Preliminary Assessment of Dynamic Voice CT in Post–Airway Reconstruction Patients

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Abstract

Objectives. To compare the ability of the dynamic voice computed tomography (CT) scan to characterize laryngeal function in airway reconstruction patients vs bedside endoscopic nasopharyngolaryngoscopy and videolaryngostroboscopy.

Study Design. Case series with chart review.

Settings. Pediatric tertiary care center.

Subjects and Methods. Retrospective case series of children and young adults with a history of complex airway surgeries with subsequent dysphonia. We analyzed clinical data for all patients who underwent an airway reconstruction procedure between January 1, 2010, and April 30, 2016, and also had a dynamic voice CT and bedside endoscopic exam during the same period.

Results. Twenty-four patients were analyzed (4 male, 20 female) with a mean age of 15.1 years (95% confidence interval [CI], 12.9-17.22). Patients had a mean of 2.2 airway surgeries (95% CI, 1.8-2.6), with 62.5% of them being open procedures. Laryngotracheoplasty with a cartilage graft was the most common procedure (40.0%). The pattern of laryngeal closure could be detected in all cases with the dynamic CT scan (n = 24/24, 100%) compared to 87.5% (21/24) with the standard endoscopic examination (P = .04). The location of gap closure could be detected in all cases (24/24) with the dynamic voice CT while 20.8% (5/24 patients) could not be rated with standard endoscopy/stroboscopy (P = .02). Dynamic voice CT was able to assess the vertical closure pattern of the glottis 100% (24/24) while it could be detected in 83.3% (20/24) cases with endoscopic study (P = .04).

Conclusion. Dynamic voice CT shows promise as an additional tool for evaluation of patients with a history of complex airway procedures by providing complementary information.

Keywords

dynamic voice CT, computed tomography, cine CT, voice, airway surgery, laryngotracheoplasty, VHI, pVHI, CAPE-V

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Voice disturbance following airway reconstruction has been previously described by several studies. More than half of children who undergo airway reconstruction are reported to have dysphonia, with a substantial portion with severe dysphonia. Dysphonia has been associated with social withdrawal and depression, as well as having a negative influence on social, emotional, educational, and occupational outcomes. Historically, the main measure of success for airway reconstruction has been decannulation. Given the negative impact of a poor voice, dysphonia should not be overlooked. Voice outcomes after complex airway surgeries have slowly gained popularity in the past decade.

Nowadays, voice surgery can be offered to patients to improve their voice quality. Such surgery requires planning and individualization of treatment to address anatomical and physiological changes due to their unique complex history.

Evaluation of laryngeal structures, including glottis pattern of closure and tissue vibration, is challenging in this population. The classic way to evaluate laryngeal function is to perform a bedside nasal flexible nasopharyngolaryngoscopy.

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or an oral rigid endoscopy with or without videostro- 


bscopy. Various reasons can preclude adequate visualization 


of the larynx, including patient’s cooperation and complex 


postsurgical anatomical changes. Moreover, the videostro- 


scopy can only take place if the motion being observed is 


adequately periodic, making it sometimes impossible in that 


population. Last, supraglottic phonation and collapse may 


hide the underlying vocal fold function. Such information is 


vital prior to planning a voice surgery.


Computed tomography (CT) scan has been long used to 


assess static anatomic structure, including the head and neck 


area. CT scan has been used to capture dynamic images of 


various areas, mainly described in cardiology for dynamic 


myocardial perfusion, starting in the 1980s. It has since 


been expanded to many other areas, including dynamic 


assessment in laryngology looking at vocal fold dysfunction, 


upper airway collapse, and vocal folds paralysis.


Given the potential for anatomic and physiologic changes 


following airway reconstruction, as well as the occasional 


difficulty of a complete assessment with a bedside endo-


scope, a better understanding of laryngeal mobility and post-


surgical changes would be beneficial for future voice 


surgeries. The goal of this study was to compare dynamic 


voice CT to a bedside endoscopic laryngeal function assess-


ment after complex airway surgery.


