease in the pediatric population. We describe the safety, efficacy, indications, and limitations of this technique and discuss variables that influence laser-tissue interactions.

**METHODS**

Institutional review board approval from Children's Hospitals and Clinics of Minnesota was granted. We identified 17 patients who received laser bronchoscopy for distal airway lesions from December 2, 2001, through December 14, 2011. Lesions were limited to the trachea and upper bronchi. We excluded patients who received laser treatment solely via the laryngoscope and then removed before laser use. Magnification through the laser coupler was used during laser application. Ventilation was maintained through the rigid bronchoscope and was intermittent during laser firing to ensure accuracy. To minimize the risk of airway fire, the fraction of inspired oxygen was maintained at less than 30%, and nonflammable general anesthetics were used. Only metal instruments were used to avoid potential sources of combustion. A helium-neon light was used as an aiming beam, and the laser was tested for precise alignment before each operation. Standard laser precautions were observed that included protection of the patient's skin and oral region with saline-soaked material, eye shields, wavelength-specific eyeglasses, airway fire prevention, and signs indicating active laser use.

The laser was delivered through an appropriately sized pediatric rigid laser bronchoscope, which ranged in inner diameter from 3.5 to 6.0 mm. A metal suction catheter was placed down the lumen of the endoscope for the removal of fluid and debris only when the laser was in standby mode. The secondary suction port on the bronchoscope was used during laser treatment to evacuate smoke. When necessary, laser therapy was combined with mechanical debridement or use of the rigid bronchoscope itself to remove masses. Circumferential laser application was avoided diligently to prevent scar formation.

A total of 234 laser bronchoscopic procedures were performed in 17 pediatric patients, including 9 boys and 8 girls. The mean age of the patients at the first procedure was 4.7 years (range, 3 months to 17 years). The mean duration of the procedures was 29 (range, 2-89) minutes. Patient demographics, indications for laser therapy, the number of procedures performed, and the results are presented in the Table. Patients who did not undergo follow-up endoscopies were monitored for symptom recurrence. Patient 17 had a vascular malformation and underwent Nd:YAG laser treatment.

Ten of the 17 patients received laser treatment for granulation tissue formation secondary to posttraumatic causes, such as tracheotomy or tracheal reconstruction. For the group of patients, 5 (50%) had the granulation formation around the tracheotomy site, and a mean of 1.2 laser sessions were needed to achieve symptom or lesion resolution. Three patients underwent laser ablation for prolapsed cartilage causing tracheal obstruction, and all were successfully treated after 1 laser session.

The diagnosis requiring the most laser sessions was recurrent respiratory papillomatosis of the trachea and bronchi. Although only 2 of our patients had this chronic disease, these cases accounted for 197 of the 234 procedures (84.1%). The mean duration of time between each session was 27.5 (range, 6-124) days. Given the propensity of the papillomas to recur, the emphasis was on maintaining a patent airway for longer symptom-free intervals. Because complete tumor resolution was unachievable owing to the nature of the disease, laser treatment was understood to be palliative only.

Management of the granular cell tumor in a single patient produced an 8-month interval without obstructive symptoms. When tumor recurrence with extension into the mediastinum was detected, he underwent further treatment with tracheal resection and median sternotomy. This patient was the only one in our study population who underwent carbon dioxide laser therapy and did not meet the criteria for successful treatment.

The carbon dioxide laser was set to a mean power of 12.5 (range, 5-18) W and was delivered using a 0.5-second pulse duration and a 0.5-second pulse interval. Intraoperative complications were limited to the loss of a posterior mandibular tooth and 1 misfiring of the laser beam. No significant complications, such as perforation, airway fire, or blood loss of greater than 20 mL, occurred during any procedure.

The hallmark of the carbon dioxide laser is its precision. With a minute extinction depth of 30 µm, the laser emits light in the invisible electromagnetic spectrum at a wavelength of 10.6 µm and produces negligible scattering. These properties keep thermal diffusion to adjacent tissue minimal. The carbon dioxide laser possesses a high water-absorption coefficient (250 cm⁻¹) that makes it readily absorbed by soft tissue in a color-independent manner. Vaporization of extracellular and intracellular water is attained at 100°C and is followed by carbonization of the residual organic matter. Therefore, tissues with higher water content, such as a polyp or fresh papilloma, will react more readily to the laser than will scar tissue or a fibrosed papilloma.

