

Pediatric Tracheal Reconstruction Using Cadaveric Homograft

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Objective: To examine the indications, risks, and surgical outcomes after tracheal reconstruction using cadaveric homograft in children.

Design: Retrospective medical record review.

Setting: Tertiary referral center.

Patients: Ten children (4 boys and 6 girls).

Intervention: Tracheal reconstruction using cadaveric homograft.

Main Outcome Measures: Cause of stenosis, number and type of procedures before homograft reconstruction, severity of preoperative stenosis, surgical approach, homograft length, duration of stenting, number and type of procedures after reconstruction, and rates of decannulation and survival.

Results: Ten children (mean [SD] age, 8.4 [5.5] years) underwent 14 tracheal reconstructions using cadaveric homograft. Patients had an average of 7.0 (range, 1-16) procedures before homograft reconstruction, including an average of 2.8 (range, 0-6) major open airway reconstructions. Mean (SD) pretracheoplasty Myer-Cotton grade of stenosis was 3.80 (0.42) (range, 3-4), and all patients were tracheotomy dependent. A cervical approach was used in 12 reconstructions (86%), and 2 (14%) required median sternotomy. Mean (SD) homograft length was 3.9 (1.7) cm (range, 2-8 cm), which was approximately 0.60 times the length of the total recipient tra-

chea. Mean (SD) duration of stenting for all homografts was 0.67 (0.46) years (range, 0.24-1.98 years). The survival rate was 90% after a mean follow-up of 5.47 (1.52) years (range, 3.32-7.55 years). Surviving patients required an average of 7.38 (5.52) procedures (range, 1-19) after homograft transplant, including an average of 1 major open airway reconstruction (range, 0-4). The mean (SD) grade of stenosis after the final homograft placement was 1.89 (1.27) (range, 1-4). Although the operation-specific decannulation rate was only 7% (1 of 14), the overall decannulation rate eventually reached 60%. Statistical bootstrapping methods and a multivariate regression model determined that increasing patient age (odds ratio, 1.21; 95% confidence interval, 1.07-1.36), increasing number of prior procedures (1.26; 1.02-1.57), and increasing homograft length (2.42; 1.60-3.40 [$P < .001$]) were associated with an increased risk of no decannulation after tracheal homograft reconstruction.

Conclusions: Tracheal reconstruction using cadaveric homograft is an option in children who have undergone multiple airway surgical procedures and present with long-segment stenoses that cannot be bridged using conventional methods. These patients must receive close postoperative follow-up. Subsequent procedures are almost always required before decannulation, and eventual decannulation rates are only 60%. Decannulation rates are lower in older patients who have previously undergone many procedures and require a long tracheal homograft.

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TRACHEAL STENOSIS IN infants and children is largely congenital, due to complete cartilaginous tracheal rings, or acquired secondary to prolonged intubation, trauma, or failed previous tracheoplasty.¹⁻⁴ Stenotic tracheal segments in children can be classified as short or long, depending on whether they involve less than or more than 30% (50% in adults) of the tracheal length, respectively.^{5,6} The initial treatments of choice for short-segment tracheal stenosis remain resection with primary end-to-end anastomosis or slide tracheoplasty.^{2,4,7} Long-segment tracheal

stenoses, congenital lack of tracheal cartilage, dehiscence tracheal resection, failed tracheoplasty, and cartilage loss owing to infection or chondritis often cannot be resected and reanastomosed under minimal tension and therefore require other treatment methods.

The first tracheal reconstruction using cadaveric homograft in adults was described in 1980 by Herberhold et al.⁸ The homograft was initially implanted paratracheally, where it became vascularized and, after a period of 2 to 3 months, was turned into the defect like a pedicled flap. Jacobs et al⁹ reviewed the worldwide experience with single-stage homograft re-



Figure 1. Cadaveric tracheal homograft before implantation.

construction in 31 children, 3 of whom underwent reconstruction in North America. At 5 years, 26 (84%) survived; 22 (85%) of these were asymptomatic, 1 (4%) had a tracheotomy, 1 (4%) had intraluminal stents, and 2 (8%) were still undergoing treatment. The use of tracheal homografts in pediatric airway surgery remains extremely uncommon. The purpose of the present study was to review our experience with cadaveric homograft tracheoplasty and elucidate factors that could predict success with this procedure.