Methods


Our study design was reviewed and approved by our institu-


tion review board (IRB) prior to collecting data (IRB 2016-


3467). The records of all patients with a history of airway 


reconstruction and dynamic voice CT from January 2010 


and May 2016 were identified. All patients from this cohort 


were also seen for voice disorders at the Center for 


Pediatric Voice Disorders (a tertiary referral center) during 


the same period. Twenty-four subjects had complete data 


for all analyses. Demographic data, operative notes, endo-


scopic evaluation, and dynamic voice CT images were 


obtained. We also obtained the Pediatric Voice Handicap 


Index (pVHI) and the Consensus Auditory-Perceptual 


Evaluation of Voice (CAPE-V) at the time of the visit for 


voice evaluation after their airway reconstructions. Patients 


were excluded if there was no history of airway reconstruc-


tion or both endoscopic exam and dynamic voice CT were 


not performed in the same period. The most recent endo-


scopic exam performed by an otolaryngologist was used for 


this study. The same otolaryngologist performed and 


recorded all endoscopic exams and was thus aware of the 


vocal fold mobility status. Dynamic voice CT was then 


blindly read by a radiologist. Results of these 2 techniques 


were then compared by a third observer at separate times.


Dynamic Voice CT


Dynamic voice CT is performed in a supine position with- 


out sedation. Voice protocol starts with the patient at rest 


and then phonating the vowel “eee” for approximately 5 to 


10 seconds. Dynamic data are obtained at a rate of 3 rota-


tions per second from the hard palate to the thoracic inlet 


with a 0.35-second gantry rotation for 6 rotations and 12 


phases with half-scan reconstruction. Slice thickness is 0.5 


mm. This scan is performed with no contrast. Images are 


then combined to re-create a dynamic sequence of the laryn-


geal closure. This is possible in multiple planes, including 


axial and coronal views. Tridimensional surface-rendered 


display also provides for a view from below the vocal cords 


(Figure 1). Finally, tridimensional laryngeal reconstruction 


is possible for a general overview.


Radiation doses were 0.4 (95% confidence interval [CI], 


0.3-0.5) millisievert (mSv). Radiation exposure is less than 


the standard CT scan of the same area of anatomy. It is pos-


sible to drastically decrease the radiation dose to image the 


differences between air (which has almost no density) and 


soft tissues (which have a density slightly greater than 


water), allowing us to tolerate substantially increased noise 


in the surrounding tissues. Each study was reviewed frame 


by frame by 1 otolaryngologist and 1 radiologist with exper-


tise in interpretation of dynamic voice CT. The radiologist 


was blinded to the strobe findings.


Endoscopic Exam


Each patient underwent a transnasal flexible and/or transoral 


rigid examination. Selection of the flexible and/or rigid 


endoscope used was made by the same team’s pediatric
otolaryngologist and speech therapist, who determined the most appropriate instrument given the size of the child and the technical needs of the examination. The pediatric otolaryngologist and the speech therapist have more than 10 years of experience in pediatric laryngology and voice clinic. The same otolaryngologist and speech therapist performed all the endoscopic exams. Presentation of the flexible endoscope was made after the application of oxymetazoline hydrochloride and tetracaine hydrochloride. The phonatory tasks included connected speech, sustained “eee,” sniff-“eee,” and maximum loudness. When the rigid endoscope was used, it was the Pentax Medical (Montvale, New Jersey) 70° scope. The speech-language pathologist and otolaryngologist performed the transoral examination by having the child sit upright, extend the chin forward, and sustain the sound “eee” once the scope was in place. The standard voice evaluation includes several aspects of laryngeal function, including the source of phonation, glottic closure pattern, the presence of a gap, and the vertical closure pattern.

Statistical Analysis
For demographics and CAPE-V and pVHI variables, the 1- and 2-sided Fisher exact tests and Wilcoxon rank-sum test were used for all continuous variables, and the Kruskal-Wallis test was used for categorical variables (race, sex, comorbidities, past surgeries). Because the results were not normally distributed, significance results were obtained with the 2-sample Wilcoxon rank-sum (Mann-Whitney) test. Spearman correlation was used to assess the relation of voice parameters and voice quality. Data of the dynamic voice CT scan while 20.8% (5/24 of patients) could not be rated with the dynamic voice CT, which was similar for both the pediatric otolaryngologist and speech therapist. The localization of phonation was possible in all cases (24/24, 100%) with the dynamic voice CT scan (24/24, 100%). The pattern of glottic closure could be detected in all cases (24/24, 100%) with the dynamic voice CT while 20.8% (5/24 of patients) could not be rated with mobility. Bedside rigid oral pharyngolaryngoscopy was the most common mode of laryngeal evaluation (11/24, 45.8%). Quality of images of the dynamic voice CT were similar across all range of ages, and all patients were able to follow instructions.

