The future of thoracoscopes

Nicholas K. H. Fok[1], Philip K. C. Ma[2], Calvin S. H. Ng[1], Zheng Li[1,3]

[1]Department of Surgery, The Chinese University of Hong Kong, Hong Kong, China; [2]Department of Medicine and Geriatrics, Tuen Mun Hospital, Hong Kong, China; [3]Chow Yuk Ho Technology Center for Innovative Medicine, The Chinese University of Hong Kong, Hong Kong, China

Contributions: (I) Conception and design: Z Li; (II) Administrative support: Z Li; (III) Provision of study materials or patients: NK Fok, CS Ng, Z Li; (IV) Collection and assembly of data: NK Fok, Z Li; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Zheng Li. Department of Surgery, Chow Yuk Ho Technology Centre for Innovative Medicine, The Chinese University of Hong Kong, Shatin N.T., Hong Kong 999077, China. Email: lizheng@cuhk.edu.hk.

Abstract: Designs of thoracoscopes have undergone radical transformation on the growing predominance of minimally invasive surgical techniques over the open thoracotomy method for a multitude of thoracic indications. The actualized benefits and remaining challenges identified amongst commercial and experimental thoracoscopes must to be consolidated to formulate a clear direction for further advancement of the field. As such, a review of published literature on thoracoscopes, or more broadly, visualization systems employed in minimally invasive thoracic surgery has been performed. Via PubMed, 46 articles met the inclusion/exclusion criteria for this review. The thoracoscope designs were summarized into seven categories: (I) rigid thoracoscopes; (II) flexible thoracoscopes; (III) miniaturized thoracoscopes; (IV) flexible thoracoscopes for Natural Orifice Transluminal Endoscopic Surgery (NOTES); (V) thoracoscopes embedded in robotic systems; (VI) 3-dimensional thoracoscopes; and (VII) thoracoscopes with intra-parenchymal visualization. The appraisals were made according to the clinical data, experience and feedback from the experimenters within the respective category. The results were then compared across the different categories. Insights gleaned through this review reveal that commercial and experimental thoracoscopes have been making strides to overcome the two major challenges in thoracoscopic visualization: limitations in view maneuverability and misaligned intuition in control. Additional objectivity is required for comparison across the various categories of thoracoscopes to further ascertain clinical evidence regarding surgical performance and post-operative outcomes. Nevertheless, considerable room for innovation exists in tackling these two challenges, which, together, form the fundamental premise for future progression. A paradigm shift, therefore, from the current emphasis on hardware development is paramount to breakthroughs against the aforementioned challenges. The future of thoracoscopes points towards a complementary advancement of both hardware and software designs within visualization systems, with the ultimate ambition of replacing and surpassing the visual experience perceived through the open thoracotomy method.

Keywords: Endoscope; thoracoscopy; video-assisted thoracic surgery (VATS); minimally invasive thoracic surgery; robotics

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Introduction

The roots of thoracoscopes can be traced back to 1910, when the Swedish internist Han Christian Jacobaeus first peered through the small aperture of a modified cystoscope (1) to facilitate pleural adhesiolysis. A new perspective into the human thoracic cavity was thus discovered. Despite the waxing and waning enthusiasm in its application since (1), the ingenious union of the charge-coupled device with the thoracoscope in the early 1990s took the field by storm with the advent of video-assisted thoracic surgery (VATS) (2).

In the ensuing two decades up to this very point in time, a revolution in the designs of thoracoscopes has been unfolding before our eyes. These innovations are the fruits of a shared passion amongst patients, surgeons, and engineers. With unprecedented clarity of vision (3), comparable surgical performance (4), equivalent or enhanced perioperative outcomes (4-7), and the consequent cost reduction (8), thoracoscopic surgery in its different forms, particularly VATS, has established itself as the superior surgical approach in many centers. As a result, this approach is gradually replacing open thoracotomy as the standard of diagnosis and treatment for a number of thoracic conditions.

