Robot-assisted Endoscopic Surgery

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Introduction

More and more procedures are being carried out with the use of flexible endoscopy to treat gastrointestinal diseases. These include, among others, endoscopic mucosal resection and submucosal dissection of pre-cancerous lesions. The development of pure flexible endoscopic surgery has been in spotlight for some time now. The development of natural orifice transluminal endoscopic surgery (NOTES) in recent years encapsulates the trend. More than any other obstacles, current lack of dextrous endoscopic platforms and instruments makes entry into this uncharted domain daunting. Due to the natural orifice approach and the anatomically confined working space, high motor skills are required on the part of the operator. It also calls for new customized instrumentations to facilitate easy and safe performance of the procedures. Thus far, exploration into endoscopic surgery has been restricted to less technically demanding transluminal procedures. NOTES remains very much an investigational procedure at this stage. Some novel multi-tasking endosurgical platforms and a range of better articulated instruments to mitigate manoeuvring challenges in endoscopic surgery are already under evaluation for use in NOTES. More dextrous robotics-based endoscopic systems with high degrees of freedom for easier instrumental mobility are also under development, but a complete platform capable of supporting pure NOTES is still awaited. We believe that emerging innovations, in particular, highly dextrous robotics-enabled endosurgical systems are best poised to meet most, if not all of the present technical demands in endoscopic surgery.

Current developments in advanced endoscopic surgery

1. Approaches and techniques in endoscopic surgery

The most significant paradigm shift in surgical development in the past decade has been on the concept of performing surgery through natural orifices using flexible endoscopy. The objective, apart from avoiding the need for making an incision through the abdominal wall, thereby providing better cosmesis, is to reduce operation related morbidity, and hopefully, shorten patient’s recovery period. Although the concept of NOTES has seen a fair share of skepticism since its inception, it has undergone substantial development and extensive clinical testing in recent years. Hundreds of human NOTES-based procedures have since been performed at tertiary
centres across the world. Procedures performed included splenectomy, nephrectomy, adrenalectomy, oophorectomy, appendectomy and cholecystectomy conducted via the transgastric, transvaginal, or transrectal route.\textsuperscript{1-7} NOTES has also been successfully applied with laparoscopy to perform more complex surgical procedures such as rectal tumor removal with total mesorectal excision.\textsuperscript{8} In the process of development, the model of NOTES has evolved in terms of application and technical approaches, alongside novel innovation of various endoscopic systems and associated instruments. Based on a recent review on development in the field of NOTES, investigative procedures conducted in human were prominently transvaginal procedures, with transgastric procedures being next common.\textsuperscript{1,2} However, most trials have used a hybrid approach with laparoscopic assistance on standby, for safety reason. Trials conducted thus far have shown that the transvaginal route is the safest approach for NOTES. This approach, in a way, is not entirely new to surgeons as many of today’s gynaecologic procedures use the route to reach surgical targets in the peritoneum and reliable closures of colpotomies have long been practiced. There is less potential for contamination of the peritoneum or pelvic cavity. In contrast, development of transcolonic and transgastric surgery has encountered major setbacks mainly due to the lack of proper instruments, especially closure devices to safely close the gastrotomy/colectomy created during transluminal surgery. The risk of gastrointestinal contents leaking into the peritoneal cavity and causing inadvertent peritonitis is a big concern. Recent discovery of access to the peritoneal cavity through submucosal tunneling, and closure of the gastrointestinal defect to minimize the risk of leakage of gastrointestinal contents to the peritoneal cavity has enabled the performance of novel procedures including submucosal endoscopic tumorectomy and per oral endoscopic myotomy.\textsuperscript{9-12} Recent trials in patients with achalasia have shown that per oral endoscopic myotomy is effective in reducing dysphagia and may even reduce the risk of esophageal carcinogenesis.\textsuperscript{13}