Results
Twenty-four patients were analyzed (20 females, 83.3%) with a mean age of 15.1 years (95% CI, 12.9-17.22) (Table 1). The main associated comorbidity was reflux (6/24, 25%). Nine patients (9/24, 37.5%) had a history of intubation with a mean duration of 13.8 days (95% CI, 2.8-24.9). Seventy-one percent of these 7 (5/7) patients required multiple intubations. Tracheostomy was required in 8 of 24 patients (33.3%) with a mean duration of 230.0 days (95% CI, 45.8-414.2) before being decannulated. All patients (24/24, 100%) were decannulated by the time they were seen at the voice clinic. Patients had a mean of 2.2 airway surgeries (95% CI, 1.8-2.6) before being referred to our institution. Patients had thereafter a mean of 2.1 airway surgeries (95% CI, 1.4-2.6). Bedside rigid oral pharyngolaryngoscopy was the most common mode of laryngeal evaluation (11/24, 45.8%). Quality of images of the dynamic voice CT were similar across all range of ages, and all patients were able to follow instructions.

The localization of phonation was possible in all cases evaluated by the dynamic voice CT scan (24/24, 100%) while it was detected in 21 of 24 (87.5%, P = .04) with the endoscope (Table 3). The most common source of phonation was the true vocal folds, which was similar for both methods (P = .19). The pattern of glottic closure could be detected in all cases (24/24, 100%) with the dynamic voice CT while 20.8% (5/24 of patients) could not be rated with

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patients (n = 24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, female, No. (%)</td>
<td>20 (83.3)</td>
</tr>
<tr>
<td>Age (95% CI), y</td>
<td>15.1 (12.9-17.22)</td>
</tr>
<tr>
<td>Race, No. (%)</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>21 (87.5)</td>
</tr>
<tr>
<td>Black</td>
<td>2 (8.3)</td>
</tr>
<tr>
<td>Other</td>
<td>1 (4.2)</td>
</tr>
<tr>
<td>Comorbidities, No. (%)</td>
<td></td>
</tr>
<tr>
<td>Reflux</td>
<td>6 (25.0)</td>
</tr>
<tr>
<td>Asthma</td>
<td>4 (16.7)</td>
</tr>
<tr>
<td>Dysphagia</td>
<td>3 (12.5)</td>
</tr>
<tr>
<td>Heart condition</td>
<td>5 (20.8)</td>
</tr>
<tr>
<td>Pulmonary</td>
<td>3 (12.5)</td>
</tr>
<tr>
<td>Cigarette exposure, No. (%)</td>
<td>2 (8.3)</td>
</tr>
<tr>
<td>Prior intubation, No. (%)</td>
<td>9 (37.5)</td>
</tr>
<tr>
<td>Duration (95% CI), d</td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>13.8 (2.8-24.9)</td>
</tr>
<tr>
<td>Multiple intubations, No. (%)</td>
<td>7 (28.8)</td>
</tr>
<tr>
<td>Prior tracheotomy, No. (%)</td>
<td></td>
</tr>
<tr>
<td>Duration (95% CI), d</td>
<td>230.0 (45.8-414.2)</td>
</tr>
<tr>
<td>Major airway surgeries prior</td>
<td>2.2 (1.8-2.6)</td>
</tr>
<tr>
<td>referral. No. (95% CI)</td>
<td></td>
</tr>
<tr>
<td>Number of airway surgeries</td>
<td>2.1 (1.4-2.8)</td>
</tr>
<tr>
<td>CCHMC, No. (95% CI)</td>
<td></td>
</tr>
<tr>
<td>Recent surgery prior to</td>
<td></td>
</tr>
<tr>
<td>dynamic CT, No. (%)</td>
<td></td>
</tr>
<tr>
<td>Endoscopic</td>
<td>9 (37.5)</td>
</tr>
<tr>
<td>Laser</td>
<td>4 (44.4)</td>
</tr>
<tr>
<td>Posterior graft</td>
<td>1 (11.1)</td>
</tr>
<tr>
<td>Other</td>
<td>4 (44.4)</td>
</tr>
<tr>
<td>Open</td>
<td>15 (62.5)</td>
</tr>
<tr>
<td>ACCG</td>
<td>6 (40.0)</td>
</tr>
<tr>
<td>AC reconstruction</td>
<td>1 (6.7)</td>
</tr>
<tr>
<td>Laryngofissure</td>
<td>1 (6.7)</td>
</tr>
<tr>
<td>Posterior cricoid split</td>
<td>2 (13.3)</td>
</tr>
<tr>
<td>Thyroid ala graft</td>
<td>1 (6.7)</td>
</tr>
<tr>
<td>Other</td>
<td>4 (26.7)</td>
</tr>
</tbody>
</table>