The radiant exposure concept depicts the relationship between power density and the time of laser use. The power density or irradiance (measured in watts per square centimeter) of the light dictates the beam's power based on its ability to be focused to a concentrated area, rather than its absolute intensity (measured in watts). When the irradiance is multiplied by exposure time, it is termed...
fluence (measured in joules per square centimeter). This high energy becomes the surgeon’s tool for tissue ablation. The burn imprint area increases with the power and duration of exposure, with the latter being more pertinent in the conduction of heat to surrounding tissues.\(^6\) A shorter pulse decreases the zone of adjacent thermal necrosis. The total amount of light received by tissue after 1 second can be numerically identical in a pulsed or a continuous mode; however, when compared with a continuous wave, the pulsed mode facilitates greater cooling of tissue before the next impact, thus minimizing thermal overlap and collateral tissue damage.\(^7\) Laser settings should be adjusted according to the lesion and procedure goal. A laser delivered at high power in a short time frame will minimize charring and thermal diffusion, whereas a low power setting used for a longer duration may be preferable for coagulation.

One limitation of the carbon dioxide laser is its inability to coagulate vessels with a caliber greater than 0.5 mm. For our patient who presented with a vascular malformation, we elected to use the Nd:YAG laser, which has a wavelength of 1.064 μm near the infrared spectrum of light. As such, the light is preferentially absorbed by hemoglobin and can provide coagulation of blood vessels as thick as 5 mm in diameter. However, the Nd:YAG laser is less predictable when it comes to depth of penetration. The high degree of forward and backward scatter can generate thermal injury as deep as 4 mm from the impact site. Although tissue penetration can be reduced by applying the Nd: YAG laser in brief, repeated bursts, the risk of transmural injury to underlying vascular structures remains high.\(^8\)–\(^10\)

In the absence of highly vascular lesions, the carbon dioxide laser consequently is considered the laser of choice for pediatric airway applications.\(^11\)

The search for a balance between hemostasis and tissue integrity has prompted research into other wavelengths. Rimell and colleagues\(^12\) reported their experience with pediatric tracheobronchial lesions using the potassium titanyl phosphate fiber laser. The light is absorbed by hemoglobin and pigmented tissue with an approximate penetration depth of 0.9 mm. Akin to our experience, most of their subjects presented with granulation tissue that was laser ablated with few complications. However, the potassium titanyl phosphate laser generates twice as much tissue necrosis as that seen with the carbon dioxide wavelength.\(^13\) More recently, the continuous-wave thulium laser has been introduced as a possible substitute for the carbon dioxide laser. With a wavelength

