Review Article

Innovation in rigid bronchoscopy—past, present, and future

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Contributions: (I) Conception and design: C Aravena, TR Gildea; (II) Administrative support: All authors; (III) Provision of study materials or patients: All authors; (IV) Collection and assembly of data: All authors; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

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Abstract: German laryngologist Gustav Killian performed the first "Direkte Bronchoskopie" using a rigid bronchoscope to extract a foreign airway body from the right main bronchus over a hundred years ago, transforming the practice of respiratory medicine. The procedure instantaneously became popular throughout the world. Chevalier Jackson Sr from the United States further advanced the instrument, technique, safety, and application. In the 1960s, Professors Harold H. Hopkins and N.S. Kapany introduced optical rods as well as fiberoptics that led Karl Storz to develop the cold light system improving endoluminal illumination, achievements that ushered in the modern era of flexible endoscopy. Several diagnostic and therapeutic procedures became possible such as transbronchial needle biopsy, transbronchial lung biopsy, airway electrosurgery, or cryotherapy. Dr. Jean-François Dumon from France advanced the use of Nd-YAG laser in the endobronchial tree and created the dedicated Dumon silicone stent introducing the whole new field of interventional pulmonology (IP). This major milestone revitalized interest in rigid bronchoscopy (RB). Now, advancements are being made in stenting, instrumentation, and education. RB robotic technology advancements are currently anticipated and can potentially revolutionize the practice of pulmonary medicine. In this review, we describe some of the most substantial advances related to RB from its beginning to the modern era.

Keywords: Rigid bronchoscopy (RB); innovation; Gustav Killian; Chevalier Jackson; Jean-François Dumon

Submitted Jun 06, 2022. Accepted for publication Mar 03, 2023. Published online Apr 25, 2023.
doi: 10.21037/jtd-22-779
View this article at: https://dx.doi.org/10.21037/jtd-22-779

Introduction

Everette M. Rogers described innovation as "*an idea, practice, or object that is perceived as new by an individual unit of adoption.*" (1). Rigid bronchoscopy (RB) is one such example: Gustav Killian conceived the idea, transformed it into a tool, and dramatically changed the practice of respiratory medicine for the next 100 years. Its impact was profound and widespread over the world. Since then, there have been improvements in the instrument design, optics, illumination, and utility. Many other revolutionary tools have since been developed inspired from this original and revolutionary concept, such as tracheoscopes, laryngoscopes and even flexible bronchoscopes with ever-expanding indications that have been widely adopted by the international community, bringing together multiple and previously independent specialties such as thoracic

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Figure 1 Chevalier Jackson teaching medical students. Reproduced with permission from the American Thoracic Society (7).

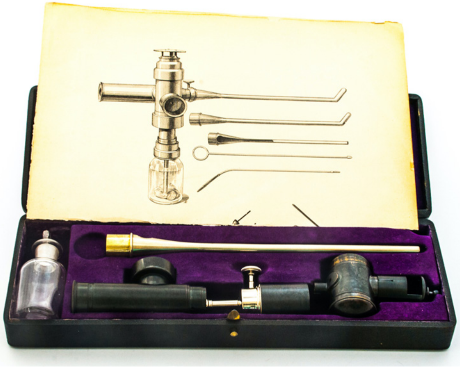

Figure 2 Antonin Jean Desormeaux's illuminating device. Reproduced with permission from Museum and Archive, German Society of Urology.

surgery, otolaryngology, and interventional pulmonology (IP), to optimally manage central airway disorders in a multidisciplinary fashion. In this review, we illustrate some of the most significant innovations related to RB, describing how it started, showing the current advancement and picturing the future.