METHODS

PATIENTS

Institutional review board approval was obtained at Cincinnati Children's Hospital Medical Center. A database of physician billing activity was searched for *Current Procedural Terminology* codes 31766, 31780, and 31781 from July 1, 2001, through September 30, 2009. Medical records were reviewed to identify patients who underwent tracheal homograft reconstruction. Variables recorded included the cause of airway injury, number and type of airway procedures before the homograft reconstruction, preoperative severity of tracheal stenosis, surgical approach, homograft length, duration of stenting, number and type of postoperative airway procedures, and rates of decannulation and mortality.

HOMOGRAFT PREPARATION

Tracheal homografts were obtained from the University of Miami Tissue Bank, Miami, Florida.^{9,10} Cadaveric tracheas with trachealis muscle attached are removed from donors aged 16 to 60 years within 24 hours of death. Contraindications to donation include hepatitis B or C virus infection, human immunodeficiency virus infection, viral diseases of unknown origin, and thoracic diseases or trauma involving the trachea. The trachea is harvested and stored in normal saline solution with gentamycin or vancomycin at 1°C to 10°C. The trachea is stripped of overlying tissue and immersed in 4% formalin solution (40 mL of formalin in 960 mL of lactated Ringer solution) at 1°C to 10°C for 14 days. The trachea is then immersed in 4 g of thimerosal (sodium ethylmercurithiosalicylate) dissolved in 1 L of Dulbecco phosphate-buffered saline solution (Sigma-Aldrich Corp, St Louis, Missouri) for 56 days. The trachea is stored in acetone for a minimum of 10 days. A sample of the trachealis muscle is tested for aerobic and anaerobic bac-

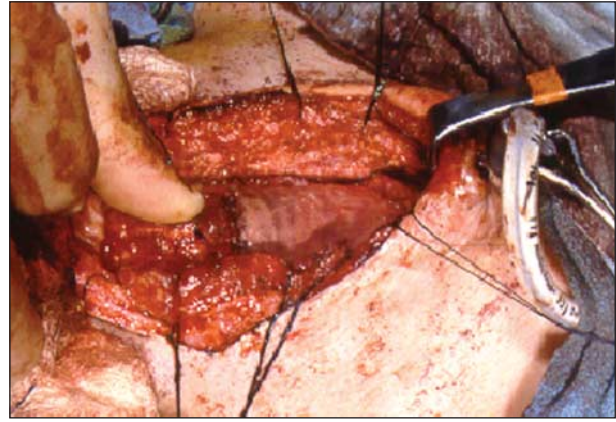


Figure 2. Cadaveric tracheal homograft in situ.

teria, fungi, mycobacteria, and hypothermic microorganisms. Histological studies confirm the absence of all cells and major histocompatibility complex markers. All homograft processing is performed at the University of Miami Tissue Bank, and the homograft needs only to be washed thoroughly in saline solution before insertion.

SURGICAL TECHNIQUE

Patients undergo preoperative flexible nasopharyngoscopy to evaluate vocal cord movement, rigid microlaryngoscopy and bronchoscopy to evaluate the degree and length of the stenotic segment, flexible bronchoscopy to evaluate the distal airways with bronchoalveolar lavage, and esophagoscopy to rule out factors that could perpetuate restenosis, such as acid reflux disease or eosinophilic esophagitis. Computed tomography with 3-dimensional reconstruction was obtained in selected cases.

The neck is exposed using a horizontal incision, and the strap muscles are separated and retracted. Stay sutures are looped around distal tracheal rings bilaterally. With the anterior aspect of the trachea exposed along its length, a flexible nasopharyngoscope is passed through the endotracheal tube and its light visualized from the neck, or a 27-gauge needle is inserted into the tracheal lumen and visualized by the nasopharyngoscope. The superior and inferior boundaries of the planned resection are marked, the trachea is isolated circumferentially between these markings, and the stenotic anterior tracheal segment is resected as best as possible off the trachealis muscle posteriorly. This is often a difficult task because the scar is intricately involved with the trachealis muscle. The goal is to leave the trachealis muscle posteriorly with a small amount of each tracheal ring attached to its posterolateral aspect on each side. The patient is intubated through the inferior open trachea if there is no prior tracheotomy. The homograft trachealis muscle is removed and the graft is cut to fit the defect (**Figure 1**). Homografts from adult donors are used in children to oversize the airway initially and because homografts do not grow with the child. A Montgomery T tube (Boston Medical Products, Westborough, Massachusetts) is placed in the trachea (≥ 8 mm for children to avoid clogging due to dry secretions and ≤ 14 mm in adults), and the homograft is placed over the defect and sutured to the native trachea with a running 4-0 polydioxanone suture (**Figure 2**). If possible, the anterior limb of a T tube is passed through native trachea rather than through the homograft. The neck is irrigated with antibiotic solution and closed in layers over a Penrose drain. Patients are given a prophylactic intravenous combination of amoxicillin and clavulanate potassium for 4 to 6 weeks and fluconazole for 3 months after homograft transplant.

