Three-dimensional (3D) Printed Model to Plan the Endoscopic Treatment of Upper Airway Stenosis

Alfonso Fiorelli, MD, PhD, Roberto Scaramuzzi, MD,* Ivana Minerva, MD,* Emanuele De Ruberto, MD,* Teresa Califano, MD,† Alfonso Reginelli, MD,† Roberto Grassi, MD,† and Mario Santini, MD**

Background: **Endoscopic management of tracheal stenosis may be challenging, especially in the case of complex stenosis placed near the vocal folds, and needing stent placement. Herein, we evaluated the utility of the three-dimensional (3D) airway model for procedural planning in a consecutive series of patients with complex airway stenosis and scheduled for endoscopic treatment.**

Methods: **This strategy was applied to 7 consecutive patients with tracheal stenosis unfit for surgery. The model was printed in a rubber-like material, and almost 7 hours were needed to create it. All patients presented respiratory failure with a mean value of 3.4 ± 0.4 Medical Research Council (MRC) dyspnea scale, 47 ± 3.9 forced expiratory volume in 1 second (FEV1%), and an impairment in the 6-minute walking test (6MWT) (mean value, 175 ± 53 m). The mean length of the stenosis was 19 ± 3.4 mm; 3 of the 7 (43%) patients presented a subglottic stenosis. In 4/7 (57%) patients the stenosis was > 5 mm, but its treatment required the placement of a stent because of the presence of tracheal cartilage injury.**

Results: **The mean operation time was 22.7 ± 6.6 minutes. No complications were observed during and after the procedure. A significant increase of MRC (3.4 ± 0.4 vs. 1.6 ± 0.5; $P = 0.003$), of FEV1% (47 ± 3.9 vs. 77 ± 9.7; $P = 0.001$), and of 6MWT (175 ± 53 vs. 423 ± 101; $P = 0.0002$) was observed after the procedure (mean follow-up, 11.1 ± 8.8 mo).**

Conclusion: **Our 3D airway model in the management of airway stenosis is useful for procedural planning, rehearsal, and education. The fidelity level of the 3D model remains the main concern for its wider use in patient care. Thus, our impressions should be confirmed by future prospective studies.**

Key Words: tracheal stenosis, three-dimensional printed model, endoscopic treatment

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Endoscopic management of tracheal stenosis is challenging, and requires refined technical skills, especially when the stenosis is complex, near to vocal fold, and needing a stent placement.[1] Modern imaging modalities, such as computed tomography (CT), allow patient-specific anatomy to be processed and manipulated, to generate a file that can be read by a three-dimensional (3D) printer, which then creates a 3D model of patient's anatomy, useful for surgical planning. Herein, we present a series of 7 cases in which the 3D printed model of stenotic upper trachea was used to plan the endoscopic procedure. In addition, we also describe our strategy of creating a 3D model, so that other centers can easily reproduce it.

STUDY POPULATION

This strategy was applied to 7 consecutive patients with tracheal stenosis who were unfit to undergo a surgical procedure because of severe comorbidities (Table 1). Patients' standard clinical evaluation included Medical Research Council (MRC) dyspnea scale,[2] spirometric assessment, and 6-minute walking test (6MWT). The diameter, length, and morphology of the stenotic trachea were defined by CT scan with 3D reconstruction and by flexible bronchoscopy.[3]

Before treatment, all patients presented respiratory failure, with a mean value of 3.4 ± 0.4 MRC dyspnea scale, 47 ± 3.9 forced expiratory volume in 1 second (FEV1%), and an impairment in the 6MWT (mean value, 175 ± 53 m). The mean length of the stenosis was 19 ± 3.4 mm; 2 of the 7 (43%) patients presented a subglottic stenosis. In 4/7 (57%) patients, the stenosis was > 5 mm, but its treatment required the placement of a stent, because of the presence of tracheal cartilage injury.

