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Short review

Integration of 3D printing and additive manufacturing in the interventional pulmonologist's toolbox

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ABSTRACT

New 3D technologies are rapidly entering into the surgical landscape, including in interventional pulmonology. The transition of 2D restricted data into a physical model of pathological airways by three-dimensional printing (3DP) allows rapid prototyping and fabrication of complex and patient-specific shapes and can thus help the physician to plan and guide complex procedures. Furthermore, computer-assisted designed (CAD) patient-specific devices have already helped surgeons overcome several therapeutic impasses and are likely to rapidly cover a wider range of situations. We report herein with a special focus on our clinical experience: *i)* how additive manufacturing is progressively integrated into the management of complex central airways diseases; *ii)* the appealing future directions of these new technologies, including the potential of the emerging technique of bioprinting; *iii)* the main pitfalls that could delay its introduction into routine care.

1. Introduction

Additive manufacturing, including three-dimensional printing (3DP) and other computer-aided conception techniques, consist of transforming numerical two-dimensional (2D) data into a physical object. This approach allows rapid prototyping and onsite production of complex and unique shapes, therefore it's likely to change the way interventional pulmonologists anticipate and manage uncommon situations. We report herein the main current applications reported so far, our expectations for the future of these appealing technologies, and the potential obstacles to its integration into clinical care.

1.1. 3DP, a new tool to plan and guide complex procedures

In 3DP, a printing machine uses data from a computer-aided design (CAD) to create a physical object, by laying down successive layers of material (liquid, powder, or sheet material). The use of 3DP for the management of select cases with atypical anatomy or before limited resection was first reported in thoracic surgery. Thoracoscopic procedures can be challenging in patients with bronchial variations. Akiba et al. used a 3D replica of the airway anatomy to guide a segmentectomy of a B3 (right upper lobe) tumor [1]. This same approach has been found to be useful for better preoperative comprehension of the uncommon anatomy of a patient planned for another conservative surgery [2]. Finally, Gillaspie et al. reported the new process of “5D-printing” for the surgical planning for removal of a thoracic tumor that has spatially complex relationships with surroundings organs [3]. Color-codes allow for the integration of the degree of tumor response to induction therapy into the 5D model using fused pre and post-treatment data: *i)* CT-changes as a fourth dimension, *ii)* metabolic activity measured by PET as a fifth dimension.

3DP then entered the field of interventional bronchoscopy. Miyazaki et al. used a 3D printed airway model to manage a stenosis of the BI (*bronchus intermedius*) in a lung-transplant recipient [4]. A Novatech® Y-shaped stent was accurately modified, the creation of an orifice on the stent to ventilate the upper right lobe being guided by the 3D device. We also described our experience with 3D printed models of corrected airways (virtual resolution of the endoluminal tumor and/or compression using dedicated softwares) to choose and customize airway stents. This approach may be particularly useful in cases of obstruction involving any secondary carina as the stent choice depends on a number of spatial factors (e.g. length and angles). In addition, other airway orifices often need to be considered so these are not occluding when the stent is deployed. We have reported a case of stenting

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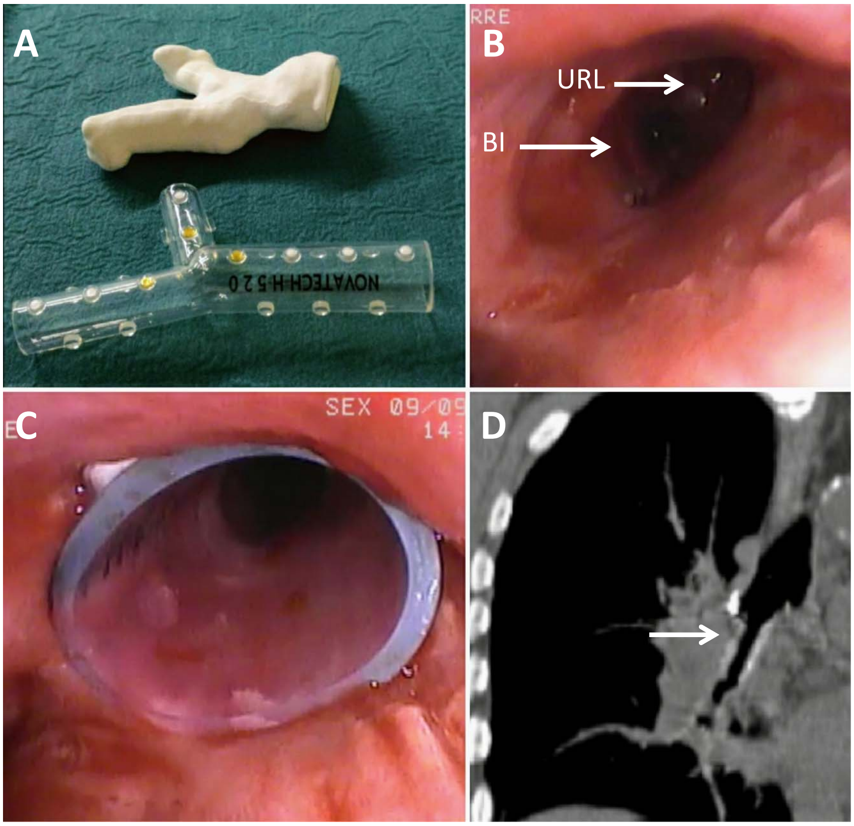