<table>
<thead>
<tr>
<th>Patient No./Sex/Age at First Procedure</th>
<th>Age at Last Procedure</th>
<th>Indication</th>
<th>Site of Lesion</th>
<th>No. of Laser Sessions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/F/3 mo</td>
<td>4 mo</td>
<td>GT from tracheoesophageal fistula repair</td>
<td>Distal trachea</td>
<td>2</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>2/F/4 mo</td>
<td>5 mo</td>
<td>GT from slide tracheoplasty</td>
<td>Distal trachea along suture line</td>
<td>3</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>3/F/1 y 5 mo</td>
<td>Same</td>
<td>GT from slide tracheoplasty</td>
<td>Distal trachea</td>
<td>2</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>4/M/9 mo</td>
<td>Same</td>
<td>GT at tracheostomy site</td>
<td>Suprastomal</td>
<td>1</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>5/M/1 y 11 mo</td>
<td>Same</td>
<td>GT at tracheostomy site</td>
<td>Suprastomal</td>
<td>1</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>6/F/2 y 8 mo</td>
<td>Same</td>
<td>GT at tracheostomy site and from tracheal reconstruction</td>
<td>Distal end of tracheostomy tube, posterior trachea</td>
<td>1</td>
<td>Remained asymptomatic</td>
</tr>
<tr>
<td>7/M/4 y 1 mo</td>
<td>Same</td>
<td>GT at tracheostomy site</td>
<td>Suprastomal</td>
<td>1</td>
<td>Remained asymptomatic</td>
</tr>
<tr>
<td>8/M/9 y 6 mo</td>
<td>Same</td>
<td>GT from partial lung resection</td>
<td>Trachea</td>
<td>1</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>9/M/11 y 3 mo</td>
<td>Same</td>
<td>GT from prolonged intubation</td>
<td>Proximal trachea</td>
<td>1</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>10/F/17 y</td>
<td>Same</td>
<td>GT at tracheostomy site</td>
<td>Tip of tracheostomy</td>
<td>2</td>
<td>Some residual disease but noneobstructive</td>
</tr>
<tr>
<td>11/F/4 mo</td>
<td>Same</td>
<td>Tracheal obstruction from prolapsed cartilage</td>
<td>Bilateral collapse of lateral anastomotic sites in trachea</td>
<td>1</td>
<td>No evidence of residual disease on endoscopy</td>
</tr>
<tr>
<td>12/M/1 y 1 mo</td>
<td>Same</td>
<td>Tracheal obstruction from prolapsed cartilage</td>
<td>Prolapsed cartilage of left distal lateral tracheal wall at site of sliding tracheoplasty</td>
<td>1</td>
<td>No evidence of significant stenosis, remained asymptomatic</td>
</tr>
<tr>
<td>13/F/1 y 7 mo</td>
<td>Same</td>
<td>Tracheal obstruction from prolapsed cartilage</td>
<td>Right inferior tracheal collapse of stoma site</td>
<td>1</td>
<td>Mild residual tracheal stenosis, remained asymptomatic</td>
</tr>
<tr>
<td>14/F/1 y 3 mo</td>
<td>6 y 3 mo (ongoing)</td>
<td>RRP</td>
<td>Stoma, trachea, carina</td>
<td>72</td>
<td>Improved ventilation</td>
</tr>
<tr>
<td>15/M/11 y 10 mo</td>
<td>21 y 8 mo (ongoing)</td>
<td>RRP</td>
<td>Stoma, trachea, carina, both mainstem bronchi</td>
<td>125</td>
<td>Improved ventilation</td>
</tr>
<tr>
<td>16/M/11 y 5 mo</td>
<td>12 y 1 mo</td>
<td>Granular cell tumor</td>
<td>Anterior trachea</td>
<td>4</td>
<td>Asymptomatic for 8 mo before extratracheal tumor regrowth</td>
</tr>
<tr>
<td>17/M/2 y 7 mo</td>
<td>3 y 10 mo</td>
<td>Vascular malformation</td>
<td>Distal trachea, carina, left mainstem bronchus</td>
<td>15</td>
<td>Symptom recurrence</td>
</tr>
</tbody>
</table>

Abbreviations: GT, granulation tissue; RRP, recurrent respiratory papillomatosis.

\(^a\)Patient 17 underwent bronchoscopy with the Nd:YAG laser; all others underwent carbon dioxide laser treatment.
of 2.013 μm and a target chromophore of water, it has found a niche in office-based laryngeal laser surgery for adults.14 Indications for use in the pediatric airway in 1 series included laryngomalacia, laryngeal cysts, vocal cord palsy, tracheal hemangioma, and papillomatosis.15 The thulium laser offers improved hemostasis at the cost of greater thermal damage. The laser was initially designed to offer a fiber-based alternative to rigid carbon dioxide laser bronchoscopy.16

Fiberoptic lasers purportedly offer the capacity to aim around tight bends and vaporize lesions in distal, difficult-to-reach areas of the tracheobronchial tree. A flexible hollow-core, photonic, bandgap fiber with omnidirectional mirrors has been developed for the delivery of carbon dioxide laser.17 From our experience, the fiber-based laser may be preferable for tangential dissection involving difficult angulations, particularly for en bloc resection of masses. Still, the nonfiberoptic delivery system allowed us to ablate lesions as distal as the third-generation bronchial segment. One study10 noted that traditional carbon dioxide laser bronchoscopy was used with minimal difficulty in the trachea of neonates as young as 1 day. In our opinion, the fiber's aiming beam has inferior focusing capabilities when compared with the rigid micropost laser system. The shortcomings of the fiber delivery system include loss of collimated and coherent light. Each nonreusable fiber is costly, and more than 1 fiber may be needed for bulkier lesions. When the fibers reach higher temperatures, they can break off and dislodge in the airway. Most important, laser delivery through a flexible bronchoscope carries a significant risk of fire because the bronchoscope itself is combustible.