Still, the field confronts two major challenges, namely its limitations in view maneuverability and misaligned intuition in control. Therefore, the following review will evaluate the strengths and weaknesses of commercial thoracoscopes on the market in parallel with experimental thoracoscopes on laboratory benches in the light of these challenges. The insights gleaned will illuminate the next steps in pushing thoracoscope designs to new heights.

Methods

Inclusion/exclusion criteria

Articles published between 1 January 1999 to 31 December 2017; articles published in English; articles published on thoracoscopes were included. Articles without full text paper; articles published on other thoracoscopic surgical instruments were excluded.

Search strategy

A PubMed search using the Medical Subject Heading "thoracoscopic surgery; instrumentation" identified 296 articles. A broad screen of titles and abstracts yielded 97 articles. 46 full text articles were included for evaluation in this review. Reference lists of relevant articles were searched as well.

Analysis

Articles published on thoracoscopes were summarized into seven categories: (I) rigid thoracoscopes; (II) flexible thoracoscopes; (III) miniaturized thoracoscopes; (IV) flexible thoracoscopes embedded in Natural Orifice Transluminal Endoscopic Surgery systems; (V) thoracoscopes embedded in robotic systems; (VI) 3-dimensional thoracoscopes; and (VII) thoracoscopes with intra-parenchymal visualization.

Rigid thoracoscopes

Since the introduction of thoracoscopic surgery, the rigid thoracoscope has served the field well with its sturdy mechanical construct (9) and excellent image quality (9). Intra-thoracic views are transmitted from the distal objective lens of its elongated rigid shaft to the proximal charge-coupled device via fiber-optics, offering reliable video streaming of the operative scene. Building on its strengths, the rigid thoracoscope has evolved significantly to overcome its limitations in view maneuverability through reduced dimensions, beveled tips and the rotating prism mechanism.

Unlike conventional iterations with a 5–10 mm diameter, a novel rigid thoracoscope features a mere 2–3 mm diameter (10,11), hence also known as the needle-scope (Karl Storz, Germany). Such compact dimensions mitigate the maneuverability issue of instrumental fencing, both at the operative field and the incision site. The application of the needle-scope has previously been restricted for diagnostic purposes (12) because of its narrow field of view and poor image brightness (11,13,14). However, its therapeutic benefits have now been demonstrated in the management of primary spontaneous pneumothorax (11,12) and palmar hyperhidrosis (15), as well as for major procedures such as lung wedge resection (13,16) and lobectomy (13). Favorable perioperative outcomes include reduced post-operative neuralgia (13,17), length of hospital stay (12) and markedly improved cosmesis (10,11,17). Yet, its fixed 0° viewing angle and restrained three degrees of freedom combine to cause a failure in visualizing critical aspects of the operative scene. A main concern, for example, is the inability to observe the tip of surgical instruments (e.g., endostapler) while performing delicate surgical tasks (e.g., pulmonary artery ligation), leading to an inevitable compromise in terms of accuracy and safety (18).

To further optimize view changes, the rigid thoracoscope equipped with a fixed 30°/45° beveled tip allows for efficient modification of viewing angles attained through simple rotational maneuvers. Instrumental fencing is reduced compared to 0° thoracoscopes, as the oblique lens permits the scope's tip to be placed at a tangent to the operative field. However, the alternation between the 30° and 45° viewing angle comes at inconvenience of switching scopes (9). Moreover, such viewing angles are still limited, especially in uniportal VATS (UVATS), in which all instruments are inserted through a single incision and positioned towards the same direction. The lack of triangulation and persistent instrumental fencing (9) jeopardize operative safety, for example during the dissection of segmental vessels and bronchi in UVATS (19).

