Role of Multidetector CT Virtual Bronchoscopy in the Evaluation of Post-tracheostomy Tracheal Stenosis - A Preliminary Study

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Abstract

Aim: To study the technique and utility of virtual bronchoscopy (virtual reality endobronchial simulation, VRES) as a tool to evaluate post-tracheostomy tracheal stenoses and to correlate the findings of virtual and invasive bronchoscopy and to follow-up treated lesions or those currently under treatment that were initially diagnosed with VRES.

Methodology: This prospective study comprised nine patients in the age group 13 to 65 years presenting with breathlessness and stridor following one or multiple tracheostomies. They underwent plain CT using a multidetector CT (MDCT) scanner (Siemens Volume Zoom) using narrow (1mm) collimation. These thin slice images were post-processed using an Irix-based workstation with a 'Fly-Through' endoscopy application. These patients also underwent a rigid (three patients) or fiberoptic (six patients) bronchoscopy.

Results: Of the nine patients that underwent VRES, five were found to have stenoses, three had obstructing granulation tissue, one had an obstructing membrane and one had synechiae. The invasive bronchoscopic findings supported the VRES diagnosis in all but one case of stenosis, one of granulation tissue and the case with synechiae. Membranes and synechiae were relatively difficult to diagnose without the corresponding axial and multiplanar images. VRES achieved a higher sensitivity, while invasive bronchoscopy a higher specificity.

Conclusions: VRES proved to be comparable to invasive bronchoscopy in the depiction of post-tracheostomy tracheal stenoses, with a notable advantage in critical stenoses in that the airway distal to the stenosis could be assessed with VRES but not with invasive bronchoscopy. A preliminary VRES was found to be of assistance in the selection of patients for the more invasive therapeutic procedures such as laser ablation of granulation tissue and its follow-up.

INTRODUCTION

Post-tracheostomy tracheal stenosis presents as sudden onset of dyspnea, stridor either as a single or multiple episodes and can even result in death. With the advent of compliant, high-volume, low-pressure cuffs, the incidence of tracheal stenosis following intubation has fallen from 20% in the past, to as low as 1%.1 There are two principal types of strictures that occur after intubation: strictures at the site of the endotracheal tube cuff, which is the most common location of postintubation stenosis, and those that occur at the site of a tracheotomy stoma.1 It can occur in etiologies and indications for tracheostomy as diverse as potentially curable conditions such as tetanus, ARDS, poisoning2 and potentially bad prognosis conditions like carcinoma larynx. It is important to recognize this high-risk subset of patients, so that appropriate, early intervention may be directed towards preventing further life-threatening events.

VRES is a non-invasive medical imaging technique computed using data obtained from thin section axial CT scans of the airways.3,4 The data is presented as if visualized from an internal perspective to simulate an endoscopic procedure. VRES has a role in planning endobronchial therapy (e.g. laser ablation of granulation tissue, balloon dilatation and stent placement5). Hence, we studied the utility of VRES as a tool to evaluate...
post-tracheostomy tracheal stenoses and to correlate the
findings of virtual and invasive bronchoscopy.

**MATERIAL AND METHODS**

**Study Group**

The present study was conducted prospectively over a
twelve month period. Nine post-tracheostomy patients
ranging in age from 13 to 65 years referred for symptoms of
stridor and breathlessness were included in our study. Five
patients had undergone a single tracheostomy, three
underwent two tracheostomies and one underwent three
tracheostomies. The preceding conditions and indications
for doing tracheostomy were as enumerated in Table 1. These
patients also underwent fiberoptic (six patients) and rigid
(three patients) bronchoscopy, and these findings were used
to generate comparative data.

**Scan Protocol and Parameters**

Thin-slice axial CT scans of the neck and upper chest
were obtained for nine patients. In keeping with the medical
urgency associated with the condition at the time of
presentation, volume data acquisition was limited to include
the main-stem bronchi and VRES was obtained for a maximum
distance up to the carina, i.e. well beyond the site of tracheal
obstruction. The 3D data set of the airways was derived from
diagnostic imaging data and displayed on a computer.

Patients first underwent plain, non-enhanced CT scans of
the neck and upper chest using a Multidetector CT Scanner
(Siemens, Volume Zoom, Siemens Corp., Siemensstrasse,
Forchheim, Germany), followed by transfer of these images
to a workstation for post-processing.

**Volume Data Acquisition Technique**

Patients were given adequate breathhold instructions and
were scanned without contrast. Five millimeter slices with a
collimation of 1mm were acquired (resolution of 1 mm or less,
so that fine detail can be observed) with a multidetector CT
scanner, with a single breathhold of 28.96 seconds and a
rotation time of 0.5 seconds using an effective mAs of 100
and a kV of 140. Patients were scanned in a caudocranial
direction to reduce respiratory artifacts. The acquired images
were then reconstructed in 1mm slice thickness.