### 2. Clinical and instrumental barriers to development of endoscopic surgery

NOTES comes with significant instrumental development burdens because current endoscopy platforms and instruments were not designed for NOTES. Flexibly steered endoscope allows surgeons to reach remote targets in the abdomen; yet because of the endoscope’s flexible shaft, the rigidity requires for stabilization of surgical instruments cannot be attained. Moreover, with endoscopic deployment of surgical tools in the same axis with the endoscope, triangulation of the tools for surgical maneuvers is almost impossible. In addition, retroflexion or even just bending of the endoscope during application means constant changing of the imaging perspective which may result in the operator losing visual orientation. This, plus the unstable visualization of the surgical field and the lack of depth perception make the surgical operation very challenging for endoscopic surgeons. The only solution for better mobility of the tools is to redesign the endoscopic platform to delink the movement of the surgical tools from that of the endoscope to allow independent control of each of the deployed instrument.

In addition, in flexible endoscopic surgery, the sense of touch and force feedback is lost. This loss is probably of little consequence in very fine surgery where the force applied is very small, but the issue is proportionally exaggerated in surgery involving larger surface area where larger force application is called for. Undue forces applied during manipulation of the tissue could thus risk inadvertent ripping of tissue. With current standard endoscopy instruments, the risk of injury during performance of endoscopic surgery such as NOTES is quite significant. This is why standby laparoscopic assistance is deemed necessary during conduct of intricate NOTES trials. Common complications reported in NOTES trials thus far include mucosa laceration, injury to adjacent
tissue or organs, and inflammation. A study by Lehmann et al (2010) on the outcome of NOTES on 572 target organs operated in 551 patients revealed that complications occurred in 3.1% of the patients. This is even when all the NOTES procedures included in the study are conducted transvaginal, deemed the safest route for NOTES. Of all the NOTES procedures performed, 85.3% involved cholecystectomy; 4.9% of the cholecystectomy procedures had to be converted to open surgery.1

3. Advanced technological solutions for endoscopic surgery

Indeed, the lack of proper instrumentations has prevented the tapping of the full potential of NOTES. However, some progress is on the way to make performance of endoscopic surgery easier, with better articulated instruments designed specifically to meet the technical challenges in endoscopic surgery emerging. Novel multi-tasking endosurgical systems and platforms, including some robotics-enabled innovations, are already in pre-clinical animal trials or human clinical trials. Three main types of endoscopic surgery systems are emerging. Technically, these systems may be classified as either mechanically-driven, direct-drive, or robotics-enabled systems. Notable of those systems introduced in the recent years are: (i) the EndoSAMURAI™ integrated system (Olympus Corp, Japan), (ii) the Anubis-scope (Karl Storz, Germany), (iii) Incisionless Operating Platform (USGI Medical, USA), (iv) the Direct Drive Endoscopic System (Boston Scientific, USA), (v) the i-snake in-vivo robotic system (Wellcome Trust, UK), (vi) the R scope (Olympus Corp, Japan), and (vii) Viacath (Hansen Medical), (viii) Endomina (Endo Tools Therapeutics, Belgium), and (ix) the master and slave transluminal endoscopic robot (MASTER) (Endomaster, Singapore).14 The EndoSamurai, R-Scope and the Anubis-scope are systems with integrated instrument manipulation and visual function. The other systems rely on the conventional flexible endoscope for visualization, while instrument manipulation is achieved through a flexible multi-channel access device. The use of the access device dissociates the optics from the main instrument. Actuation is controlled either by hand or by a traction cable or by a robotic system like in the case of the Viacath, i-snake, Endomina, and the MASTER.