Table 1. Patient Characteristics

Patient No./ Sex	Diagnosis	Age at Homograft, y	Prereconstruction Procedures			
			Total No.	No. of Open Airway Reconstructions	Myer-Cotton Stenosis Grade	Tracheotomy
1/M	Larsen syndrome	8.3	8	2	3	Yes
2/F	Type II laryngeal cleft, tracheal agenesis	2.6	1	0	4	Yes
3/F	Asthma, multiple intubations, SGS	15.2	16	6	4	Yes
4/M	Laryngeal atresia	16.0	13	2	4	Yes
		10.6				
		12.4				
5/F	Complete tracheal rings, pericardial patch	13.3	2	1	4	Yes
		2.7				
		2.7				
6/M	Asthma, MVC, prolonged intubation, SGS	16.9	9	3	4	Yes
7/F	Premature, prolonged intubation	4.3	4	4	3	Yes
8/F	Down syndrome, prolonged intubation	4.6	3	2	4	Yes
		6.3				
9/F	Complete tracheal rings	4.2	10	4	4	Yes
10/M	Burn injury	14.4	4	4	4	Yes

Abbreviations: MVC, motor vehicle collision; SGS, subglottic stenosis.

Table 2. Reconstruction Characteristics

Patient No.	Surgical Approach	Homograft Length, cm	Stent Type	Stent Duration, y	Postreconstruction Procedures			Time to Decannulation, y	Duration of Follow-up, y
					Total No.	No. of Open Airway Reconstructions	Trach		
1	C	3	Salivary	1.98	10	1	None	5.29	5.31
2	CT + CPB	8	T tube	Died	Died	Died	Died with Trach	NA	Died
3	C	4	T tube	0.70	1	0	T tube	NA	4.23
4	C	2	T tube	0.71	2	0	T tube		
		2.5	T tube	0.29	4	1	Trach		
		3.5	T tube	0.84	6	1	Trach		
5	CT + CPB	3	T tube	0.43	2	0	None	0.81	4.36
		2	None	None	6	2	None		
		5	T tube	0.74	11	0	Hood stent		
6	C	5	T tube	0.74	11	0	Hood stent	NA	3.32
7	C	3	T tube	0.50	16	1	None	5.79	6.81
8	C	4	T tube	0.40	7	1	Trach	NA	4.19
		3	Trach + Aboulker stent	0.24	3	1	Trach		
9	C	5	T tube	0.45	19	4	None	4.79	7.55
10	C	6	T tube	0.82	9	1	None	5.97	6.49

Abbreviations: C, cervical; CPB, cardiopulmonary bypass; NA, not applicable; Salivary, salivary bypass tube; T, thoracic; Trach, tracheotomy.

RESULTS

Ten children underwent 14 tracheal reconstructions using cadaveric homograft (2 patients had 2 homograft procedures and 1 patient had 3 homograft procedures). There were 4 boys and 6 girls. The mean age at the time of initial homograft transplant (10 patients) was 8.4 (5.5) years (median, 6.5 [range, 2.6-16.9] years). (Unless otherwise indicated, data are expressed as mean [SD].) The mean age at the time of homograft transplant for all 14 procedures was 9.4 (5.3) years (median, 9.4 [range, 2.6-16.9] years). Patient demographics are provided in **Table 1**; surgical variables are provided in **Table 2**.

Before undergoing initial tracheal reconstruction with cadaveric homograft (10 patients), patients underwent an average of 7.00 (5.01) airway procedures (median, 6 [range, 1-16]). These included major open airway reconstructions (ie, laryngotracheoplasty, pericardial patch,

and laryngeal cleft repair) and minor closed airway procedures (ie, granulation removal, tracheal dilation, endoscopic laser treatment, mitomycin application, stent placement, tonsillectomy, and adenoidectomy). Patients underwent an average of 2.80 (1.75) major airway reconstructions (median, 2.5 [range, 0-6]). The mean Myer-Cotton grade of stenosis¹¹ before initial homograft transplant (10 patients) was 3.80 (0.42) (median, 4 [range, 3-4]). The mean grade of stenosis before all homograft transplants (14 reconstructions) was 3.79 (0.43) (range, 3-4). All patients had a tracheotomy in place before each tracheal homograft reconstruction.

