Latest technology in minimally invasive thoracic surgery

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Abstract: From the introduction of video-assisted thoracoscopic surgery (VATS) in the 1990s, to performing major lung resections using a uniportal VATS approach, technology has paved the way for the development of minimally invasive thoracic surgery. Natural orifice access to achieve a 'no port' approach, is also on the rise, with advancements in bronchoscopic techniques for diagnosis and therapy, as well as development of soft robotics to achieve desired flexibility, dexterity and stability in future platforms, which may involve *in vivo* deployment to bring the surgeon totally inside the body. Development of haptic feedback in robotic platforms to enhance the surgical experience is also a major goal, with vibrotactile and mechanical feedback generation, to replicate the traditional touch. In addition, the aid of technology in the form of procedural guidance mechanisms, like augmented reality, will further improve the safety and accuracy of future operations.

Keywords: Incisionless; natural orifice transluminal endoscopic surgery (NOTES); robotic; video-assisted thoracoscopic surgery (VATS); uniportal

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Introduction

As technology continues to shape our future and integrate into every aspect of our lives, it has become almost indispensable to live without the buzz or glow of gadget screens. Likewise, it has been the backbone of the advancement in thoracic surgery over the recent decades; with the advent of the thoracoscope, minimally invasive thoracic surgery has gone beyond large, painful incisions in promise of better patient recovery and outcomes. From multiple ports to single port operations, the envelope has been pushed for less invasive and for smaller approaches. As seen in other fields of surgery, minimal access has been the common battleground, giving rise to "incisionless" natural orifice transluminal endoscopic surgery, and the increasing adoption of robotics, harnessing enhanced 3-dimensional (3D) visuals and increased dexterity (1,2). Despite the challenges in the pursuit of more intelligent robotic designs for better outcomes in patient care, the future of thoracic surgery will surely take on a similar path, to incorporate robotic technology and the concept of natural orifice, "incisionless" or "no port" techniques. The following article will discuss the possible directions robotic technology can take in the field of thoracic surgery, with respect to possible robotic designs, and notable challenges faced in areas of haptic feedback, as well as lesion localisation for more safe, and effective surgical procedures.

Video-assisted thoracoscopic surgery (VATS) has evolved over the past 2 decades to become a safe, viable alternative to lung cancer treatment, with the proportion of VATS lobectomies increasing from 8% in 2003 to 44.7% by 2010 as shown in data from The Society of Thoracic Surgery General Thoracic Surgery Database (3). At the forefront of this paradigm shift is the birth of the uniportal approach to lung resection first described in 2004 by Rocco *et al.* (4). Since then, the adoption of this minimally invasive approach has seen popularity worldwide, especially in China. Take for example, the Shanghai Pulmonary Hospital (SPH), which saw its first VATS operation in 1994, rising to over 8,000 operations performed in the year 2016, and the majority of these being VATS operations. After its introduction in 2012 to SPH, in between 2012 and 2014 alone, over 1,000 lobectomies were performed via the novel uniportal VATS approach (5).

Given increasing trends of lung cancer screening, evidenced by improved outcomes using low-dose CT as established by the National Lung Screening Trial Research Team (6), the potential increase in incidental findings of small lung nodules requires different management approach that aims to provide early precise diagnosis, good oncological outcomes, whilst using minimally invasive techniques. This has been an area of development in thoracic surgery, and the role of the bronchoscope in diagnosis and staging of lung cancer has also been on an increasing trend, especially with introduction of novel techniques such as endobronchial ultrasound (EBUS) and electromagnetic navigation bronchoscopy in hybrid operating theatres (7,8). In a single centre observational retrospective study in Taiwan over an 11-year period, the proportion of subjects diagnosed using bronchoscopy increased from 39.4% to 47.4% in the period after the introduction of EBUS, with a significant decrease in the reliance of other diagnostic modalities including CT guided biopsy and pleural effusion cytology (9).

Natural orifice access & soft robots

Natural orifice techniques have also been an area of interest; with studies looking at various access points like transesophageal, transgastric or transtracheal, but some of these have been limited by lack of flexible instrumentation, or confined workspace leading to suboptimal results (1). With this, the future may see soft robots, utilising natural orifice access like the transoral route to traverse the airways, for excisional biopsies, or even curative resection. This would advance beyond using hand held endoscopic or thoracoscopic instruments that may be restrictive at the access points, but rather deploying soft, flexible "*in vivo*" miniature robots that could squeeze through the airways, and reach lung nodules whilst being controlled at a console by the surgeon.