The beginning

Gustav Killian, a German laryngologist, learned the laryngoscopy technique from Kirstein and had the idea to modify Rosenheim's esophagoscope to access the lower airways (2,3). He was the first to reach passed the larynx into the trachea and beyond the main carina into the bronchi (4). In 1897, he successfully removed a foreign body from the right main stem bronchus for the first time (4). It was the beginning of a new era, which instantly reduced the mortality rate significantly from foreign body aspiration (5). Later, in the United States, Algernon Coolidge performed the first tracheo-bronchoscopy using an open urethroscope and a head-mirror to remove a hard-rubber cannula from the right main bronchus at the Massachusetts General Hospital in 1898 (6). In 1904, Chevalier Jackson Sr, a US otolaryngologist, developed a safer and simpler bronchoscopic technique by adding distal illumination and designing numerous tools to remove foreign bodies and take biopsies, thus advancing bronchoscopic management of benign and malignant airway diseases (*Figure 1*) (3,8-12). The Mutter Museum in Philadelphia, Pennsylvania, exhibits the collection of numerous foreign bodies removed by Dr. Jackson over the years.

Illumination

The crucial step in the advancement of endoscopy was endoluminal illumination. The French urologist Antonin Jean Desormeaux (1815–1894) is considered the real founder of practical endoscopy. In 1853, he introduced an illuminated urethroscope to the Academy of Medicine in Paris (12). The design of the instrument was similar to that introduced by Bozzini, but the source of light was "gazogene", a mixture of alcohol and one part turpentine (*Figure 2*). Kussmaul used the device to perform the first illuminated rigid esophagoscopy.

A significant milestone was reached in 1887 when the German urologist Maximilian Nitze introduced the first miniature electric bulb without a separate cooling system (12-16). Up to this point, all endobronchial illumination was achieved using an external source. Einhorn from the United States built the first esophagoscope with a distally illuminated tube. Chevalier Jackson Sr used this concept for his laryngeal and endobronchial procedures (12). In 1940, Broyles perfected optical bronchoscopic telescopes and forceps illuminated by a small bulb at the tip, and later, introduced the first fiber illuminated bronchoscope (12).

The invention of the rod-lens system by Harold H. Hopkins and N.S. Kapany in 1959 led Karl Storz, a German physician, to develop the cold light illumination system, which was instrumental in the design of the current rigid telescope and the flexible fiberbronchoscope (17-20).

Anesthesia

Improvement in anesthesia techniques was fundamental to the practice of bronchoscopy. In 1884, Jellinek introduced cocaine as a local anesthetic, blunting pharyngeal and laryngeal reflexes. Cocaine allowed Killian to perform his human procedures using topical anesthesia (3,4). Progressive pharmacological advancement led to the development of general anesthesia (21). In 1967, Sander's ventilation technique using thiopentone, suxamethonium, and jet ventilation, further improved anesthesia during bronchoscopy (22,23).

Diagnostic and therapeutic tools

Following these achievements in anesthesia techniques, several procedures became possible using the rigid bronchoscope as a diagnostic as well as a therapeutic tool. In 1949, Eduardo Schieppati was the first to perform a transbronchial needle aspiration (TBNA) for subcarinal adenopathy using a RB. The technique was later perfected by Euler in 1955 and Schiessle in 1962 for mediastinal masses (3,24,25). Euler, in 1948 used a similar technique of transbronchial access to perform pulmonary and aortic angiography (3). Howard Anderson from the Mayo Clinic was the first to carry out transbronchial lung biopsy using RB and forceps in 1965 (26).

The rigid bronchoscope was recognized as a tool that kept the airway secure, allowing safer re-canalization of central airways while managing major hemoptysis in expert hands (27-31).

The application of airway electrosurgery through RB was described in 1932 when Francis E. Gilfoy reported a case of a sessile tumor just above the main carina. He fulgurated it successfully several times (32). Then, in 1933, Kernan published a series of ten cases of carcinoma of the lung and bronchus treated with radon implantation and diathermy (33). Afterwards, significant complications decreased its use until new advancements allowed improvements in this technology to regain its usage, especially in flexible bronchoscopy (34,35).