At the time of surgery, 12 of 14 tracheal homograft reconstructions (86%) were performed through a cervical approach alone, and 2 of 14 (14%) required the sternum to be split and used a combined cervical and thoracic approach. Two of 14 procedures (14%) were performed using cardiopulmonary bypass. The mean

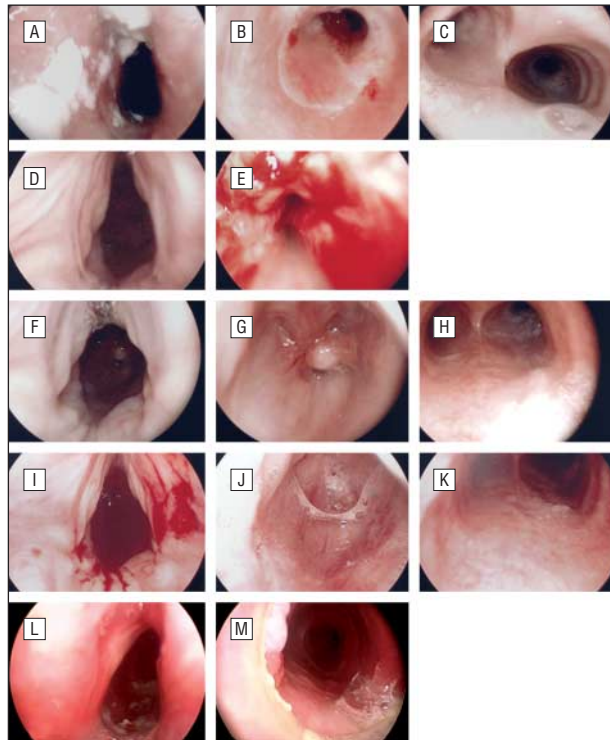


Figure 3. Short-term appearance of tracheal homograft in patient 3. Photographs taken on the day of stent removal following the first homograft demonstrate the glottis (A), an edematous subglottis and trachea (B), and normal carina (C). One week later, images demonstrate a patent glottis (D) and increased subglottic swelling (E). Two weeks later, images reveal a patent glottis (F), complete tracheal obstruction (G), and a patent distal trachea (H). A second homograft was placed. One week after removal of the stent placed during the second homograft, there is a patent glottis (I) with repeated midtracheal occlusion (J) and a patent distal trachea (K). Despite looking patent following a balloon dilation and long-term stenting (L and M), this patient still requires a T tube to prevent tracheal occlusion.

length of the homograft was 3.9 (1.7) cm (range, 2-8 cm). According to previously published tracheal lengths determined for each age group in children,¹² homograft lengths were on average 0.60 (0.29) times the total length of the patients' tracheas. All 14 procedures were double-stage procedures in which the patient was left with a tracheotomy at the end of the procedure, and 13 of 14 airways (93%) were stented after surgery, including 11 with a Montgomery T tube, 1 with an Aboulker stent (France), and 1 salivary bypass tube with the smooth end in the distal trachea and the proximal cut end sutured shut sitting above the level of the vocal cords. The mean duration of stenting for 12 procedures (1 patient did not undergo stenting and 1 patient died before removal of the stent) was 0.67 (0.46) years (range, 0.24-1.98 years). The mean duration of stenting after placement of the last homograft (8 patients) was 0.73 (0.54) years (range, 0.24-1.98 years).