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From the *Thoracic Surgery Unit; and †Radiology Unit, Università degli Studi della Campania "Luigi Vanvitelli," Naples, Italy.
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Reprints: Alfonso Fiorelli, MD, PhD, Thoracic Surgery Unit, Università degli Studi della Campania "Luigi Vanvitelli," Piazza Miraglia, 2, Naples I-80138, Italy (e-mail: alfonso.fiorelli@unicampania.it).

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TABLE 1. Characteristics of the Study Population

					Characteristics of Stenosis (mm)		Characteristics of Dumon Stent (mm)			
Patients	**Sex**	**Age (y)**	**Etiology**	**Site**	**Diameter**	**Length**	**Diameter**	**Length**	**Operative Time (min)**	**Follow-up (mo)**
1	M	70	Postintubation	Subglottic	7	20	16	40	25	9
2	F	69	Postintubation	Upper Trachea	5	15	14	40	35	8
3	M	58	Postintubation	Upper Trachea	4	20	14	40	25	12
4	M	65	Postintubation	Subglottic	7	20	15	40	20	9
5	F	53	Postintubation	Upper Trachea	5	25	15	50	17	10
6	M	67	Postintubation	Subglottic	6	15	16	40	15	14
7	M	73	Postintubation	Upper Trachea	7	20	14	40	22	16
Mean ± SD		65 ± 7.1	—	—	5.8 ± 1.2	19 ± 3.4	14.8 ± 0.8	41.6 ± 4.0	22.7 ± 6.6	11.1 ± 8.8

F indicates female; M, male.

PROCEDURE TO CREATE THE 3D PRINTED MODEL

The process is summarized in Figure 1. Each patient was scanned by multislice spiral CT in the supine position, and 1 mm slice thickness was obtained. The CT scan data were saved as DICOM files and were inserted into the Osirix software program (Pixmeo SARL, 266 Rue de Bernex, CH-1233 Bernex, Switzerland). The tracheal area was selected using the thresholding function to create a 3D digital model. Airway and bony structures were easily segmented because of the density differences between air, bone, and adjacent mediastinal structures. The computed imaging data were saved in Standard Tessellation Language (STL), and then they were sent to a 3D printer (MakerBot Replicator; Makerbot, Brooklyn, NY) to create a 3D model. The 3D model was printed in Elasto Plastic material that was robust, flexible, and fairly soft. All these characteristics made it suitable for endoscopic dilation and stent insertion. From a technical point of view, almost 7 hours were needed to prepare the STL file and to print the models (preprocessing = 2 h; printing = 4 to 5 h size-dependent). Once printing had been completed, the 3D model was screwed to a rigid baseplate, and it was ready for rigid bronchoscopy intubation and other endoscopic maneuvers (Fig. 2).

RESULTS

The sequential endoscopic maneuvers such as rigid bronchoscopy intubation, dilation of the stenosis, and placement of the silicone stent were planned using the 3D model, and then successfully performed live in the patient 24 hours later, as summarized in Figure 3.

The mean operation time was 22.7 ± 6.6 minutes. No complications were observed during and after the procedure. Patients were monitored monthly. No stent dislocation or other complications were seen. A significant increase of MRC (3.4 ± 0.4 vs. 1.6 ± 0.5; $P = 0.003$; *t* student test); of FEV1% (47 ± 3.9 vs. 77 ± 9.7; $P = 0.001$; *t* student test) and of 6MWT (175 ± 53 vs. 423 ± 101; $P = 0.0002$; *t* student test) was observed after the procedure (mean follow-up, 11.1 ± 8.8 mo).