4. Multi-tasking endosurgical systems

Each of the above mentioned systems has its own niche and advantage over the conventional endoscopy system or other competing newer system. The EndoSAMURAI™, for instance, is an ergonomically designed mechanical system that takes advantage of its customized instruments deployed through two extra articulating instrument channels alongside the usual non-articulating working channel. The design maximizes the mobility of deployed instruments, and provides the operator the ability to exert traction and countertraction during manipulation of tissue.14 A recent evaluation on the use of its later prototype on transgastric small bowel resection summarised that with the EndoSAMURAI™, the majority of complex surgical tasks could be performed if “technically independently moving instruments can be used via an ergonomic workstation interface that allows for laparoscopy-like maneuvers by the operator”.15 The R-scope is a multi-bending endoscope equipped with two deflectable operative channels. The shaft of the endoscope is so designed that the proximal bending section allows up/down movement while the distal section allows up/down as well as left/right movement. In addition, the two deflectable channels allow instrument to move in perpendicular planes. The R-scope has been successfully used to perform endoscopic submucosal dissection (ESD) of gastric lesions and had been shown to reduce operating time.16 The Incisionless Operating Platform, which is based on the TransPort multi-lumen access de-
vice, features a steerable flexible over-sheath with ShapeLock function. The system includes auxiliary devices such as tissue approximation device, and accessories such as tissue anchors and various graspers. The Direct Drive Endoscopic System is an access device platform comprising a conventional endoscope, steerable flexible articulating guide sheath with a visualization channel, two instrument channels, and mechanically controlled articulated instruments. Trials showed it provides efficient bimanual coordination of instruments and speeds up operation time. The Anubis-scope features two flexible flaps at its tip that can be opened to dilate incisions for easier transluminal access, two deflectable instrument channels that facilitate instrument triangulation, and a third central channel to use for suction. Instruments have four degrees of freedom for mobility to execute dissection and suturing motion. Movements are controlled via a trigger handle. Thus far, the Anubis-scope has been used to conduct NOTES cholecystectomy and mucosal closure in animal models and cadaveric models.

5. Robotics-enhanced endosurgical systems

In contrast to the aforementioned mechanically driven systems, the Viacath, i-snake, Endomina, and MASTER are robotics-enabled. The Viacath is a teleoperated robot comprising a master console with haptic interfaces, a slave drive system, and electronically controlled, long shafted, flexible instruments. The articulated robotic instruments on the tip of the endoscope facilitate easy performance of bimanual surgical manipulations. The i-snake is an example of a hybrid tendon-micromotor mechantronics combined with robotics to facilitate fully controllable articulation of the surgical instruments. In the i-snake system, imaging and sensing are integrated with the instruments’ kinematics, enabling thus the capability of unique curved navigation along the winding anatomical pathway of the gastrointestinal tract. The MASTER, on the other hand, is both robotics-enhanced and haptics-enabled. This master and slave transluminal endoscopic robot comprises an intelligent central controller and a human-machine interface whereby the operator can remotely control the actions of the end surgical effectors deployed at the tip of the endoscope. MASTER is intuitively operated, highly dextrous and is equipped with haptic feedback capability to give the operator a sense of touch while manipulating the tissues through the winding endoscope. Its capability was demonstrated in its debut first-in-man trial in 2011 when ESD of gastric cancer were successfully performed on 5 patients in Asia. The early technical/clinical experiences with using the system has led to further development which has resulted in a much improved version of the equipment which now has its own customized endoscope.

6. Auxiliary Devices and Accessories

Along with the innovations in endoscopy platforms are specially designed auxiliary endoscopic devices and accessories which are designed for specific needs in endoscopic surgery. The devices include endoscopic incision and closure devices which include the Stringer (LSI Solutions, Victor, NY, USA), a device for emplacing purse-string sutures, endoscopic staplers such as the one made by Ethicon Endo-Surgery, Inc, tissue approximation device such as the g-Cath/g-Prox (USGI Medical Inc, USA), the flexible Endostich system (Covidien, North Haven, Connecticut, USA), the OverStitch device (Apollo Endosurgery, USA), (ix) the Plicator™ (NDO Surgical Inc., Mansfield, MA, USA), and the Overstitch (Apollo Endosurgery, USA). Available are also novel endoscopic accessories designed to support the safe closure of the deliberate viscus perforation made in NOTES. These accessories includes various designs of endoscopic clips, T-tags, T-bars, T-fasteners, Padlock-G clips, over-the-scope clip system, and septal occluders, some of which are already available in the market.
7. Robotic-assisted endoscopic surgery