The wide-angled rigid thoracoscope, such as the EndoCAMeleon Telescope (Karl Storz, Germany), has therefore extended the viewing arc to 120° through the rotating prism mechanism (20). The direction of view is controlled with an adjustment knob without the need to switch scopes or move the scope shaft. Such wide, modifiable viewing angle eradicates instrumental fencing by allowing the scope's tip to be positioned entirely away from the operative field while maintaining the visual target (21). This same feature minimizes surgical errors by enabling visual confirmation, such as visualizing the tip and exit site of the endostapler anvil during the dissection of critical structures in the lung hilum (21). Similarly, the need to torque between the ribs is obviated along with the resulting intercostal nerve damage (21).

Flexible thoracoscopes

Taking a step further in terms of maneuverability, the flexible thoracoscope provides a greater field of view than open thoracotomy (22). The Endoeye Flex (Olympus, Japan) exemplifies this category by featuring a tendon-actuated tip section that can be angulated to over 100°. Its unique looking-round-the-corner/backside view (6) is essential for more extensive exploration of the thoracic cavity. Superior visualization of the difficult-to-access posterior lung hilum (6,23) and lower mediastinum (24) have been demonstrated in thoracoscopic lobectomy and esophagectomy respectively. As a result, the duration of dissection is reduced in these regions (6) by expediting major vessel and lymph node resection (25) and endostapler positioning (25). Likewise, the bendable tip facilitates adhesiolysis of pleural-parenchymal adhesions by visualizing the thoracic cavity immediately adjacent to the port (6), which otherwise could contraindicate the continuation of UVATS. More fundamentally, operative safety is augmented in the dissection of two parallel pulmonary arterial trunks (6), as the posterior branch can be visualized "from behind" (6) and avoided during endoscopic stapler positioning.

As with the wide-angled rigid thoracoscope, the tip of the Endoeye Flex can be located beyond the operating field (6) and the scope body can remain stationary at the entry port during view changes (6). These two factors combine to minimize both intra- and extra-thoracic instrumental fencing. Furthermore, the bendable tip permits the camera assistant to stand across from the surgeon (26), as opposed to the typical arrangement of standing side-by-side. Thus, surgeon fencing is eliminated as well. Taken together, thoracoscope manipulation is made to be more efficient. The stationary scope body also diminishes post-operative neuralgia with lesser torque applied onto the intercostal nerves.

Despite the progress, limitations in maneuverability still exist as instrumental fencing. This is because the Endoeye Flex's bendable tip occupies a considerable working space, leading to instrumental collision and hence unstable image. Consequently, the Cardioscope is being developed with an adjustable length of flexible segment that can bend to over 180° (27). The more dexterous control of angulation lessens the working space occupied by the tip while achieving the same angle of view.

At the far end of the spectrum, the flexible bronchoscope (Olympus, Japan) is bendable along its entire shaft length. It has been proposed to be a superior tool than the standard rigid thoracoscope in blebectomy for primary spontaneous pneumothorax (28). The high rate of recurrence after rigid thoracoscope-guided blebectomy is hypothesized to be due to the inadequate visualization of small blebs on a deflated lung, which is a prerequisite for rigid thoracoscope use (28). The flexible bronchoscope, on the other hand, can operate with an inflated lung owing to its high conformability. The tangential view of the lung surface provided while manipulating between the inflated lung and the thoracic wall assists effective identification of superficial irregularities (28). However, because of the instrument's intrinsic flexibility, support is lacking for the scope to remain stable within the thoracic cavity, rendering it difficult to maneuver.

Miniaturized thoracoscopes

As observed in the above two categories, limitations in maneuverability arise from the physical construct of thoracoscopes: tethering cables, shaft length, and overall weight. Taking advantage of the breakthroughs in optic and electronic miniaturization, novel designs have sought to alleviate these structural constrains. The Airscope eliminates the need for tethering cables with a wireless video transmitter and miniature LED lights powered by rechargeable batteries (29). Designs utilizing the magnetic anchoring and guidance system (MAGS) (30) have gone further by subtracting the scope shaft, as the camera is positioned and manipulated through the interaction of two magnets coupled across the thoracic wall.