Sedation was used only for children and trauma patients,
under guidance of an anesthetist. For the former, Trichlofos
(100mg/ml, American Remedies) 50 mg/kg p.o. or IV
Midazolam 0.04mg/kg were used. For trauma patients, IV
Diazepam was used with apnea during the scan period.

**Hardware**

VRES was performed using a Fly-through Virtual
Endoscopy package using an Irix based workstation-3D
Virtuoso, an SGI O2 workstation (Silicon Graphics, Mountain
View, CA). The operating system used was Irix 6.5.2m with
Common Desktop Environment (CDE). The workstation was
equipped with 512 MB of RAM and a 4GB hard disk drive.

**Software**

The Fly-Through Virtual Endoscopy application package
used allows medical data to be visualized in multiple modes:
volume rendered, surface rendered and multiplanar reformats
(MPRs i.e. 2D projection images in standard orthographic
directions, as well as ‘curved’ reformats), in an integrated
fashion.

Virtual endoscopic views of the segmented data can be
generated using surface shaded display (SSD) techniques.
Also, virtual endoscopic views of the raw volume data can
be generated using volume-rendering techniques (VRT).
Segmentation creates 3D solid objects of the anatomy that is

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Gender</th>
<th>Age</th>
<th>Preceding condition(s)</th>
<th>Indication for tracheostomy (symptoms)</th>
<th>No. of Tracheostomies/ Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>18y</td>
<td>OPC poisoning</td>
<td>Stridor</td>
<td>One, 28 days</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>75y</td>
<td>Total laryngectomy for carcinoma larynx</td>
<td>Breathlessness with discharge from tracheostomy site</td>
<td>One, 45 days</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>24y</td>
<td>Vehicular accident; dashboard injury to neck and complete tracheal rupture</td>
<td>Suturing of anterior wall of trachea to posterior wall and vice-versa, O₂ saturation falling</td>
<td>Two; 1st for 120 days, 2nd after granulation excision</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>20y</td>
<td>OPC poisoning</td>
<td>Stridor</td>
<td>Two; 1st tracheostomy for 28 days after poisoning and 2nd for decanulation stridor</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>18y</td>
<td>Accidental strangulation (with a dupatta on a two-wheeler)</td>
<td>Stridor</td>
<td>Three; 1st for 4 days, 2nd for 7 days done for decanulation stridor, 3rd done for sudden late onset stridor 182 days later.</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>14y</td>
<td>Trauma</td>
<td>Stridor</td>
<td>One, 26 days</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>13y</td>
<td>Trauma with tracheal tear</td>
<td>Stridor post-repair</td>
<td>One, 42 days</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>65y</td>
<td>Carcinoma larynx with laryngectomy</td>
<td>Stridor</td>
<td>One, 36 days</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>23y</td>
<td>OPC poisoning</td>
<td>Stridor</td>
<td>Two; 1st for 7 days followed by decanulation stridor, 2nd for 3 days.</td>
</tr>
</tbody>
</table>

OPC - organophosphorus compounds.
An algorithm is then used to generate a surface at a set threshold at the boundary between the detected lumen and the adjacent undetected border voxels (the ‘wall’ of the structure). This process makes use of the large attenuation gradient between the bronchial wall and the air-containing lumen. The procedure is a technique for real time display wherein the images are updated in real time during the fly through endoscopy i.e. as the operator navigates through the airway; the global map display gets updated simultaneously.

We found it useful to grade stenosis subjectively into mild, moderate, severe (Fig. 1) and total occlusion, based on the VRES images.

All observations were made by an experienced radiologist and endoscopist who were blinded to each others results.

**RESULTS**

Nine patients underwent a total of 13 VRES examinations. Table 2 lists the findings on VRES and invasive bronchoscopy. Six patients had stenoses, but only five were diagnosed by VRES and four by invasive bronchoscopy. Granulation tissue was diagnosed more often by VRES than by invasive bronchoscopy. Synechiae, found on VRES in one patient, proved to be a false-positive finding. A membrane was diagnosed by both modalities. Seven patients had more than one finding at final diagnosis, while two were normal. The sensitivity, specificity and error rates for each diagnostic modality have been tabulated above. Overall, VRES achieved a higher sensitivity, while invasive bronchoscopy a higher specificity.

As seen in Table 3, our VRES findings correlated well with findings of fiberoptic and rigid bronchoscopy in patients with granulation tissue. However, the diagnosis of granulation tissue could be made with confidence only on comparison with axial (Fig. 2) and multiplanar reconstructions. VRES was stored as binary bit volumes.