The advantages of rigid laser bronchoscopy are the ability to palpate the tumor-cartilage interface, control ventilation, and provide a direct tamponade in cases of hemoptysis. The wider lumen of the rigid bronchoscope allows for access of larger surgical equipment, which may be required for airway stent placement or foreign body removal. In our experience, the rigid bronchoscope was used to dilate stenoses mechanically and debulk masses when necessary. We found no need to use vocal fold distracters for subglottal and high tracheal lesions with the laser bronchoscopy equipment readily available. Also, the bronchoscope allows for more controlled ventilation because it acts as an endotracheal tube. With growing interests in newer instrumentation and a fiber-based mode of delivery for the carbon dioxide laser, large-scale comparisons with the traditional coupler system deserve more investigation.

The most current literature on bronchoscopic carbon dioxide laser treatment for tracheobronchial disease in children was by Ayache et al12 in 2000. Their group experienced similarly high success rates and minimal complications with this technique. Overlapping indications included posttraumatic tracheobronchial granulomas and tumors. Our report adds 2 new indications to the literature, which are tracheal obstruction from prolapsed cartilage and recurrent respiratory papillomatosis.

Ayache et al12 and other groups18,19 have described poor prognostic factors for treatment with laser bronchoscopy, including circumferential stenosis of greater than 1 cm, collapse of the cartilaginous support of the airway, carinal involvement, and extratracheal involvement. Our results challenged some of these observations, because we were able to treat tracheal obstruction caused by collapsed cartilage effectively in 3 patients without long-term recurrence. We also excised lesions of the carina without complications in both patients with recurrent respiratory papillomatosis. The mainstay of treatment for this disease is surgical ablation of all visible papillomas with the carbon dioxide laser. In their study of more than 200 patients with respiratory papillomas undergoing carbon dioxide laser treatment, Dedo and Yu20 suggested that treatment should be limited to every 2 months to avoid scar tissue formation from the laser treatment process. Extrinsically compressed of the trachea or bronchus has been cited as a contraindication to the procedure,21 and our experience supports that extratracheal involvement of the tumor is a poor prognostic factor. With the realization that our patient with granular cell tumor had mediastinal extension, we discontinued laser therapy and opted for a tracheal resection.

Incidents such as airway wall perforation and exsanguinating hemorrhage from carbon dioxide laser surgery are extremely rare in the pediatric literature.22 The most feared complication of laser bronchoscopy remains major airway fire. Combustible materials are nonmetallic and include plastic suction catheters, polyvinyl endotracheal tubes, and flexible fiberoptic bronchoscopes. The nonfiberoptic delivery system lacks such fibers or materials to catch fire. A rigid ventilating bronchoscope obviates the need for endotracheal tubes, which can melt and produce toxic fumes on combustion.

Practices to enhance safe delivery of the carbon dioxide laser include preoperative laser testing, switching to standby mode when appropriate, and constant communication with the anesthesiologist. Nonflammable anesthetics and the lowest concentration of oxygen to maintain saturations should be selected to decrease risk of a flash ignition. Adherence to such protocols will reduce the risk of serious complications in bronchoscopic laser surgery.

**CONCLUSIONS**

The carbon dioxide laser remains an important tool in tracheobronchial endoscopic surgery, especially in the pediatric airway, in which shallow tissue structures limit the use of deeper penetrating lasers. We successfully reduced the tumor burden and improved ventilation in most of our patients with endotracheal and endobronchial masses. The results from this series suggest that treatment with the nonfiberoptic carbon dioxide laser system provides a safe, precise method for ablation of lesions in the tracheobronchial tree, particularly granulation tissue. Although the Nd:YAG laser should be reserved for highly vascular tumors, the carbon dioxide laser can achieve hemostasis of the microcirculation and minimize thermal injury when used under optimal laser settings. A thorough understanding of laser-tissue interactions and carefully selected laser settings will augment the successful use of the carbon dioxide laser in pediatric tracheobronchial lesions.
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Author Contributions: Both authors had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Sidman. Acquisition of data: Sjogren. Analysis and interpretation of data: Sjogren and Sidman. Drafting of the manuscript: Sjogren. Critical revision of the manuscript for important intellectual content: Sidman. Administrative, technical, and material support: Sidman. Study supervision: Sidman.

Conflict of Interest Disclosures: None reported.

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REFERENCES