Without a shaft, the MAGS camera is not locked at the incision site as are thoracoscopes with shafts (31) but enjoys unrestricted steering across the thoracic wall. Combined with motions of panning, rotation and magnification, the MAGS camera has revolutionized view maneuverability to 6 degrees of freedom. Moreover, because the MAGS camera is attached onto the thoracic wall via magnets and occupies a vertical working space of as little as 7 mm, there is utterly no scope interference at the operative field or incision site. Although current designs do require cables for video transmission and power, it is foreseeable that the MAGS camera would become both shaft-less and wire-less. Such a boost in maneuverability is evidenced by enhanced task performance (suturing) over conventional UVATS, with reduced workload and improved ergonomics, visualization, and needle handling (32). Additionally, image quality is heightened since the MAGS camera is anchored onto the stable thoracic wall.

To simultaneously tackle the other major challenge of misaligned intuition, future developments in this category point towards hands-free control mechanisms and image reconstruction. Eye-gaze tracking (33) and image tagging/guidance are intuitive command methods currently being investigated. Such surgeon-controlled view adjustments would allow perfect alignment between the visual axis of the camera with the motor axis of the surgeon. The resulting enhancement of hand-eye coordination would be in contrast to thoracoscopes with elongated shafts, where the axes are inevitably angled against each other.

The benefits of hand-eye coordination would not be limited to the main surgeon. Because multiple MAGS cameras could be inserted into the thoracic cavity via a single incision, the assistant surgeon, who would be operating with a different motor axis to the main surgeon, could also attain alignment with his/her own visual axis provided by another dedicated camera. Therefore, with their respective cameras orientated along the same axis as the surgeons, the surgical target, and their monitors, both surgeons would be empowered to perform in their optimal ergonomic positions. Relieved from the mental effort required to adapt to the visual axis of the main surgeon while sharing the same camera, the assistant surgeon could collaborate with the main surgeon in a more orchestrated fashion. Such concerted effort could lead to increased efficiency in performing established thoracoscopic procedures while paving the path to more complex surgeries demanding extensive team work between multiple surgeons.

Building further on the possibility of deploying multiple MAGS cameras, image reconstruction is another promising step in restoring intuition. Video inputs from contiguous viewing angles can be stitched together to generate a panoramic image of the operative scene (33,34). An alternative application could be to stream the same viewing angle at different degrees of magnification in parallel, thus indirectly overcoming the drawback of tunnel vision encountered in a magnified thoracoscopic image. These expanded fields of visualization could potentially simulate the peripheral vision experienced in open thoracic surgeries, a fundamental factor for intuitive surgical performance lost in thoracoscopic surgery.

Yet, obstacles to MAGS camera usage are anticipated in cases of increased magnetic coupling distance, for example at the extremes of the thoracic cavity (apex and diaphragm), and in the presence of an obese patient or the contours of the female breasts. Besides, from its vantage point adjoining the thoracic wall, visualization of deep tissue spaces (hilum) and hidden structures would be problematic for the MAGS camera despite magnification. This issue may confine its adoption for superficial surgical pathologies. In addition, recent advancements in anesthetic techniques for VATS involving non-intubated patients could threaten image stability as the thoracic wall (anchoring site) is expected to move with respiration throughout the procedure.

Flexible thoracoscopes embedded in Natural Orifice Trans-luminal Endoscopic Surgery (NOTES) systems

Being a radical departure from current practices, flexible thoracoscopes embedded in NOTES systems endeavor to visualize the thoracic cavity by experimenting with alternative access routes: trans-esophageal, gastric, vesicular, vaginal, umbilical approaches and percutaneous via cervical incision (35,36). Empirical research on human cadavers has demonstrated excellent visualization and exploration of the mediastinum and pleural cavities using a flexible gastroscope (Karl Storz, Germany) through a validated cervical incision (36). Progressing to in-human application, an ultra-thin flexible gastroscope has been employed for thoracic sympathectomy via the trans-umbilical approach (37). The procedure resulted in less post-operative pain and better comesis as compared to needlescopic