DISCUSSION

Endoscopy is the management of choice for benign tracheal stenosis when surgery is unfeasible. Although 3D radiological reconstructions have notably improved the visualization of tracheal stenosis and have provided an important tool for the interventional pneumologist, there are specific cases where this information might be insufficient to properly conceive certain features of tracheal stenosis, such as the presence of cartilage fracture, or to define the distance between the stenosis and the vocal folds. In the last years few years, the 3D printing technology combined with digital technology allowed one to obtain a 3D printed model of the patient's anatomy that overcomes the limitations of 2-dimensional radiologic findings. This approach has been used for complex procedures in several specialties,[4–7] but it has been scarcely used for bronchoscopic

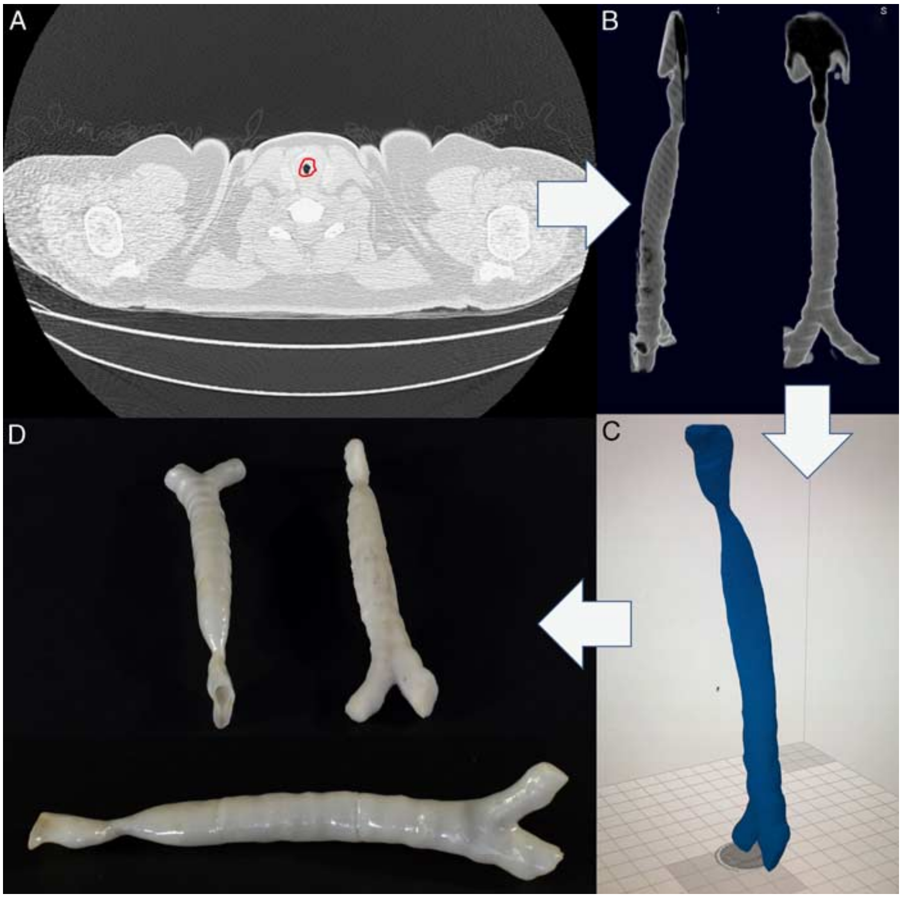

FIGURE 1. Figure, representing patient 2 from the Table 1, shows the main steps (white arrows) to create the 3D printed model as the selection of the trachea and stenosis (A), the 3D reconstruction of the airway (B), the 3 D digital model (C), and the 3D printed model (D).