Perhaps as an intermediate step towards this, a study (10) on the use of concentric tube robots and steerable needles, have allowed for the biopsy of peripherally located nodules with the aid of robotics. A 3-stage approach consisted of navigation to desired location with bronchoscopy, concentric tube robot for aiming and moving through the bronchial wall, while a bevel tip steerable needle manoeuvres through lung tissue to reach the target for biopsy. This allows for targeting of lesions in the lung via a transoral route, and also sets the scene for potential integration of *in vivo* robots to perform the task. Given the possible higher degree of dexterity for navigation, and integration of all the components of the bronchoscope, the concentric tube and needle instrumentation into one robot that can be deployed to reach the desired location, cut through the bronchial wall and lung tissue to arrive at the target.

Soft robots will be advantageous for navigation through confined spaces, however, retaining the necessary stability for traction and instrumentation, is necessary for procedures. This could be achieved with the design of the robot that allows it to be flexible at desired areas, i.e., distally, while remaining rigid in other areas, i.e., proximally (11). Although not currently achieved at a miniature level to allow for *in vivo* deployment, a large number of prototype flexible robots are being developed, utilising different techniques to achieve flexibility, including tendon/cable driven designs as seen in MASTER, Flex Robotics Systems and I^2-Snake, as well as research stage concentric tube designs, pneumatic or hydraulic control, linkage-based systems, as well as continuum arms. Other novel soft robotic platforms include STIFF-FLOP, with tuneable flexibility, the Cardioscope, as designed specifically for thoracic surgery, Anubiscope, EndoSAMURAI, and many more (12-16).

Magnetic anchored guidance is also an emerging technology in uniportal VATS, which can be seen as an intermediate stage to integrate soft robotic platforms in surgery. By overcoming challenges of fencing of instruments, the anchoring of a wireless steerable endoscope magnetically to the intrathoracic wall to replace the conventional thoracoscopic camera, would allow for more space for surgical instruments at the incision, and possibly an even smaller incision. The use of magnetic anchoring may even allow for the possibility of anchoring multiple working soft robots, in addition to the camera, for a single incision, but high flexibility intraoperative experience (17).

Flexibility in soft robots can also be achieved with use of specialised materials; Cheng *et al.* (18) at Massachusetts Institute of Technology developed a material out of foam and wax that could switch between soft and hard states by applying current, with the intention of utilising this to create a deformable robot that can traverse confined spaces in a soft state, minimise damage to its surroundings, but adopt a rigid state to perform meaningful tasks when desired. One particular inspiration for this was from observing octopuses, and certainly in the area of robotic research, biomimetic design by drawing inspiration from nature, is not uncommon (15,19). Invertebrates like worms are also obvious candidates for soft robots to mimic, and serve well to navigate through tight spaces like the airways; introduction of various flexible materials actuated by shape memory alloy actuators, as inspired by worm locomotion, have potential application in advancing soft robotics in the future (19). Similarly, in the 2017 Japan Society of Mechanical Engineers Conference on Robotics and Mechatronics in Fukushima, Japan, a group from the Tokyo Institute of Technology and Toho University presented a self-propelling catheter for navigation of the airways in a peristaltic, earthworm like motion (20). The movement of the robot was perpetuated by generating waves through pressure changes throughout its length to reach the programmed target, while another earthworm inspired soft robot designed for the gastrointestinal (GI) tract was pneumatically driven, using different sections; two expanding and one extending section allowing bending as well for crawling (21). If soft robotic technology can be married with the likes of these biomimetic self-propelling catheters, to be able to figuratively place the surgeon inside the airways to reach pulmonary nodules for procedures, would become a new reality.

Haptic feedback

In addition to the design of flexible soft robots, a major challenge faced in robotic surgery nowadays, is the complete lack of haptic feedback due to the remote control in a modern master-slave control system like the da Vinci robot, demanding the surgeon to learn visual cues instead. In the palpation and dissection of tissue, haptics is important, for example in identifying lung nodules and gauging force limits during tissue manipulation. This is especially so, when vision is limited in confined areas like the airways, force or tactile feedback becomes useful in avoiding accidental trauma and improve precision. Taking reference from video gaming consoles, vibrations are often provided to handheld controllers to alert the player during a situation, with the addition of some form of visual input to correlate with the vibration. Haptics are also seen in modern day smartphones, either similarly as feedback for the user during certain touchscreen actions, i.e., typing on the keyboard, or seen in various Apple products like the iPhone, a force sensor to produce actions (22). Specifically, the Force Touch, and 3D Touch functions, based on force sensing and a brand name Taptic engine, is an interesting piece of technology that can register a user's varying degrees of force applied to produce different actions on the phone, or laptop, with various vibrations to simulate and generate tactile feedback, even vibrotactile illusions. This concept can be adopted in development of haptics in robotic surgery, for example being able to sense, through vibrating feedback, exactly how much force is being applied via an instrument to delineate the resistance of the tissue being handled, and therefore be able to know the limit of how much force to apply. This may even help determine various anatomical structures, or tumours through determining the force applied to grasp, or "palpate" the tissue. Prior calibration of various tissue, or material "consistencies", like the limit of particular sutures, or the force applied when grasping lung tissue, can help the robot set constraints or actively resist, to alert the surgeon whether the force applied is within normal range. This is similar to haptic virtual fixtures; to provide physical constraint or force resistance in some robotic haptics development (23,24).