In addition, features such as cross-references to standard two-dimensional projections, orientation cube and a virtual light source help the operator navigate through the airways and at the same time provide adequate orientation. Stereoscopic viewing provides enhanced depth perception and a realistic 3D effect to the endobronchial simulations. These images may be viewed in stereo on the computer monitor during a fly through while wearing liquid crystal display (LCD) glasses.

The diameter of the endoscope can be altered when required. This enables the operator to navigate small-diameter third generation bronchi in children and at least the fourth generation bronchi in older children and adults. In addition, the viewing angle, VRT depth and endoscope speed can be altered to suit situations and preferences. The endoscope can be advanced, withdrawn and turned in steps. The collision correction feature alerts the operator against wall collisions. The entire VRES image can be rotated by moving the orientation cube or by simply using the image rotate feature.

Annotation, measurement and other such tools permit computation of various data parameters and complete the armamentarium of aids for a detailed VRES study. The VRES images thus generated can be saved as stills or in a cine format.

**Generation of the VRES image**

A representative voxel is selected from the data set and is called a ‘seed’ voxel. All voxels connected to the seed and within a specified threshold range are recursively selected until the entire lumen is detected. A ‘marching cubes’ algorithm is then used to generate a surface at a set threshold at the boundary between the detected lumen and the adjacent undetected border voxels (the ‘wall’ of the structure). This process makes use of the large attenuation gradient between the bronchial wall and the air-containing lumen. The procedure is a technique for real time display wherein the images are updated in real time during the fly through endoscopy i.e. as the operator navigates through the airway; the global map display gets updated simultaneously.

We found it useful to grade stenosis subjectively into mild, moderate, severe (Fig. 1) and total occlusion, based on the VRES images.

All observations were made by an experienced radiologist and endoscopist who were blinded to each others results.
found to be of value in the pre-treatment assessment of subglottic stenosis and upper airway stenosis as for example in our patients with post-tracheostomy stridor. In these situations, correlation with cross reference axial and MPR images and especially 3D SSD and VRT images for subglottic stenosis was found to be useful. 3D SSD images, taken in isolation however, were found to underestimate the stenosis. Thus, for the evaluation of stenoses, a combination of various types of image formats is recommended. This was also noted in another patient who developed a membrane (Fig. 3), which was diagnosed with confidence only after comparison with coronal and sagittal images.

**DISCUSSION**

Of the six patients who had stenoses, five were diagnosed by VRES as against four by invasive bronchoscopy. This was principally because the latter could not be negotiated past an incomplete obstruction, where the symptom-producing stenosis was. VRES could easily surmount this hindrance. VRES however, missed one stenosis as it was subtle and not readily appreciated even on axial and multiplanar images. Also, obstructing granulation tissue was missed more often by invasive bronchoscopy (two patients) than by VRES (one patient). This was probably due to the fact that VRES images were supported by axial and multiplanar reformats in arriving at this diagnosis. The inability of VRES to define surface characteristics led to the false diagnosis of synechiae in one patient with strings of viscid mucus (Fig. 4). A membrane was diagnosed by both modalities, though more easily by invasive bronchoscopy due to the superior depth perception it affords and its dynamic nature viz. the movement of the membrane with respiration. Again, coronal and sagittal MPRs came to the rescue of VRES in the demonstration of this membrane, without which it would have been overlooked thus re-emphasizing the integral role of axial and MPR images in a VRES study. Overall, VRES achieved a higher sensitivity, while invasive bronchoscopy a higher specificity.

VRES has been studied in animal models but human studies of post-tracheostomy tracheal stenosis employing MDCT-generated VRES are not reported. Eliashar et al evaluated laryngotracheal stenoses in canine models using VRES generated with a spiral CT scanner and found these simulations to be superior to regular endoscopy, in that they were better for depiction of structures that are complex or tortuous, like the trachea and bronchi. They found that VRES can depict very narrow stenotic segments and distal parts of laryngotracheal lesions that cannot be reached by a conventional endoscope because of proximal airway obstruction.
subtle mucosal lesions. One of our patients was found accurate for the demonstration of mucosal discoloration and granulation tissue for subsequent laser excision. It is useful in the post-operative evaluation of these stents and decision-making and the post-operative follow-up of patients with airway malignancies. VRES also obviates the need for general anesthesia, especially so in children. VRES not only demonstrates granulation tissue and high-grade stenoses well, but is also excellent for the visualization of the distal airway. Often, a fiberoptic or rigid bronchoscope cannot be negotiated past such obstructions. Quantification of the visual information is possible with VRES. A bronchoscope, on the other hand, cannot provide adequate quantification: the inherent perspective distortion of invasive bronchoscopy makes it difficult to assess distance and length correctly even when the structures are unobstructed. Further, with VRES, there is no restriction on the viewing direction and the operator can view the distal end of a stenotic lesion by retroflexing the virtual scope ("retroscopy"). The operator can also track his or her 3D position during navigation.