Figure 1 Examples of NOTES systems. (A) The Cobra's (USGI Medical, USA) shape lock provides a stable platform for the independent motion of its three arms (40); (B) the MASTER (Endo Master) is a standard dual-channel endoscope equipped with two arms capable of 4 degrees of freedom (41); (C) the Flex System (Medrobotics, USA) boasts superior flexibility in its shaft and arms to conform to anatomical lumens (42); Common drawbacks across this category include large diameter, limited triangulation, imprecise positioning.

sympathectomy (38). Given the proof-of-concept, NOTES platforms have emerged on the market, including the EndoSamurai (Olympus, Tokyo, Japan), the Anubiscope (Karl Storz, Germany), the Cobra (USGI Medical, USA), the MASTER (Endo Master), and the Flex System (Medrobotics, USA) (34,39) (*Figure 1*). Designed to work through anatomical lumens, these flexible thoracoscopes are bendable with adjustable stiffness and shape lock. The scope shaft, once locked, provides a platform on which independent actuation units at its tip are supported to perform surgical tasks.

These unorthodox approaches provide superior maneuverability to and within difficult-to-access regions. As exemplified by the trans-esophageal route, the mediastinum, the medial aspect of the lung and the hilar structures are visualized to an extent beyond conventional thoracoscopy (35). However, limitations in maneuverability arise from their ultra-flexibility as they lack firm anchorage to ensure accurate repositioning and stable images (39). The poor triangulation between the camera and the actuation units further compromises camera manipulation and the visualization of operative actions (39).

Thoracoscopes embedded in robotic systems

In spite of the swift advancement of hand-held thoracoscopes, minute adjustments are difficult when operating in narrow, poorly accessible tissue spaces. Together with the hand-eye incoordination secondary to the lack of depth perception, these factors hinder fine dissection and complex 3-dimensional motion sequences during procedures involving large and vulnerable structures such as the pulmonary artery (43). Therefore, thoracoscopes embedded in robotic systems, namely the Da Vinci surgical system (Intuitive Surgical, USA), are designed to provide unparalleled precision in camera navigation actuated by motion-scaled robotic arms (9), stability with the elimination of the tremor or fatigue factor (9), and 12-fold magnification (44). Enhanced visualization into restrictive tissue planes is realized through this delicate maneuverability.

On the intuition front, the surgeon-controlled robotic arm maintains a camera viewing axis that closely approximates his/her motor axis (25,45). Furthermore, because the input-effector interaction can be customized, the fulcrum effect is completely eliminated (2) to facilitate accurately-mirrored view changes as intended. Most essentially, the 3-dimensional binocular vision restores the sense of depth for gauging inter-object distances between surgical instruments and tissues (25,44), instead of relying on inferior, indirect 2-dimensional cues (31). The latter prolongs the learning curve and can result in mental fatigue (31). The revived depth perception is most impactful in performing fine dissection of lymph nodes, blood vessels and bronchus at the hilum (31). These benefits of robotic technology, therefore, recreate the intuitive surgical experience in open thoracotomy.

These technical advantages have translated into favorable perioperative outcomes (9), including reduced tissue trauma, blood transfusion (46), length of stay (46), and comparable or even improved mediastinal lymph node dissection (47). Further investigations are required to confirm superiority in oncological clearance, nodal detection and cancer-related survival in the long term (2). Despite being reproducible at high-functioning centers, outcome comparisons between robotic and conventional VATS are limited in sample size and difficult to interpret (9).

On the flipside, the absence of tactile feedback is a key disadvantage of robotic systems (2). Without the visual-haptic feedback, a surgeon's intuitive judgement regarding the appropriate force to be exerted through the surgical instruments is impaired for dissection, grasping and suturing. Additionally, he/she is unable to "feel" for the border of the lesions, which impedes his/her decision on the optimal resection margin. Considering the practical aspects, the high costs compared to VATS (8), steep learning curve, and prolonged setup time are major hurdles in the adoption of this technology.

