

The role of technology in minimally invasive surgery: state of the art, recent developments and future directions

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ABSTRACT

The diffusion of minimally invasive surgery has thrived in recent years, providing substantial benefits over traditional techniques for a number of surgical interventions. This rapid growth has been possible due to significant advancements in medical technology, which partly solved some of the technical and clinical challenges associated with minimally invasive techniques. The issues that still limit its widespread adoption for some applications include the limited field of view; reduced manoeuvrability of the tools; lack of haptic feedback; loss of depth perception; extended learning curve; prolonged operative times and higher financial costs. The present review discusses some of the main recent technological advancements that fuelled the uptake of minimally invasive surgery, focussing especially on the areas of imaging, instrumentation, cameras and robotics. The current limitations of state-of-the-art technology are identified and addressed, proposing future research directions necessary to overcome them.

INTRODUCTION

Minimally invasive surgery (MIS) has experienced a surge in popularity over the past few decades, thanks to rapid technological advances and growing consensus in the clinical community. According to a report on laparoscopic devices recently released by Global Industry Analysts, 7.5 million laparoscopies were performed worldwide in 2015.¹ For a number of operations—such as appendectomy, tubal ligation, cholecystectomy, gastric bypass, myomectomy and prostatectomy—more than 90% of interventions are now performed through minimally invasive approaches, with projected growth rates of up to 15% in the next 5–10 years.² The main reason behind this paradigm shift is the significant reduction of trauma to the patient's body that results from the minimisation or even elimination of surgical incisions. The reduced physical trauma, in turn, leads to a number of additional benefits for the patient: lower incidence of postsurgery complications, reduced pain, quicker recovery, shorter length of hospital stay, minimal cosmetic disfiguration, decreased psychological impact and overall improved quality of life.^{3–8} Choosing to perform MIS over open surgery, however, means also embracing a series of potential disadvantages from the surgeon's perspective. These include limited operating space and field of vision; the lack of haptic feedback; the loss of stereo vision and depth perception; diminished hand-eye coordination;

prolonged learning curves and training periods; extended operation times and increased costs.^{9–11} With the recent developments in medical and surgical technology, such complications are gradually being overcome, enabling the adoption of minimally invasive procedures in hospitals and clinics around the world. The latest high-resolution miniaturised cameras now provide surgeons with a detailed view of the operating space, supplying stereo vision and optimal lighting of hidden targets regardless of their location in the body. In some cases, it is even possible to access and view certain anatomical locations better than with open interventions. Minimally invasive instruments have also been designed and engineered to allow routine tasks to be performed safely and accurately even in a limited space. Modern imaging technology and image processing techniques, moreover, provide accurate guidance and navigation throughout the intervention, increasing precision and safety while speeding up the procedure. Recent navigation systems offer drastic improvements in the way information is acquired, displayed and integrated in the surgical workflow, through augmented reality and multimodal image registration. Virtual reality simulations have revolutionised training of new practitioners by providing novel ways to steepen the learning curve. Advances in robotics, lastly, have contributed heavily to improve the surgeon's dexterity and skilfulness through articulated tools and human-robot collaborative platforms. This review will discuss the main and most recent developments in the aforementioned areas, analysing the current limitations that still need to be addressed and suggesting possible future directions.

CAMERAS AND VISION

By eliminating or reducing the size of the incision on the body, the accessibility and visibility of the operating space becomes severely limited. While in open surgery the target can be easily exposed, in MIS other means must be used to gain a clear view of the operation. First, it is necessary to obtain good illumination in an otherwise dark environment. The scene must also be viewed in colour and at high-resolution, in order for the surgeon to discern possible important details on the tissue. Moreover, it is often necessary to reach the target through long, tortuous paths in order to exploit the body's natural orifices and passages.

In the second half of the 20th century, fibre optics first provided the bases to develop the first flexible endoscopes, gastroscopes, ureteroscopes



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and colonoscopes.¹² In the modern versions of these devices, illumination is most commonly provided by using either a bundle of optical fibres illuminated by a xenon lamp, or light-emitting diodes placed directly at the tip of the scope.¹³ The xenon light source provides wide-spectrum light and is generally augmented with a heat (infrared) filter to avoid overheating of the cable and tip, and to reduce the risk of damaging the target tissue. Until the advent of charged-coupled devices (CCD), coherent fibre optic bundles were also used to transmit images back to the viewer. In most modern setups, high-resolution CCD cameras are used instead to transmit a live video stream to a flat screen via an analog-to-digital converter and processing unit.¹³ Advanced laparoscopes, usually based on rod lens systems, have also benefitted from the employment of cameras by eliminating the requirement for the surgeon to look into the binocular eyepiece, minimising discomfort and stress. The operation can also be viewed by the whole surgical team, thereby enhancing team collaboration and cooperation. Furthermore, using digital cameras means that videos can be recorded and stored for future use. Image processing can be performed in real time, allowing the surgeon to tweak properties such as contrast or brightness to improve the visibility of the scene. Newer laparoscopic systems may also use a CCD at the endoscope tip, allowing the lenses to be removed from the interior of the endoscope shaft. These modern setups have been adopted almost universally in surgical theatres, substituting the more obsolete optical systems (figure 1).