At the time we submitted this article for publication, 9 of 10 children (90%) were alive, with a mean follow-up of 5.47 (1.52) (range, 3.32-7.55) years from the placement of their last stent until evaluation and sizing using the Myer-Cotton grading scale. The 1 death (patient 2) occurred within a few weeks of the homograft transplant after the patient developed aspiration, gram-negative sepsis, dehiscence of the neck wound and ho-

mograft with an air leak into the chest, and a subclavian/carotid artery blowout, after which the parents withdrew care. It remains unclear whether this infection began in the homograft or in a different part of the body or was transmitted from another patient who was found to be infected with this same bacteria at the same time. Surviving patients (9 patients after 13 homograft reconstructions) underwent an average of 7.38 (5.52) major and minor airway procedures (range, 1-19). These included major open airway reconstructions (ie, laryngotracheoplasty and slide tracheoplasty) and minor closed airway procedures (ie, granulation removal, tracheal dilation, endoscopic laser treatment, mitomycin application, stent placement, supraglottoplasty, endoscopic arytenoidectomy, tonsillectomy, and adenoidectomy). Patients underwent an average of 1.00 (1.08) major airway reconstruction (range, 0-4). It is quite difficult to perform an open airway reconstruction on a patient who has previously received a tracheal homograft because of scarring and rigidity of the tissues. Nevertheless, in this series, we were able to perform 5 anterior costal cartilage grafts (1 had an additional posterior cricoid split and 1 had an additional lateral graft), 3 anterior and posterior costal cartilage grafts, 1 tracheal resection with reconstruction using costal cartilage on 3 sides to recreate a lumen, 1 slide tracheoplasty, and 1 cricotracheal resection. Despite antibiotic therapy after homograft transplant, 8 of 10 patients (80%) had an infection after at least 1 of their transplants, and 8 of 13 homograft surgical procedures (62%) were followed by an infection. Two patients developed pneumonia, 6 developed a neck abscess, and 1 developed laryngeal thrush. The Myer-Cotton grade of stenosis was evaluated approximately 4.74 years after removal of the last stent placed in each patient (5.47 years of follow-up minus 0.73 years of stent placement duration). The mean Myer-Cotton grade of stenosis¹¹ after homograft transplants in each patient (13 transplants) was 2.46 (1.39) (range, 1-4); after the last homograft transplant for each patient (9 patients), the grade was 1.89 (1.27) (range, 1-4). The operation-specific decannulation rate (ie, not requiring subsequent major open airway reconstruction) for tracheal reconstruction using cadaveric homograft was 7% (1 of 14). The patient who underwent decannulation without requiring a major open airway procedure still required an endoscopic arytenoidectomy and subsequent granulation removal. Overall, 6 of 10 patients (60%) underwent decannulation, 1 (10%) has a tracheotomy tube, 1 (10%) has a T tube, 1 (10%) has a Hood tracheal stent, and 1 (10%) died with a tracheotomy tube in place. **Figure 3** and **Figure 4** show the immediate and short-term appearance of a tracheal homograft postoperatively. **Figure 5** shows the long-term appearance of several tracheal homografts (most children required additional airway procedures after homograft transplant).

As part of an exploratory analysis, the 6 patients who underwent decannulation were compared with those who did not to determine potential differences and future predictors for decannulation (or failure to decannulate). There was no significant difference between groups regarding mean age (7.4 vs 9.8 years, respectively [$P = .53$]). Patients who did not undergo decannulation had a lon-

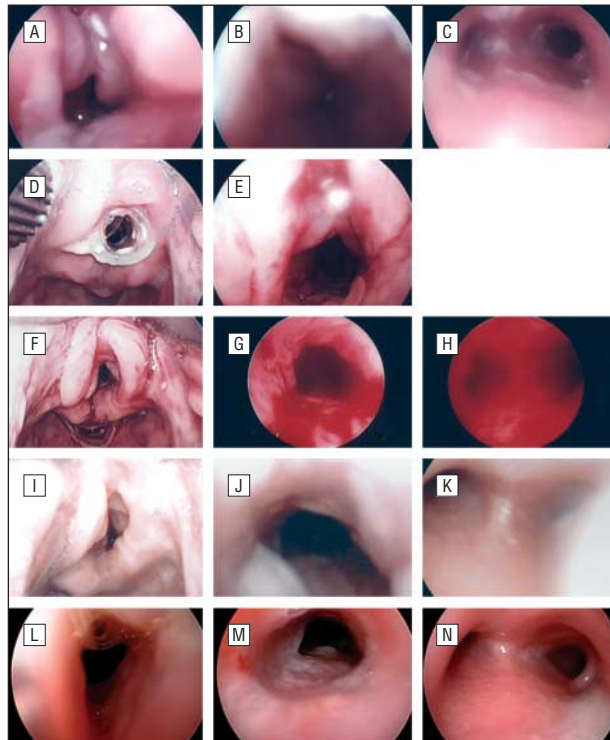


Figure 4. Short-term appearance of tracheal homograft in patient 8. Photographs taken 1 week after stent removal after the first homograft (A-C) demonstrate granulation tissue at the glottis (A) and marked edema in the subglottis (B). Four months later (D-F), a second stent was required (D), and edema followed its removal (E). The stent was removed 4 months later (F-H). This patient underwent epiglottoplasty, multiple balloon dilations, and cartilage grafting and eventually required a second homograft. Six months after stent removal following the second homograft (I-K), a more patent trachea is seen (J). Three years later, after several balloon dilations and anterior and lateral cartilage grafting (L-N), a narrow subglottis (L) and reactive but patent midtrachea (M) are seen.