The use of cryotherapy in the tracheobronchial tree started in the US in 1974 (36). Neel, Sanderson, and Carpenter experimented with animals and carried out the first cases on humans (37-40). They developed the technique and a 55 cm. cryosurgical probe (36,37,39). After a few years, this method dropped in favor of the laser. Posteriorly, Maiwand in the United Kingdom and Homasson in France began to use this technique again (41-43).

Strong, in 1974, and Laforet in 1976, were the first to use Carbon Dioxide (CO_2) laser in benign and malignant diseases of the trachea and bronchi respectively (44,45). Toty and Dumon from France, and Shapshay and McDougall from the United States were the pioneers in using neodymium-doped yttrium aluminum garnet (Nd:YAG) laser through the rigid bronchoscope (3,27,28,46-52).

The use of endobronchial stents can be traced back to the 19th century (53). However, the development of the Montgomery T-tube and the dedicated Dumon silicone stent revolutionized the management of benign and malignant central airway diseases (54-57). Today, J. F. Dumon is recognized as the father of modern RB and IP for his contribution to managing central airway diseases using laser and silicone stents, improvements in the rigid scope, and RB teaching to physicians worldwide (7,58).

Advancements in the modern era

Education

The introduction of the flexible fiberbronchoscope by Shigeto Ikeda in 1966, resulted in a precipitous drop in the number of RB performed (20,59). However, J. F. Dumon in Marseille, France continued to promote the practice of RB, especially to carry out laser photocoagulation and stent placement. He also designed several devices to efficiently place silicone stents in the endobronchial tree. Thus, Dumon has been rightly credited for the resurgence and instruction of the technique (60).

Today, a number of hands-on courses in RB are routinely offered around the world, and IP has become a well-recognized subspecialty (60,61). More than 50 fellowship programs in IP have emerged in the United States alone, carrying on the torch of RB (62). The American Association for Bronchology and Interventional Pulmonology, founded in 1992, the American College of Chest Physicians and the Association of Interventional Pulmonary Fellowship Directors have worked tirelessly to formalize IP training, establish standards, and develop the curriculum necessary for accreditation of IP fellowships (7,62-66). Similar efforts have also been made in Europe, Australia and New Zealand, India and South America (67-69).

RB is also performed in thoracic surgery as well as otolaryngology, yet not all specialties have adopted a standardized curriculum to demonstrate that necessary competencies have been acquired (70).

The role of simulation training specific to RB using mannequin and cadaver models has continued to improve the educational training of both trainees and physicians seeking to gain knowledge and competency in RB (71).

In an effort to improve skills acquisition and standardization, simulators have been introduced and are now commonly used in many training programs. In a systematic review, Cook *et al.* showed that simulation-based bronchoscopy training is effective for various tasks, including RB (72). Salud *et al.* assessed RB performance in a manikin-based simulation with pressure sensors. When experienced and novice operators were evaluated, novices touched more areas and exerted more tissue pressure (73). Hsiung and colleagues designed a pediatric RB model to retrieve airway foreign bodies to train and assess pediatric surgical trainees' RB skills (74).

Deutsch *et al.* investigated multiple modalities for RB training and suggested that animal models remain superior for the acquisition of psychomotor skills, with the obvious ethical caveats entailed (75). A study lead by Barrete characterized the forces and torques in RB. This study showed discrepancies between forces and torques applied during manikin and patient intubation, indicating a possible mismatch between the haptic feedback received by clinicians in RB training and its application in real cases (76). These findings could mean that more emphasis should be made on training in cadavers, and simulators with physical resemblance are needed (77). In an attempt to further improve training models, Al-Ramahi *et al.* created a 3D printed airway simulating the size and mechanical properties of various age group airways for foreign body removal training (78).

The use of real-time feedback on skills as well as utilization of video assessment of the learner allows additional learner self-adjustment in procedural egometrics (71).