3-dimensional thoracoscopes

The 3-dimensional (3D) thoracoscope aims to reverse the lack of depth perception in 2-dimensional thoracoscopes. The two lenses at the scope tip are spaced apart to recreate a binocular view of the operative field. Specialized glasses are required to appreciate the 3D image.

With this restored sense of depth and spatial location, surgeons are able to discern the distances between instruments and target tissues more intuitively (48,49). As a result, hand-eye coordination is enhanced for precision tasks requiring complex 3-dimensional maneuvers, such as grasping, suturing, and ligation (49). A significant decrease in the number of motions during suturing has been established for both experts and novices under 3D vision (49,50). This observation corresponds to the fewer trial-and-error movements required with the renewed accuracy, which in turn explains the reduction in injuries to critical organs and tissues during surgery (49).

By the same token, the 3D thoracoscope aids the visualization of hilar structures and dissection planes (25). Depth perception enables sharp discrimination between tissue layers, which allows for dexterous on-the-structure dissection of hilar, fissure, and mediastinal lymph nodes with better exposure of the left recurrent laryngeal nerve (31,49). Yet, mixed results have been reported in the literature, with minor or no improvements in perioperative outcomes (48). Of note, a shortened operative time has been documented for 3D-guided VATS lobectomy and esophagectomy (48,51,52).

The realignment of intuition by 3D imaging has benefited surgical training, translating into an accelerated learning curve for laparoscopic surgery (48). This effect, which is more prominent for novices than experts (25,49,50), can theoretically be read over to VATS.

In spite of its commercial maturity, technical challenges have plagued the adoption of 3D technology in VATS. As the two lenses cannot be rotated separately, rotating the thoracoscope leads to changes in the visual horizon, and thus distorts the 3D image (48). The resulting dizziness and nausea negatively impact surgeon performance. A restricted field of view is another issue that impairs functionality (48). As a greater distance from the target object is necessary for the dual-lenses to obtain a focused image as compared to 2D cameras, a correspondingly greater magnification is required in compensation to achieve comparable visual details (48). The resulting tunnel vision hinders the dissection of hilar structures, where peripheral vision, as offered in open thoracotomy, is critical for effective manipulation (9). On the practical front, user-friendliness is questioned with the use of glasses and large-diameter scopes (10 mm) (19,48). The early stage development of glasses-free 3D systems may prove to be a future solution (33,53).

Thoracoscopes with intra-parenchymal visualization

Intra-operative localization of lung lesions previously detected or undetected by radiological imaging remains a hurdle for VATS. This challenge stems from the reliance on visual inspection (54) under white-light imaging for surface lesion localization, which provides poor contrast between lesion and normal tissue. In a similar vein, manual palpation with tactile feedback (54) for margin delineation is increasingly restricted by ever smaller incisions. The difficulty encountered with deep-seated lesions is even more dire. Pre-operative imaging has failed to serve as a valuable guide, since positions of pre-determined lesions are altered following lung deflation (55). Consequently, intra-parenchymal visualization technologies are in development to assist real-time intra-operative lesion detection, offering an indirect solution to the lack of intuitive visual and tactile localization. These innovations include near-infrared fluorescence (NIRF), ultrasound, and single photon emission computer tomography (SPECT).

NIRF systems, such as the D-light P system (Karl Storz, Germany) and the SUPEREYE system (Key Laboratory of Molecular Imaging, Chinese Academy of Science), are designed to detect the specific wavelength of indocyanine green (ICG) fluorescence dye (54), which accumulates in tumors following pre-operative intravenous infusion. High tumor-to-surrounding tissue contrast and the ability to image a wide field simultaneously increases tumor detection rate while decreasing exploration time (54). Unpredictability in the tumor uptake of ICG, however, causes inconsistencies in these benefits. Limited by signal strength, lesion detection is restricted to those situated at less than 2 cm from the lung surface.