ger mean homograft length (5.25 vs 3.58 cm [$P=.17$]), although the mean ratio of homograft to native tracheal length compared with patients who underwent decannulation was not significantly higher (0.83 vs 0.57 [$P=.22$]). Although our comparisons were not statistically significant, this is likely owing to the extremely small sample size. Simple logistic regression models were constructed to determine how predictive the homograft length and ratio of homograft to native trachea were in determining the probability of not undergoing decannulation. The odds ratio (OR) for homograft length was 1.96 (95% confidence interval [CI], 0.72-5.30 [$P=.19$]). This means that, for every 1-cm increase in homograft length, the odds of not undergoing decannulation increase nearly 2-fold. Thus, a patient with a homograft length of 5.0 cm is 3.8 times as likely to not undergo decannulation compared with a patient with a homograft length of 3.0 cm. Similar results were seen with the ratio of homograft to native trachea length; however, homograft length had a more precise CI for the given sample size. There was no association between age and failure to decannulate (OR, 1.09; 95% CI, 0.85-1.4 [$P=.48$]). The time from placement of the last homograft to decannulation (or lack of decannulation) was then compared for patients with a homograft length less than 4 cm ($n=6$) and those with a homograft length greater than 4 cm ($n=4$) using a log-

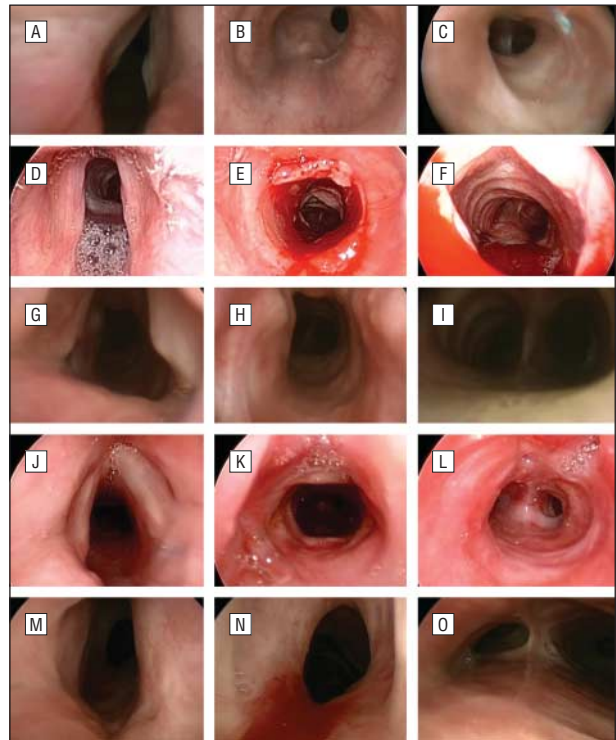


Figure 5. Long-term appearance of tracheal homograft in patients 5, 6, 7, 9, and 10. Patient 5 (A-C) has a tortuous midtrachea (B) and normal distal trachea (C); the patient has remained decannulated. Patient 6 (D-F) has a narrow trachea (E); the patient still requires stenting. Patient 7 (G-I) has a patent airway after additional anterior and posterior cartilage graft augmentation and has undergone decannulation. Patient 9 (J-L) is a child with a patent airway; the patient has undergone decannulation after 3 cartilage grafting procedures, a slide tracheoplasty, and multiple balloon dilations. Patient 10 (M-O) has a patent airway with a mild degree of subglottic stenosis; the patient underwent multiple dilations, long-term stenting, and a cricotracheal resection that eventually led to decannulation.

rank time-to-event analysis. The difference between groups with respect to time to decannulation was not statistically significant ($P=.72$, log-rank test); however, the sample size was extremely small.