Attempts have also been made to standardize skills assessment. Mahmood *et al.* developed a tool to objectively assess essential competencies in RB: this tool (RIGID-TASC) was shown to be accurate and reproducible to score and classify operators from novice to expert in RB intubation and navigation (79). This tool is may be considered an essential step to assess competency and give task-specific feedback in RB training (79).

In the near future, it will be desirable that the physicians in practice develop skills on realistic training models, complete stepwise progression to more challenging complex tasks, and be assessed objectively to have obtained the necessary competency before performing RB procedures in patients. Basic competency skills and expertise can be achieved after a routine training period but will plateau if a deliberate practice model is not adopted (71).

The primary goal of training is to establish basic competency through deliberate practice with specific rehearsal and editing of specific tasks under supervision and constructive feedback which can lead to mastery learning (71). Mastery in procedural skills remains a dynamic ongoing process beyond a dedicated year of IP fellowship training. Adaptation to evolving technology beyond postgraduate training requires the same deliberate skills practice (71).

Instrumentation

A few notable changes have taken place in the scope design and instrumentation since the end of the last century. The most widely used RB devices at this time are those built by Karl Storz, Richard Wolf, and Dumon (58).

The Efer-Dumon® rigid bronchoscope (EFER Endoscopy, La Ciotat, France) was designed in 1985. Enhancements were made in 2000 and then in 2014 with improvements in intubation tubes, stent placement instrumentation, accessories, and video bronchoscopy system. One of the most prominent characteristics of the Efer-Dumon® RB is its modular connector. This locking system has a 360° rotating ventilation port and an airtight union between the tubes and the universal base. Its video system has autoclavable optics with digital technology and a variable focal length coupler allowing loss-less image size adjustment (80).

Additional advancements have been made by Richard Wolf GmbH, a company based in Germany. It developed the TEXAS bronchoscope, which has an integrated semi-flexible telescope in a separate scope channel, allowing for a larger inner lumen for instrumentation. It has a distal lens irrigation system which allows intraprocedural cleaning if the lens gets obscured with secretion or blood. Additionally, there are other accessories like endobronchial shaver blades and tip-controlled instruments (scissors and forceps) with articulation in the distal tip and a 360-degree rotatable shaft. Images advances have been achieved integrating the 4K technology (ENDOCAM logic 4K®) which provides four times improvement in the resolution of a regular HD camera (81).

Stenting

In 1987, Dumon created a studded cylindrical prosthesis made of silicone to maintain patency in patients with extrinsic or mixed airway obstruction (56,57). The use of RB is essential in silicone stent placement and removal (57,82). Additionally to the indispensable proceduralist expertise, the rigid scope and several rigid tools are crucial

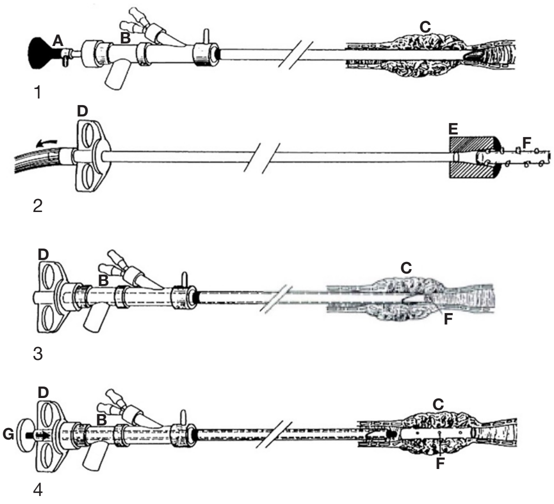

Figure 3 How to load and deploy a silicone stent in this illustration. Step one: using the telescope the RB is advance to the stenosis. Step two: the prosthesis is inserted in the introducer tube. Step three: the introducer tube is passed through the RB. Step four: the prosthesis is pushed into the stenosis. (A) Telescope. (B) RB. (C) Stenosis. (D) Prosthesis introducer tube. (E) Funnel loader. (F) Prosthesis. (G) Prosthesis pusher. Reproduced with permission from Elsevier (55). RB, rigid bronchoscope.

for the stenting technique (57) (*Figure 3*).