Fig. 1. 1A: 3D-printed model of right main bronchus (Builder premium medium®) after virtual correction of the obstruction (VGStudioMax 3.0, Volume Graphics GmbH®), allowing for the customization of an Oki Stent (Novatech®); **1B**: Bronchoscopic view of the right main bronchi after mechanical debulking of the intraluminal obstruction and dilatation **1C:** Bronchoscopic view after stent insertion under rigid bronchoscopy, showing good accuracy of the modified stent; **1D**: Sagittal CT-scan view after stenting, showing good congruence of the modified stent with the right main bronchus, right upper lobe and *bronchus intermedius*. URL: upper right lobe; BI: *bronchus intermedius*.

a right main bronchus malignant compression guided by 3D printed airways after virtual resolution of the obstruction [5]. Another example is shown in Fig. 1. We are now expanding the use of these new technologies to other complex airways diseases, such as complex tracheal stenosis [6].

1.2. Additive manufacturing of patient-specific medical devices

Zoft et al. used a dedicated bioresorbable 3D printed polycaprolactone airway splint to relieve a compression of the left mainstem bronchus between abnormal ascending and descending aortas in a premature child. This customized device allowed for the management of a therapeutic impasse: a patient suffering recurring cardiopulmonary arrests despite tracheostomy, sedation and ventilation [7]. This approach has been successful in three other pediatric patients [8] and in a 46 years-old patient with tracheomalacia [9] and may become routine practice in a not too distant future.

Stenting is a major tool in the therapeutic arsenal of the interventional pulmonologist but suffers from many pitfalls. The ideal stent should *i)* be easy to place and remove *ii)* have sufficient external diameter to prevent migration but not too wide as to avoid granulation tissue reaction *iii)* maintain mucociliary drainage *iv)* be rigid enough to relieve the compression but maintain flexibility to mimic the physiology of the airways that it covers and *v)* be as suitable as possible to the patient's anatomy. Computer-assisted design and fabrication, based on CT data, may lead to improved tolerance and a decrease in complication rates. Recently, we reported, for the first time, the treatment of a post-transplant central airway obstruction by a fully customized silicone airway stent using CAD (3D CNC machine) [10]. The clinical status of this patient was very worrying because the evolution of his *bronchus intermedius* stenosis was unfavorable and no conventional stent was suited for the complex anatomy of his airways. Fig. 2 illustrates another example of a patient suffering from anatomically complex localized tracheomalacia complicating an aortic aneurysm surgery. Lower

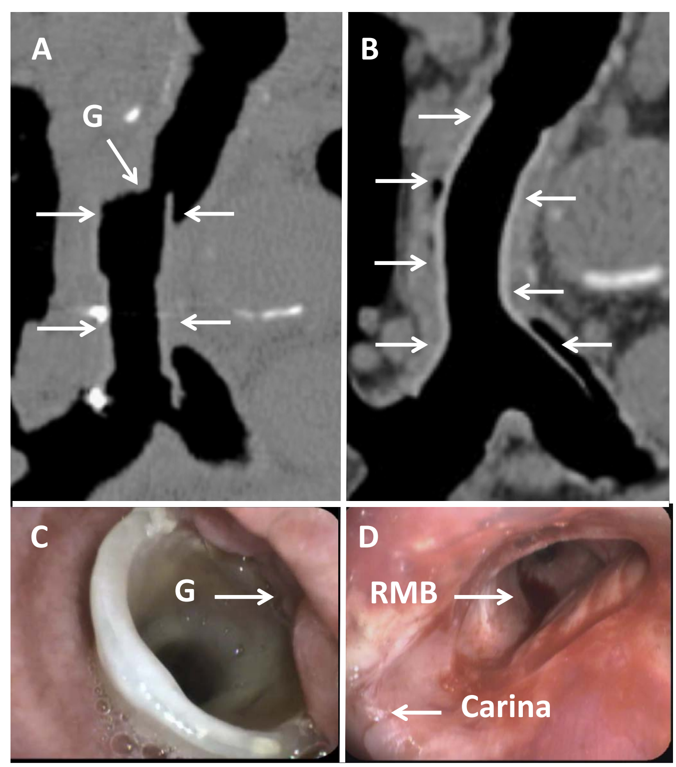

Fig. 2. Malacia limited to a short portion of the trachea, complicating an aortic aneurysm surgery. 2A: Previous stent, non-suitable for the particular anatomy of the trachea, resulting in significant granulation tissue reaction (G) at its upper extremity. 2B: Same patient after electro-coagulation of the granulation tissue and implantation of a customized computer-assisted designed, 3D stent, resulting in great congruence. 2C: Bronchoscopic view of the granulation tissue reaction (G) at the upper extremity of the conventional Novatech stent. 2D: Bronchoscopic view of the customized stent, showing perfect congruence with the airways (RMB: Right main bronchus).

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