Abbreviations: ACCG, anterior costal cartilage graft; AC, anterior commissure; CCHMC, Cincinnati Children’s Hospital Medical Center; CI, confidence interval; CT, computed tomography.
standard endoscopy/stroboscopy ($P = .02$). Out of the 19 cases where phonation could be seen with the endoscope, 5 patients had a supraglottic phonation. Four of these 5 patients had a similar phonation pattern on the dynamic voice CT. There was no correlation between vocal folds hypomobility and supraglottic phonation.

Dynamic voice CT scan was also superior to assess the vertical closure pattern of the vocal folds (24/24, 100%), while 4 patients (16.7%) could not be rated with endoscopic evaluation ($P = .04$). The main reason to preclude airway evaluation with the bedside endoscope was the complex postsurgical change associated with supraglottic collapse and/or phonation. The mean duration between dynamic voice CT and endoscopic examination was 118.5 days (95% CI, 65.7-171.3 days). The strongest correlation between voice quality was between the location of phonation and CAPE-V ($R = 0.536$, $P = .007$).

### Discussion

Patients who have undergone complex airway reconstruction represent a unique subset of patients. Most have undergone numerous hospitalizations involving complex medical and surgical interventions. Any further interventions should be individualized, which require a thorough and complete workup.

Dynamic voice CT contributed to the assessment of the following: (1) source of phonation, (2) glottic closure pattern, and (3) vertical closure pattern and was diagnostic in all cases. The main cause of limitation of endoscopic evaluation was from supraglottic collapse. This is in agreement with what is currently known in the literature; supraglottic phonation is a potential voice outcome in patients who have undergone complex airway reconstruction such as LTP with cartilage graft. As shown in Figure 2, supraglottic collapse or phonation will prevent visualization of the underlying structures, including vocal fold mobility. The postsurgical laryngeal findings in complex airway surgery can include scarred true vocal folds (TVFs), off-level TVFs, prolapsed arytenoid cartilages, prolapsed petiole, unilateral or bilateral restricted cricoarytenoid joint mobility, and anterior commissure blunting. Dynamic voice CT scan could be especially indicated for such cases. Coronal cuts and virtual endoscopic views from below the vocal folds provide complementary and valuable information. Moreover, patients with a more severe degree of dysphonia cannot get an adequate stroboscopy examination due to the motion of the larynx not being periodic. This may prevent visualization of the source of phonation. Dynamic CT can provide complementary information of vocal fold motion in such cases. The vertical closure pattern of the glottis also offers valuable information. This would contribute to surgical planning, including the need of complete laryngofissure for future voice surgeries, which could bring by itself dysphonia and other complications. It should be noted, however, that the dynamic voice CT does not evaluate the mucosal wave.

More than 80% of our patients were female. Female patients have an increased tendency to seek out voice surgery. As previously noted in literature, complex airway surgeries are associated with postsurgical change, which may include a decrease in fundamental frequency. Females with deeper voices are less socially accepted than males with the same problem, as their voice has a quality similar to their male counterparts. Our mean CAPE-V and pVHI scores are similar to what is already known in the literature for patients with a history of complex airway surgery. This supports that our population is similar to what was previously described in other studies.