This study had a small sample size because tracheal homograft reconstruction is so rare. Such rare occurrences often preclude the ability to use statistical procedures to guide good evidence-based practices. An alternative is to apply bootstrapping methods using the distributions of the available data. Bootstrapping allows for the derivation of CIs for an OR with an increased sample size, which is helpful in this case because the available sample size is extremely small owing to its rare occurrence. As part of the exploratory analysis, the sample size was increased to 100 using random sampling with replacement (each observation was randomly sampled from the original population of 10 patients, and each observation could be sampled repeatedly). A simple logistic regression model was constructed on the “new” data with homograft length as the main predictor. The OR for failure to decannulate was 2.42 (95% CI, 1.60-3.40 [$P<.001$]). Thus, if it is assumed that the rate of decannulation along with the distribution of variables were similar in a new sample of 100 patients, we should expect to see similar results. Post hoc power calculations indicate that we would require a sample size of approximately 100

patients who had received tracheal homografts to find these ORs with a significance level of .05. Using bootstrapped data from an actual patient population will also allow for the inclusion of multiple variables in a regression model when the study size prohibits the use of multiple regression techniques. With the bootstrap sample data of 100 subjects (and with a 40% rate of decannulation failure), we were able to evaluate multiple risk factors (age, number of previous procedures, and homograft length) in the same regression model. With these variables in a single regression model, factors found to be associated with an increased risk of no decannulation after tracheal homograft were increasing patient age (OR, 1.21; 95% CI, 1.07-1.36), increasing number of previous procedures (1.26; 1.02-1.57), and increasing homograft length (2.42; 1.60-3.40 [$P < .001$]).

COMMENT

We report the results of 14 tracheal reconstructions using cadaveric homograft in 10 children. The mean age at the time of initial homograft transplant was 8.4 (range, 2.6-16.9) years, which is in accordance with previously published results (mean age, 7.86 [range, 0.42-18.00] years).⁹ This suggests that cadaveric homograft transplant can be used in children of a wide range of ages, even in the first few years of life.

Before initial cadaveric tracheal reconstruction, patients underwent an average of 7.00 major and minor airway procedures, including an average of 2.80 major open airway reconstructions. All but 1 patient underwent at least 1 previous open tracheal reconstruction. Jacobs et al⁹ similarly found that most of their patients had previously undergone tracheal reconstruction; however, the authors did not report the number and type of previous surgical procedures. Nevertheless, results from both studies suggest that tracheal reconstruction using cadaveric homograft should be an operation of last resort after other tracheal procedures have failed. The mean preoperative Myer-Cotton grade of stenosis was 3.80, which is essentially a complete occlusion of the lumen, and all patients had a tracheotomy. Results further reinforce the fact that previous airway procedures were not beneficial in this difficult-to-manage population.

A cervical approach alone provided sufficient access for 86% of homograft procedures, and 16% required an additional sternotomy. Only 14% of procedures were performed using cardiopulmonary bypass. In contrast, Jacobs et al⁹ performed 68% of procedures through a cervical approach and required an additional sternotomy in 32%. In their study, all procedures requiring sternotomy were performed using cardiopulmonary bypass. Sternotomy and cardiopulmonary bypass facilitate dissection of distal lesions and simplify intraoperative airway maintenance but also increase the duration of the procedure and risk injury to the heart, lungs, brain, and kidneys. The lower rate of sternotomy and bypass in the present study could be because tracheal lesions were more proximal, rendering them easier to access, or because of surgeon preference and training. In any case, our results demonstrate that most tracheal

homografts can be placed through a cervical approach without sternotomy or bypass. The mean homograft length was approximately 4 cm, which was on average 0.60 times the total length of the recipient's native trachea. This demonstrates that long-segment tracheal replacement is achievable in children. All procedures were performed in 2 stages, with tracheas stented for an average of 0.67 years. Tracheal homografts require long-term stenting to prevent tracheal collapse, which may be a consequence of processing methods.⁹ The minimum duration of stenting required to prevent tracheal collapse has not yet been determined. Homograft mucosalization is in the order of many months; however, the exact time to mucosalization could not be determined because stents remained in the trachea for such an extended period.