Robotic-assisted endoscopic surgery is a promising area that clinicians and innovators alike look forward to. The development of robotics for endoscopic surgery is still a fledgling field, with some prototype endosurgical systems such as the ones mentioned above gradually emerging. Preliminary trials involving robotic technology have mostly been conducted in animals and human cadavers, with only a very small fraction of the studies conducted in human. Apart from the successful MASTER human trial, other successful robotic-assisted endoscopic gastrointestinal surgeries in human had mostly used rigid endoscopes, and were therefore more laparoscopic than endoscopic in approaches. Presently, one of the promising robotics-enabled endosurgical endoscope being evaluated in the laboratory is the new MASTER-endosurgical system. Jointly built by the original innovators of MASTER at their startup company, EndoMASTER Pte Ltd, Singapore, and Pentax Corporation, Tokyo, Japan, the new prototype endosurgical system is a significant improvement of the MASTER system used in the debut first-in-man clinical trial in 2011. Instead of adapting the robotic system to a standard Olympus dual-channel therapeutic endoscope, the MASTER is now integrated with a customized endoscope that features larger than usual instrument channels for easier deployment of the robotic slave which holds the surgical instruments. The surgical instruments are controlled via a human-machine interface. The system allows a minimum of 5 degrees of freedom for instrumental maneuverity. The MASTER-endosurgical system is being tested with SPACE (Steady Pressure Automatically Controlled Endoscopy), a novel flexible automatic gastrointestinal endoscopy CO2 insufflation platform. When applied together with SPACE, the MASTER-endosurgical system is able to provide a highly dextrous endosurgical platform to support the performance of a range of endoscopic surgical interventions, including NOTES. Preliminary animal trials have shown the combined system works well for the performance of ESD in the colon (unpublished data). More pre-clinical trials are being undertaken by the group at the moment.

A robotics-enhanced endosurgical system such as the novel MASTER-endosurgical system with SPACE presents a viable platform for the performance of endoscopic surgeries. The advantage in employing intelligent robotic control in endoscopic surgery is that the technology is able to maximise the degrees of freedom for articulation of deployed surgical instruments and facilitates free spatial orientation of instruments. This provides an unprecedented freedom of instrumental mobility which is far less restrictive than mechanically driven articulation systems. The system also makes easy off-axis bimanual coordination of the surgical instruments to allow easy triangulation of the surgical arms, and facilitates performance of retraction, grasping, approximation, and dissection of target tissue. Moreover, the incorporation of MASTER-endosurgical system with SPACE, a system designed to provide a highly reproducible and automatically re-distending endoscopic exposure in the gastrointestinal tract during endoscopic surgery, a pneumoperitoneum for adequate exposure and visualization of the surgical field during the entire surgical procedure is ensured. The MASTER-endosurgical system, together with SPACE, thus provides an ideal endosurgical system that allows enhanced dexterity in surgical maneuvers, efficient force transmission, dual-arm triangulation of surgical tools, haptic feedback, and full visualization of surgical field. With further development of adaptable auxiliary devices such as those for suturing, better imaging, precise navigation, as well as a range of easily deployable instruments and swappable end-effectors for use in various surgical tasks, even intricate endoscopic surgeries such as NOTES could be made easier to perform.
8. Further challenges ahead

The development of robot-assisted endosurgical systems such as the MASTER-endosurgical system represents a small but significant step towards the realization of easy and safe performance of intricate endoscopic surgery such as NOTES. There are obvious challenges ahead and instrumentation is obviously just part of the solution. While further advances in robotic technologies are expected to offer the optimal interface for NOTES, the refinement of clinical indications and development of surgical techniques are expected to be main drivers of innovations that would define the future of robot-assisted endoscopic surgery.

References