Approaching the problem from a different angle, the ultrasound thoracoscope (XLTF-UC180; Olympus, Japan) features a flexible convex ultrasound probe at its tip (56,57). Small, non-visible, or non-palpable lesions can be localized intra-operatively (56) without the need for pre-operative procedures. Precise estimation of lesion size and border has been evidenced by a stronger correlation between the actual tumor size and the ultrasound measurement, than with the pre-operative CT measurement (56). Nonetheless, image quality can be severely degraded in the presence of a poorly deflated lung, because the residual air between the probe and the lung nodule would cause the scattering of ultrasound (56,57). Limitations in detection depth exist as for NIRF systems.

To extend lesion detection beyond the superficial lung parenchyma, a hand-held SPECT system (declipse SPECT, SurgicEye GmbH) is being developed. The system utilizes a thoracoscopic gamma detector in conjunction with a rigid thoracoscope. Both instruments are being tracked by an optical navigation system (58). The gamma detector identifies areas of maximal radioactivity, as lesions are radioactively marked pre-operatively (58). These lesions are visualized on the video monitor as superimposed augmented reality to provide 3-dimensional information on their size and depth (58). An optimal trajectory is displayed in terms of angle and count rate in real-time to guide dissection towards the lesion (58). This assistance decreases exploration time and boosts surgeon confidence in achieving adequate resection margins (58).

Discussion

Throughout the development of thoracoscopes, both commercial and experimental solutions have attempted to tackle the two major challenges in thoracoscopic visualization: the limitations in maneuverability of view and the misaligned intuition of control. The field has risen to confront these hurdles via three distinct approaches: structural design, operational design and add-on functions.

Structural design

Ingenious structural designs have heightened the mechanical properties, and thus, capabilities of thoracoscopes in various ways, orchestrating a diversified effort to surmount key obstacles hindering view maneuverability. Restrains in field of view, degrees of freedom, and fencing have been overcome through designs of rigid thoracoscopes, flexible thoracoscopes, and miniature thoracoscopes. Flexible thoracoscopes embedded in NOTES systems could potentially optimize access and manipulation to difficult-to-reach spaces within the thorax. Despite the significant leaps forward, challenges remain in these same aspects of maneuverability, either because there is still room for advancement, or the innovative designs inevitably give rise to new issues.

Operational design

By the same token, operational design has enabled intuitive control of the thoracoscope. With thoracoscopes embedded in robotic systems, the restoration of depth perception, elimination of the fulcrum effect, and alignment of vantage points have been realized. These benefits have empowered a more natural interaction between the surgeon and his videoscopic sight. As is the case with structural designs, progress in operational designs is plagued by both unresolved and new difficulties in intuitive control.

Add-on functions

As for add-on functions, 3-dimensional thoracoscopes and thoracoscopes with intra-parenchymal visualization have pushed to further the intuitiveness of surgical tasks. They have provided an enhanced depth perception and an indirect solution to the loss of visual and tactile feedback for lesion localization respectively. Enduring technical challenges include 3D image stability and the application to lung lesions of greater depth and size.

To summarize the challenges ahead, four hurdles in terms of maneuverability remain: fixed vantage point, confined field of view, limited degrees of freedom and fencing. On the other hand, four hurdles in terms of intuition alignment remain: lack of peripheral vision, lack of tactile feedback, lack of depth perception and non-intuitive command systems.

Bearing the strengths and weaknesses of commercial and experimental thoracoscopes in mind, the future of the field is envisioned to strive towards two directions: hardware development and software development; or more specifically, where these two paths cross and complement one another.

Hardware development

Hardware development, which has been the emphasis of innovations in thoracoscopes across the three approaches described above, could benefit from hybridization with the integration of two or more established modalities. In view of their respective advantages and disadvantages, a compatible union can be formed to not only complement their weaknesses, but furthermore multiply their strengths.

A prime example would be the ENDOEYE FLEX 3D (Olympus, Japan) (25), a commercially available product that incorporated a dual-lens design into the bendable tip of a flexible thoracoscope. As such, the advantage of maneuverability offered by the flexible thoracoscope is complemented by the 3D technology's reinstated depth perception.