In the mid-1980s, Gianturco used a self-expandable metallic stent (SEMS) for the first time in patients with cancer (83). They were placed easily using an endotracheal tube, a Teflon catheter, and fluoroscopic guidance (83). Hence, metallic stents became more extensively used because of their properties, such as easy deployment or radiopacity (83). However, severe complications such as granulation tissue or tumor in-growth, difficulty to be removed and airway or vascular perforation discouraged their use, especially in patients with benign airway diseases, leading to a black box warning from the FDA (84,85). Since then, significant advances in metal stent technology have been achieved, leveraging the advantage of self-expandable metal stents now fully or partially covered to mitigate these complications (86,87). Despite all those improvements, some experts still recommend RB for central airway stent placement and removal irrespective of the type of stent used because it is a safe and effective method (82). A 2020 tracheobronchial stenting survey with data from 47 countries showed that respondents used RB (either alone or in combination with flexible bronchoscopy) in 84% of stent placement and 93% of removal despite SEMS being the most commonly used stents (88).

A recent study performed by the ESCODULE study group compared two sets of subjects from a retrospective cohort of patients with malignant central airway obstruction (CAO) treated with either Dumon silicone stent or third-generation SEMS (Aerstent® Leufen Medical GmbH, Germany). It showed that both stents successfully restored airway patency, but there was a significantly increase in complications with Aerstent® (89). This study used RB for all patients, and despite the improved operating characteristics in metal stents it shows that RB continues to have a value (89).

We anticipate that stents will continue to evolve with some recent promising innovations worth discussing here. Stents with biodegradable (BD) material that could maintain patency in an airway for a limited time are the subject of extensive research (90). They might be helpful in benign airway diseases when temporal stenting is desirable (84). Several synthetic degradable polymers have been studied (90-94). Research in animal models and patients have demonstrated a good safety profile, biocompatibility, and stent degradation-time depending on the polymer used (93,95-99).

3D technology is also being used to create stents. Patients with complex benign airway diseases require frequent interventions and stenting to restore airways patency (100). Thomas R. Gildea, trying to improve management in patients with complex non-malignant central airway diseases, developed a patient-specific silicone airway stent (3DPSS) using computed tomography imaging and 3D printing technology (101,102). A retrospective evaluation at the Cleveland Clinic under FDA expanded access compared 3DPSS to commercially available stents (CAS), showed no difference in stent loading, placement, or removal, and the mean duration between bronchoscopies was significantly longer with 3DPSS when compared to CAS (100,103). Common adverse events observed with CAS were less frequent with 3DPSS, and a significant increase in the lifespan of the patient-specific stents was observed (100,104) (*Figure 4*). Moreover, RB remains an important and relevant tool for these recent stent innovations (100,105,106).

In high-risk RB stenting for central airway obstruction and imminent ventilation failure, ECMO has been used as ventilatory support in patients with malignant and benign diseases. Several case reports suggest favorable outcomes and a low complication rate (107-113).