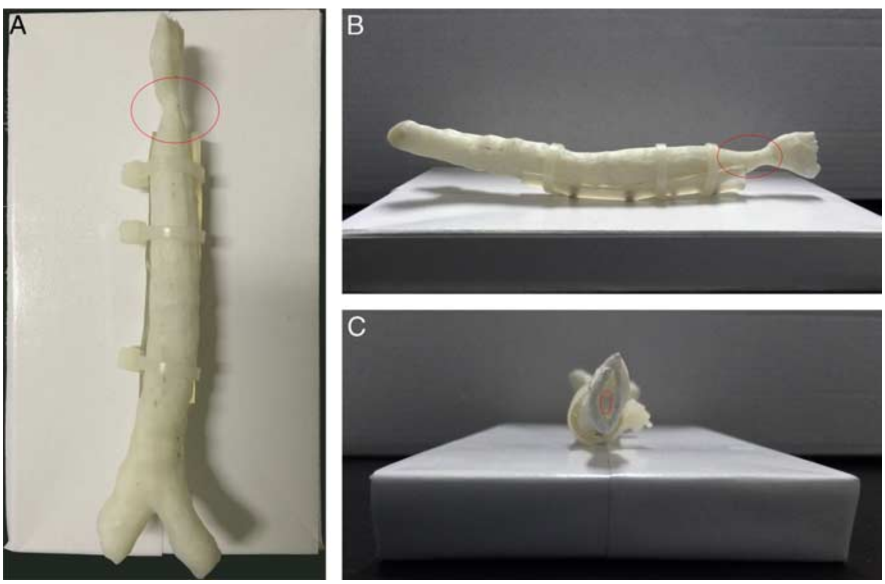

FIGURE 2. Attachment of the 3D model to a rigid baseplate. Part A: frontal view, Part B: lateral view and Part C: anteroposterior view. Stenotic area is shown within the black circle.

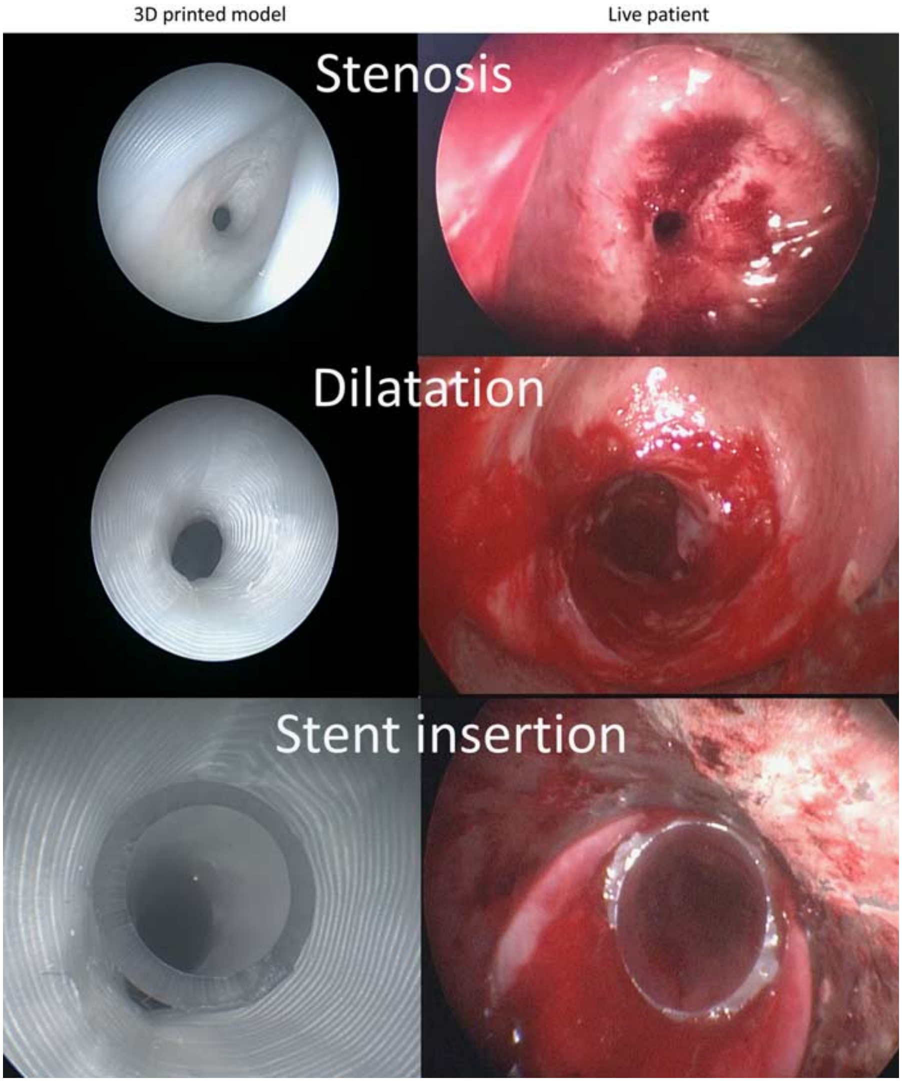

FIGURE 3. Figure, representing patient 1 from the Table 1, shows the main steps of endoscopic treatment as stenosis, airway dilatation, and stent insertion in the 3D printed model and live patient.