Another intriguing idea is to combine the application of the flexible thoracoscope with multiple MAGS cameras within the same surgery. The flexible thoracoscope could contribute its adjustable viewing angle and unique looking-round-the-corner view in deep tissue spaces; yet it is plagued by tunnel vision incapable of accommodating the entire operative field. In contrast, while the simultaneous streaming of multiple MAGS cameras could restore peripheral vision via a panoramic image, they lack the ability to look beyond the superficial visceral surface, let alone behind or around structures. Therefore, this hybrid could draw from the merits of both view maneuverability and intuition in control. The resulting effect is one that closely simulates our vision's capability of changing focal length between near and distant objects. Such a scenario could be attained while preserving the minimal invasiveness of the procedure, as a single 6-mm port is required to setup this visualization system.

Foreseeable technical challenges exist in hybridization, particularly to achieve seamless integration. Nevertheless, this process optimizes the value of existing hardware designs.

Software development

Although the field has focused primarily on breakthroughs in hardware development, the less highlighted software solutions are positioned to solve many of the persistent challenges more effectively. These softwares would aim to achieve maximal real-time exploitation of information gathered from pre- and intra-operative imaging modalities (59). Ultimately, the processed information would be presented with the endoscopic image to virtually enhance the surgeon's vision.

One type of visual augmentation would involve the overlaying of pre-operative information onto the intra-operative surgical scene (60). The information gleaned from pre-operative imaging (CT, MRI) would be tagged, coordinated, and superimposed onto the real-time endoscopic image to recreate deeper structures hidden below the surface anatomy (59). This emerging technology is exemplified by the aforementioned hand-held SPECT system (58). Such an augmentation software would offer crucial information that the surgeon is currently deprived of in VATS, including the location and margin of target lesions, the orientation to critical nearby structures (arteries, veins, nerves), and the optimal trajectory to dissect through to the desired surgical site. This solution would indirectly fulfill the need for tactile feedback, peripheral vision, and depth perception by presenting the required information visually.

Another type of visual augmentation would be a virtual expansion of the intra-operative endoscopic view realized through additional cameras and image stitching (60). Real-time imaging could be captured by multiple MAGS cameras from various angles and reconstructed into a panoramic view of the surgical field. The broaden virtual visual field would present a promising solution to the remaining limitations in maneuverability and intuition. By empowering surgeons to assume a virtual vantage point of his/her choice (59), with the ability to freely control the field and angle of view, maneuverability could become unobstructed. Moreover, tunnel vision could be eliminated to reestablish peripheral vision, which is an intuitive component to spatial orientation.

Projecting into the future, the challenges of software development would lie not merely in its technical difficulty, but more essentially, in the relevance it could possess in empowering the surgeon's visual perception (60). Considerations to the timeliness, intrusiveness, and clarity of the information presented would be necessary to precisely meet the surgeon's needs for a particular surgical task.

With the above possibilities ahead, the next steps are to define the roles of hardware and software development in future iterations of thoracoscopes. Specific pros and cons of each modality should be clearly identified to determine areas of complementation and synergy. To optimize this process, multidisciplinary collaboration between engineers, surgeons and patients will be paramount to extract the expertise and perspectives of different stakeholders while forging our way forward.

Conclusions

Over the course of this review, the thoracoscope has displayed its rapid evolution in structure and function. Looking back on its humble beginnings as a modified cystoscope, it is clear that innovations in thoracoscopes have and will continue to push the field in a converging direction: to replicate and further exceed the visual experience witnessed in open thoracotomy, while maintaining the minimal invasiveness of the surgical intervention. Therefore, these novel designs have, in their distinctive endeavors, risen to confront the two most prominent obstacles in matching the human vision: limitations in view maneuverability and misaligned intuition in control. This aspiration would remain the holy grail for future iterations of thoracoscopes yet to be born even on laboratory benches. Efforts towards this vision, via synergistic hardware and software developments, would form the foundation for revolutionary breakthroughs in thoracoscopic surgical techniques and patient care.

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Footnote

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