One concern could potentially be the radiation exposure. A recent study compared radiation doses of the dynamic upper-airway CT on 8 subjects with persistent obstructive sleep apnea to patients undergoing a facial CT scan. The dynamic CT scan could be performed to a radiation dose less than 0.4 mSv, a dose that was less than or comparable to that used for clinical facial CT. The authors concluded that a dynamic CT technique of the upper airway could be performed with a clinically reasonable radiation dose.

Our study has limitations. There are currently no data regarding the dynamic voice CT scan for a healthy population, making it impossible to compare our cohort of complex airway patients with a baseline population.

### Table 2. Voice Baseline Characteristics for Patients with Complex Airway Surgeries Who Underwent a Dynamic Voice CT Scan.

<table>
<thead>
<tr>
<th>Voice Evaluation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pVHI, mean (95% CI)</td>
<td>50.7 (43.9-57.4)</td>
</tr>
<tr>
<td>Functional</td>
<td>18.3 (16.2-20.4)</td>
</tr>
<tr>
<td>Physical</td>
<td>19.8 (17.4-22.2)</td>
</tr>
<tr>
<td>Emotional</td>
<td>14.6 (11.6-17.6)</td>
</tr>
<tr>
<td>CAPE-V overall severity, mean (95% CI)</td>
<td>47.4 (40.7-54.2)</td>
</tr>
<tr>
<td>Roughness</td>
<td>20.8 (13.0-28.6)</td>
</tr>
<tr>
<td>Breathiness</td>
<td>25.6 (18.4-32.8)</td>
</tr>
<tr>
<td>Strain</td>
<td>16.7 (10.3-23.1)</td>
</tr>
<tr>
<td>Pitch</td>
<td>18.3 (11.0-25.6)</td>
</tr>
<tr>
<td>Loudness</td>
<td>30.04 (22.4-37.7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Endoscopy method, No. (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible</td>
<td>10 (41.7)</td>
</tr>
<tr>
<td>Rigid</td>
<td>11 (45.8)</td>
</tr>
<tr>
<td>Both</td>
<td>3 (12.5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phonation time, mean (95% CI), s</th>
<th>8.2 (6.2-10.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental frequency, sustained, mean (95% CI), Hz</td>
<td>220.4 (203.9-236.9)</td>
</tr>
<tr>
<td>Fundamental speech, mean (95% CI), Hz</td>
<td>218.3 (191.7-244.9)</td>
</tr>
<tr>
<td>Maximum intensity, mean (95% CI), Hz</td>
<td>79.3 (76.4-82.2)</td>
</tr>
<tr>
<td>Peak air pressure, mean (95% CI), cm H$_2$O</td>
<td>11.9 (10.4-13.4)</td>
</tr>
</tbody>
</table>

Abbreviations: CAPE-V, Consensus Auditory-Perceptual Evaluation of Voice; CI, confidence interval; pVHI, Pediatric Voice Handicap Index.
relatively small number of patients, even for patients with a complex airway history, makes it harder to generalize our results. Furthermore, the clinical impact of the dynamic voice CT scan is yet unproven. It would be helpful to compare voice parameters of patients who undergo voice surgery using the dynamic voice CT scan as a planning tool vs patients without planning using the dynamic voice CT scan prior to voice surgery. Dynamic voice CT can consistently provide important information regarding laryngeal function, especially when considering possible surgical approaches for voice improvement in the postsurgical airway reconstruction patient.

**Conclusions**

Dynamic voice CT shows promise as an additional tool for preoperative planning in disorders such as subglottic stenosis and dysphonia for patients with a history of complex airway procedures. Dynamic voice CT could provide important complementary information that endoscopy/stroboscopy cannot do alone. Such a planning tool may provide useful information to optimize surgical approaches for voice surgery.

**Author Contributions**

Mathieu Bergeron, conception of the work, interpretation of data for the work, drafting the work; Robert J. Fleck, conception of the work, interpretation of data for the work, drafting the work; Caleb Middlebrook, conception of the work, drafting the work; Stephanie Zacharias, conception of the work, interpretation of data for the work, drafting the work; Shea Tolson, conception of the work, drafting the work; Liran Oren, conception of the work, drafting the work;
David Smith, conception of the work, drafting the work; Alessandro de Alarcon, conception of the work, interpretation of data for the work, drafting the work.

Disclosures
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