planning. Thus, in this paper, we evaluated the utility of the 3D airway model for procedural planning, rehearsal, and education in 7 patients with complex airway stenosis, who were scheduled for endoscopic treatment.

The use of the 3D printed model presented the following advantages. (i) It facilitated the understanding of the patient's anatomy and the stenosis' characteristics and allowed to plan the endoscopic treatment. In fact, the physician recreated the endoscopic procedure in the 3D model, and modified his previous strategy (originally based on radiologic reconstructions), as he realized that certain modifications could have improved the feasibility of the procedure and, eventually, the final outcome. An example was represented by patient 4 and is summarized in Figure 4. In this case, the 3D model correctly diagnosed the presence of a tracheal ring fracture localized in the stenotic trachea that was misdiagnosed as mucus by CT scan. Thus, using the information obtained with the 3D model, the physician planned to remove the injured tracheal ring, and to insert the stent after airway dilation to prevent recurrence. (ii) The 3D model allowed to plan the exact position for stent insertion. As the flexibility of the present model is different from the flexibility of the trachea, the physician could not accurately predict the end dilatation diameter and the stent size on the basis of this model. In contrast, he could obtain important information on the distance between the stenosis and the vocal folds, and plan the exact location of the insertion of the stent to cover the entire length of the stenosis, in the meanwhile avoiding injury to the vocal folds.[8] This was crucial for the treatment of subglottis stenosis (43% of our study population), as the wrong placement of the stent increased the risk of migration or the risk of vocal folds injury. (iii) Compared with traditional radiologic findings, the 3D model also helped to obtain informed consent from the patient and/or his family members. In fact, observing the 3D model, they could easily understand the disease, the endoscopic treatment, and the potential complications. (iv) The 3D model was also an educational tool for training, and for students to learn the anatomy of the airway, and to acquire the skills for endoscopic treatment.

Despite our impressions not being supported by a statistical analysis because of the lack of a control group, they were in line with the results of reviews,[9,10] and previous experiences on the utility of the 3D printed model for surgeons' practice in different specialties, including interventional bronchoscopy[11] and airway surgery.[9,12] Miyazaki et al[11] inserted a modified Y-shape stent for the management of stenosis of the intermediate bronchus after right single-lung transplantation. The procedure was mimicked in a 3D printed model that allowed to perform it easily, quickly, and successfully in the patient. Balakrishnan et al[12] reported 5 cases of complex pediatric tracheal reconstruction for which the 3D printed model had specific benefits in planning surgery. Han et al[9] used a 3D printed model to plan the intubation in a patient who had previously undergone total laryngectomy and who was scheduled for resection of a pelvic mass.

To optimize the design of the 3-D airway model, we proposed the following recommendations. (i) To print the model using a robust and fairly soft material to avoid tearing during dilation. (ii) To place the model on a rigid support, so that it is able to resist the rigid scope forces during intubation and dilation. (iii) To keep a short period of time (not exceeding 24 h) between the simulated operation and the real procedure, to avoid losing the skills acquired with the 3D model.