Small pulses of vibrating feedback can be sent to the surgeon via the controls at the console, or a wearable device on the surgeon's hand, fingers or wrist, like a glove or wristband, with varying frequency and strength of vibration to correlate with the force applied via the instruments. In addition, to vibration, lateral skin stretch feedback has been an area of research with promising results, by stretching the skin to stimulate mechanoreceptors, or normal skin deformation to simulate palpation for example. Small wearable devices over the finger pads, due to the high density of mechanoreceptors, are under development, and can see future application in surgery by providing more detailed and complex haptic feedback; vibrotactile illusions like pulling sensations, can be achieved through asymmetrical vibrations on the skin, or modelling for rough surfaces by using different frequencies of vibrations to stimulate the Pacinian or Meissner corpuscles for the desired textural sensations (24,25). A combination of vibrations and mechanic feedback like lateral skin stretch can enhance the feedback sensation, while additional visual input, like a dynamic force indicator or scale, can also be visualised on the display to further elucidate force and tension applied. Force sensors could utilise thin piezoelectric or piezoresistive actuators, strain gauge, or tactile instrumented membranes, to generate force values, and provide sensory haptic feedback—the challenge is making them small enough, and precise enough for *in vivo* robotics (23,24,26-28). Truby *et al.* (29) at Harvard recently developed an embedded 3D-printing technique that could incorporate an organic ionic liquid-based conductive ink as an embedded sensor within the matrix of a simple, soft grasping robot, with haptic, proprioceptive, and thermoceptive sensing. As this technology matures with 3D printing of miniature robots with embedded sensors, the future may see such soft robots in the field of thoracic surgery.

Procedural guidance

As mentioned previously regarding the study by Swaney *et al.* (10), and the potential use of *in vivo* soft robots entirely, to biopsy, or even excise peripherally located lung nodules, a major limitation is the "blind" nature of reaching the desired target through lung tissue. Avoiding critical structures like blood vessels, is an important element to consider, as well as enhanced pathway planning to bring about the least damage, especially when one cannot see vessels or nodules intraoperatively, and even more so in the context of confined spaces like the airways—this can be achieved with the help of augmented reality. Similar to virtual reality, augmented reality aims to connect real time imaging from cameras, i.e., intraoperative view, superimposing other imaging data, to relay information on the same screen to the surgeon. This has seen most application in neurosurgery, with stereotactic operating systems for surgical navigation, and has also been seen in other fields of general surgery to relay critical information like location of anatomical structures (30). Similar techniques can be applied to intraluminal thoracic surgery, with the addition of electromagnetic tracking like in electromagnetic navigational bronchoscopy, by knowing where a catheter, or an *in vivo* robot is during a procedure, the use of established preoperative 3D reconstructions can provide information like blood vessels or tumour/nodule location (31).

With the help of augmented reality, through superimposing reconstruction scans onto the intraoperative view inside the airways, the surgeon could see if there are any critical structures nearby extraluminally, or how far he/she is from the desired target and hence be able to plan the correct route, almost like an "X-ray vision" to see through and identify all the structures around him/her at any given time. Electromagnetic tracking is useful to delineate location of the robot, and these can correlate back to preoperative 3D reconstruction scans of the patient through some form of image alignment, and therefore the display can superimpose the correct view of the scans determined by the robot location to match. This would require accurate registration and calibration between the real time image and the 3D reconstructions, as well as tracking of the robot in a 3D space if there is any rotation for example, which could be achieved through prior calibration of the robot in terms of degrees of rotation along its axis, before deployment (30,32). Various methods of image alignment can be adopted, like infrared sensors that could be paired with electromagnetic tracking, or methods that don't require dedicated markers, but instead using a miniature stereoscopic camera for real time 3D modelling of the surgical site with a stereo-matching algorithm (31), or even the use of natural points of reference, via internal anatomical landmarks (33), to progressively register and calibrate the images as the procedure advances. Although still in its infancy, this is an area with great momentum, and would have significant impact on improving the safety and accuracy of procedures, as well as education and surgical training.

Conclusions

As technology continues to advance, the future of thoracic surgery holds many opportunities, and the integration of technology is beginning to reshape the surgical landscape. Moving forward from smaller, more intelligent robotic designs, the ultimate goal would be to recreate an all-encompassing experience for the surgeon to be enhanced by robotics, to operate in strive of better patient outcomes. While the surgical field aims to go smaller, the endeavours to do so become greater.

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Footnote

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