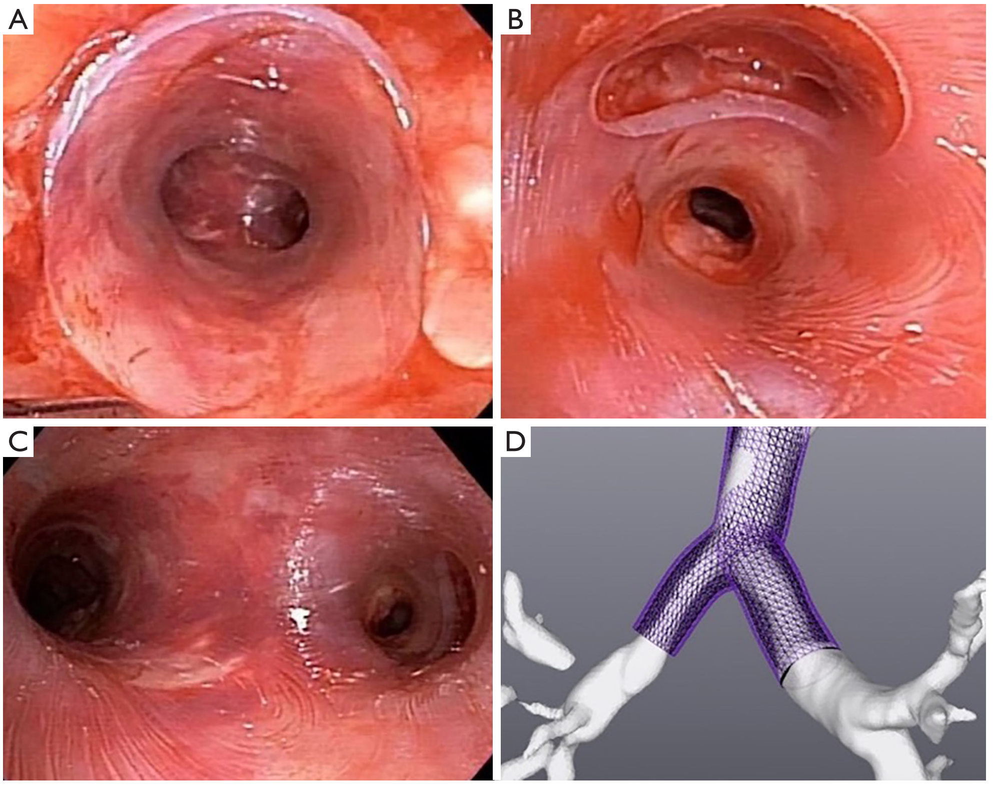

Figure 4 PSS created with 3D printing technology for a patient with a complex airway secondary to Granulomatosis with polyangiitis. Y-PSS, tracheal limb (A); right main stem limb (B); main carina, observe the PSS perfectly fit in the complex airway (C); after a 3D virtual prototype of the airway is created. The physician uses the software tools to make a virtual representation of the patient specific silicone stent based on clinical needs (D) (reproduced with permission from Visionair3D). PSS, patient specific silicone stent.

Future in RB

Robotic endoscopic technology was recently introduced in pulmonary medicine, attempting to improve the performance of flexible bronchoscopy in peripheral pulmonary lesions (114-119). Safety and feasibility studies have been performed (120). A study designed to evaluate the clinical safety and diagnostic accuracy of the robotic-assisted bronchoscopy with biopsy in pulmonary lesions is currently recruiting (ClinicalTrials.gov Identifier: NCT04182815). However, this technology has been developed for diagnosis in the lung periphery and could potentially deliver needle-based therapy.

Recent research and development have focused on therapeutic RB for treatment of CAO. Gafford *et al.* developed a new robotic system based on thin robotic manipulators embedded in a standard rigid bronchoscope. These articulated tools bend and elongate to provide maneuverability at the level of the target, without scope movement (121). They used an *ex-vivo* model to demonstrate the ability to remove tissue and restore airway patency efficiently. Pre- and post-CT scans showed a reduction of the airway obstruction from 75% to 14% (average) for five CAO resections performed (121). They also established the robotic system's potential to significantly reduce the forces applied to the patient's head and neck (from 80.6 to 4.1 N) (121).

This feasibility study opens avenues to explore endoscopic airway surgery further (*Figure 5*). Endoscopic tracheal repair is intended only when the patient is unsuitable for surgery and relies on secondary healing after stent deployment (122). Endoscopic airway surgery remains anecdotal (123).