Obviously, our model should be used for patient care with great caution for the following limitations. (i) The main concern is the fidelity level, as the flexibility of the material used to print the model is different from the flexibility of the trachea. Yet, no electrocautery or scissor cuts could be planned. Thus, the outcome of dilation in the patient cannot be accurately predicted from the results obtained in the 3D model. (ii) Our model is unable to detect inflammation of

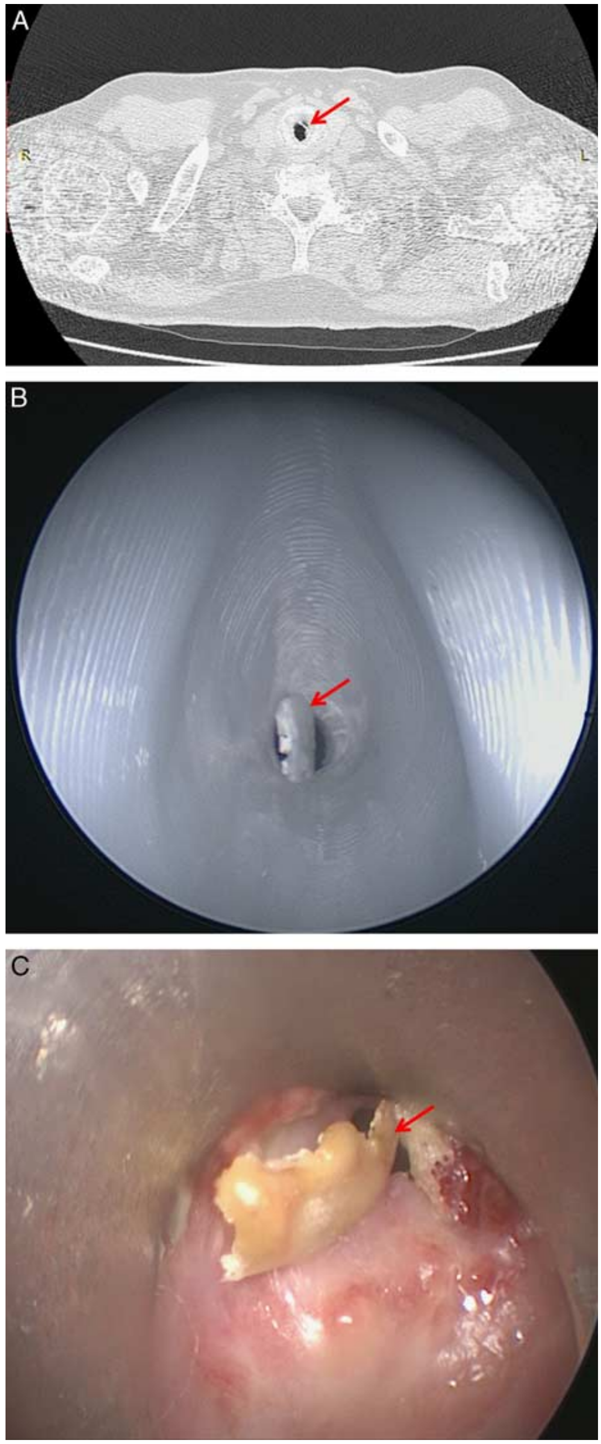

FIGURE 4. In patient 4, a tracheal ring fracture in the stenotic area (black arrow) was misdiagnosed as mucus by computed tomography (A) but correctly diagnosed by the 3D model (B) and confirmed by live bronchoscopy (C).

the airway wall, because of the lack of color variations or the presence of tracheomalacia. Under these circumstances, visual techniques such as fiberoptic bronchoscopy should be performed as a complement to the 3D printing technique. (iii) The arrangement of the model is a time and cost-consuming procedure, which ranged from 7 to 8 hours and from 75 to 90 Euros , respectively, depending on the size of the model. The limited use of the 3D model only for planning complex procedure and the presumptive reduction of operating time and complications rate could theoretically overcome these limitations. In addition, as 3D printing technology becomes widely used, it will be faster, cheaper, and simpler to obtain a 3D airway printed model.

In the future, our strategy could also have different goals, such as creating a custom home-made stent and/or a living biological tissue for replacement with structural capability by combining tissue engineering with 3D printing.

CONCLUSIONS

Our 3D airway model in the management of airway stenosis is useful for procedural planning, rehearsal, and education. Yet, it enhances communication with the patient and their family to obtain consent for the procedure. The fidelity level of the 3D model remains the main concern for its wider use in patient care. Thus, our impressions should be confirmed by future prospective studies.

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