The advantages of VRES give way to numerous definitive therapeutic options. Quantitative information derived from VRES can be used to design an effective intraluminal stent, and the sites of airway anastomoses. It also helps localize obstructions. Quantification of the visual information is possible with VRES. A bronchoscope, on the other hand, cannot provide adequate quantification: the inherent perspective distortion of invasive bronchoscopy makes it difficult to assess distance and length correctly even when the structures are unobstructed. Further, with VRES, there is no restriction on the viewing direction and the operator can view the distal end of a stenotic lesion by retroflexing the virtual scope ("retroscopy"). The operator can also track his or her 3D position during navigation.

The advantages of VRES give way to numerous definitive therapeutic options. Quantitative information derived from VRES can be used to design an effective intraluminal stent, and the sites of airway anastomoses. It also helps localize granulation tissue for subsequent laser excision. VRES was found to have limitations in that it was not accurate for the demonstration of mucosal discoloration and subtle mucosal lesions. One of our patients was found to have synechia on VRES. However, the fiberoptic bronchoscopy was normal, and what had appeared to be synechia on VRES were actually strings of viscid secretions (Fig. 4). Invasive bronchoscopy provides high-resolution frontal video images, which provide detailed information on surface characteristics (high-resolution CT technology provides voxel resolutions on the order of 1 mm, whereas the resolution of bronchoscopic video is better than 0.1 mm per pixel). Generation of zigzag artifacts in young, tachypneic patients due to rapid respiratory motion could be a disadvantage. Thus, the quality of VRES images in children and in those with stridor is lower than that of adult VRES images. Cardiogenic motion artifacts also tend to degrade image quality.

Various techniques have been employed to overcome these limitations. Respiratory and cardiogenic motion artifacts in the pediatric patient population were partially overcome with the use of a sub-second MDCT scanner. In addition, axial images, in conjunction with coronal and sagittal MPRs help predict the presence of the zigzag artifacts and thus prevent misinterpretation of the VRES study. In conjunction with VRES images, they proved indispensable for enhancing diagnostic accuracy in doubtful cases.

To conclude, VRES accurately depicted post-tracheostomy tracheal or subglottic stenosis, granulation tissue and tracheal membranes. Viscid secretions on VRES can masquerade as synechia and intraluminal granulation tissue needs axials and MPRs for confident diagnosis. A significant advantage over rigid or fiberoptic bronchoscopy in that it demonstrates distal airways better without the need for anesthesia.

Although there is a striking similarity between their images, VRES was found to be complementary to fiberoptic and rigid bronchoscopy. It is a useful, noninvasive modality for screening of patients before invasive bronchoscopy and for those patients who are not amenable to invasive bronchoscopy, a feature useful for pre and post-operative evaluation, decision-making and follow-up.

Our study is the first report describing the role of MDCT-generated VRES for the diagnosis of post-tracheostomy tracheal stenosis in a series of nine patients and should pave the way for future studies employing larger cohort sizes.

### References

1. Whited RE: A prospective study of laryngotracheal sequelae

### Table 3: Comparative findings on VRES and invasive bronchoscopy with the definitive treatment in each case

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Gender</th>
<th>Age</th>
<th>VRES</th>
<th>Fiberoptic / rigid bronchoscopy</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>18y</td>
<td>Granulation tissue with stenosis</td>
<td>FB: Granulation tissue with stenosis</td>
<td>Laser excision with silastic tube for 12 months</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>75y</td>
<td>Synchiae</td>
<td>Normal FB</td>
<td>Permanent tracheostomy</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>24y</td>
<td>Prior to tracheostomy, inspissated material seen in bronchus while after it, granulation formed twice.</td>
<td>RB. Granulation tissue</td>
<td>Laser excision of granulation tissue</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>20y</td>
<td>1st VRES: stenosis, 2nd: thin membrane below tracheostomy tube</td>
<td>FB. Thin, mobile membrane</td>
<td>Membranectomy followed by insertion of special tracheostomy tube</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>18y</td>
<td>1st VRES: stenosis, 2nd: normal</td>
<td>FB: stenosis (before 1st VRES)</td>
<td>1st laryngofissure after FB, 2nd laryngofissure after 1st VRES</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>14y</td>
<td>Normal</td>
<td>RB. Normal</td>
<td>Nil</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>13y</td>
<td>Subglottic stenosis</td>
<td>RB. Subglottic stenosis</td>
<td>Dilatation</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>65y</td>
<td>Normal</td>
<td>FB. Normal</td>
<td>Nil</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>23y</td>
<td>Stenosis</td>
<td>FB. Stenosis</td>
<td>Dilatation</td>
</tr>
</tbody>
</table>

FB=Fiberoptic bronchoscopy; RB=Rigid bronchoscopy.


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