An RB robotic system in the future could have the potential to revolutionize respiratory medicine again and treat endoscopically airway dehiscence, subglottic or tracheal stenosis, tracheomalacia, and perform thoracic natural orifice transluminal endoscopic surgery (NOTES) (124-126).

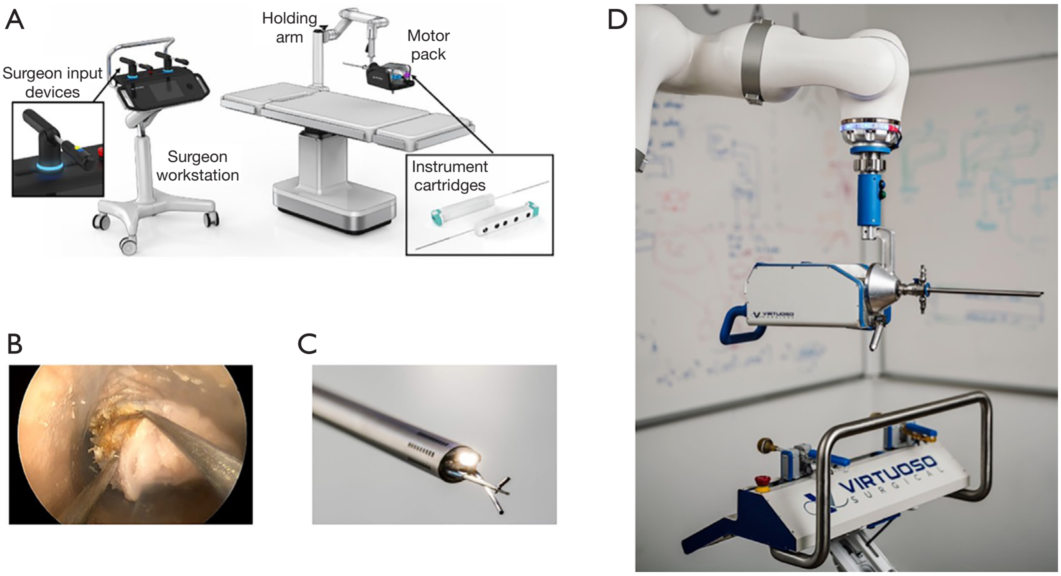

Figure 5 Rigid bronchoscopy robotic system (Virtuoso surgical Inc.). (A) Robotic system rendering. (B) Endoscopic view and pluck model. (C) Endoscopic tip and manipulators. (D) Robotic system and holding arm. Reproduced with permission from Virtuoso Surgical, Inc.

In the future, we envision the development of highly maneuverable articulated arm bronchoscopic robots that can work in small, angled areas, combining different tools that have the potential to make a precise cut, dissection, suture, resection, ablation, or coagulation to solve luminal, airway wall, or extraluminal problems.

Conclusions

We have witnessed over one hundred years of innovation in RB. Significant improvements in instruments, optics, techniques, and procedures have been achieved. Evolving diagnostic and therapeutic tools are likely to cement the important role of RB further. We envision developments in RB robotic technology to have the potential to continue to revolutionize respiratory medicine.

Acknowledgments

Funding: None.

Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://jtd.amegroups.com/article/view/10.21037/jtd-22-779/coif). Cleveland Clinic and Cleveland Clinic Institutional Officials/Leaders have an equity interest in Visionair and are entitled to royalty payments from the company for technology developed at Cleveland Clinic. Visionair is the manufacturer of the stents mentioned in this review. TRG is the inventor and may be entitled to royalty payments from the company in accordance with Cleveland Clinic policy. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Cite this article as: Aravena C, Mehta AC, Almeida FA, Lamb C, Maldonado F, Gildea TR. Innovation in rigid bronchoscopy—past, present, and future. J Thorac Dis 2023;15(5):2836-2847. doi: 10.21037/jtd-22-779