Survival after homograft transplant was 90% with a follow-up of 5.5 years, which is in accordance with previous reports of 84% survival after 5.07 years.⁹ The patient who died developed postoperative sepsis, wound breakdown, and subclavian artery rupture. Sepsis, wound breakdown, graft dehiscence, and major arterial rupture also accounted for most of the deaths in a previous study.⁹ Surviving patients underwent an average of 7.38 airway procedures, including an average of 1 major open airway reconstruction, and were left with a residual average Myer-Cotton stenosis of grade 1.89. The need for bronchoscopy and granulation tissue removal with periodic balloon dilation after homograft surgery has been alluded to; however, the frequency with which this is required and the need for subsequent open airway surgery has not been described.⁹ Perhaps patients in the present study had more severe stenoses and incurred a greater number of airway reconstructions before the homograft procedure, leaving a poorer blood supply and leading to poorer wound healing.

The operation-specific decannulation rate (with success defined as the patient not requiring subsequent major open airway reconstruction) for homograft transplant was only 7.0% (1 of 14), and this patient required an additional arytenoidectomy before decannulation. A previous study⁹ that does not describe postoperative details or operation-specific decannulation rates gives the impression that these rates are much higher. After revision surgery where required, decannulation rates in the present study eventually reached 60%. Our results suggest that although homograft reconstruction in itself is not likely to lead to immediate decannulation, it serves well as an intermediate step for patients with long-segment stenoses so that subsequent airway reconstructions could lead to decannulation in the future. However, the decannulation rate in the present study is considerably lower than the rate of 80.7% reported in the literature.⁹ Lower decannulation rates in the present study may be owing to preoperative patient characteristics because 4 of 10 patients (40%) had preconditions that have been shown to predispose to worse outcomes after open airway reconstruction. Patient 1 had Larsen syndrome (characterized by a prominent forehead, hypertelorism, a depressed nasal bridge, laryngomalacia, congenital subglottic stenosis, tracheobronchomalacia, kyphoscoliosis, and joint dislocations), which has been associated with

a lack of laryngeal and tracheal cartilage rigidity and failed laryngotracheoplasty.^{13,14} Patient 2 had tracheal agenesis and patient 4 had laryngeal atresia, which are notorious for being difficult to repair owing to a propensity for restenosis.¹⁵⁻¹⁷ Patient 8 had Down syndrome; there is conflicting evidence whether success rates with open airway reconstruction in this population are lower than or the same as in control patients with the same degree of stenosis.^{18,19} The remainder of airway stenoses were due to prolonged intubation (3 patients), complete tracheal rings (2 patients), and inhalational burn injury (1 patient), which has been shown to portend a similar rate of success as prolonged intubation after laryngotracheoplasty.³ Conversely, none of the patients in the study by Jacobs et al⁹ had preconditions known to predispose to worse outcomes after open airway reconstruction (ie, complete tracheal rings, multiple trauma, and prolonged intubation).

The major limitation of the present study is that, because of the relative infrequency with which cadaveric homografting is performed in children, the study is not powered enough to determine factors that could predict outcomes. We used bootstrapping methods to increase the sample size to 100 and analyzed the data using a multivariate logistic regression model. Our results demonstrated that increasing age, an increasing number of previous procedures, and increasing homograft length were associated with an increased risk of failure to decannulate. Children who underwent initial homograft transplant before 5 years of age had an average of 2.2 major open airway reconstructions before homograft transplant compared with children who underwent initial transplant after 5 years of age and had undergone an average of 3.4 major open airway reconstructions before receiving their homograft. The risk associated with an increased number of previous procedures is likely due to increased scar tissue with decreased vascularity, whereas the risk associated with increased homograft length is likely related to the increased time required for remucosalization of the homograft, because bare cartilage is more likely than mucosa to form granulation tissue.

Owing to the limited success with cadaveric homograft reconstruction, alternative methods of reconstructing long tracheal defects using vascularized free flaps^{20,21} and tracheas engineered in bioreactors have surfaced.⁵ Although preliminary studies appear promising, few patients have been described, follow-up is short, and equipment is expensive and not yet readily accessible. We hope that future studies aimed at creating a long, flexible, durable, integrated, biocompatible, nonimmunogenic, permanent, epithelialized patent trachea that is easy to implant will provide improved results in children with long-segment tracheal defects.

In conclusion, tracheal reconstruction using cadaveric homograft is an option in children who have undergone multiple airway surgeries and present with long-segment stenoses that cannot be bridged with conventional methods. These patients must receive close postoperative follow-up. Subsequent procedures are almost always required before decannulation, and eventual decannulation rates are only 60%. Decannulation rates

are lower in older patients who have previously undergone many procedures and require a long tracheal homograft.

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