One of the main problems associated with video-assisted MIS is the loss of stereopsis, meaning the perception of depth and three-dimensionality. This occurs when a three-dimensional (3D) image is projected on a two-dimensional screen, and is often the cause of impeded hand-eye coordination and erroneous movements of the tools.¹⁴ The employment of multiple imaging channels and cameras corrects this problem, and allows stereo vision to be recorded while providing high-resolution images that can be displayed on a 3D monitor.¹⁵ The Olympus VISERA platforms (Olympus, Shinjuku, Tokyo, Japan), for instance, include stereo videoscopes that can bend their tip of 100° in four directions and providing 3D videos in 4K resolution and offering flexibility for applications in laparoscopy and endoscopy. Another example is the 3D-Eye-Flex, developed

by Nishiyama *et al*,¹⁵ an endoscopic video system that offers a wide angle of view for minimally invasive neurosurgery. This type of technology is already commercially available and has undergone early clinical trials, yielding improved performance, shorter learning curve and greater accuracy and precision.¹⁶

The 3D data can be recovered from non-stereo cameras through image processing algorithms such as computational or photometric stereo, which extract depth information and allow a 3D image to be reconstructed and displayed.^{17 18} It is important to note that, while 3D visualisation improves performance and decreases operation time, high-definition (HD) images are still necessary for optimal clinical results.¹⁹ Recent work has focused on overcoming the problems caused by the misalignment between the operative field and the camera's optical axis. It has been shown that performance is improved when the two orientations are mapped through automatic realignment algorithms.^{20–22} Future improvements should be aimed at minimising the sense of visual fatigue and nausea that may arise upon looking at 3D display systems for a prolonged time, which could impede the surgeon's concentration in long sessions.²³

SURGICAL TOOLS

A challenge lies in designing instruments that are compact enough to fit in trocars or endoscopes, and that can operate in a confined space: the size of the tools needs to be minimised without compromising their function. A number of surgical tools have been converted into minimally invasive equivalents, leading to products such as Endo Stitch for sutures (Medtronic, Dublin, Ireland); Endo Catch pouches (Medtronic) for waste retrieval; Endo Graspers (MetroMed Healthcare, Taiwan, Taiwan) and needle drivers (LiV Instruments, Estech, San Ramon, California, USA)—all of which have been used for years and perform relatively well in simple tasks.^{24–27} In particular, staplers and endoscopic suturing devices, such as the MicroCutter XCHANGE (Cortica, New York, New York, USA), have allowed the performance of operations such as haemostatic bowel transection, closure of gastrotomy and sudden anastomosis with increasing reliability, and have provided better performance compared with manual stitching or clips.²⁸ Another specific category of tools widely employed in MIS is the one aimed at energy delivery to ablate tissue, seal vessels and cauterise wounds. Examples range from

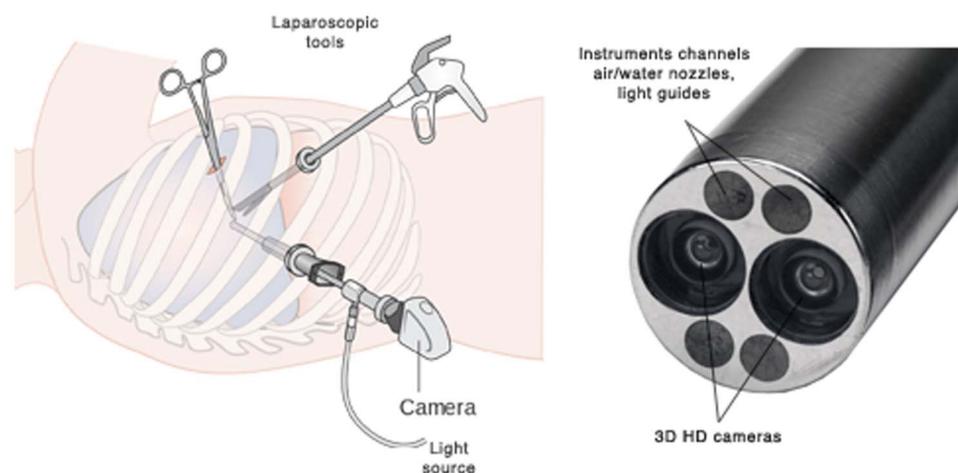


Figure 1 Laparoscopy and endoscopy. Left: diagram showing a setup for video-assisted laparoscopy. The surgeon holds the tools, while the camera is usually held by an assistant. The instruments are inserted into the body via a trocar—a hollow tube which pierces the abdomen and provide a point of access to the target. The abdominal cavity is filled with gas (usually CO₂) to create more space to operate. *Picture by Cancer Research UK (Wikimedia Commons) distributed under a CC-BY-SA 4.0 licence.* Right: a flexible endoscope, which can be equipped with three-dimensional high-definition cameras, light guides, instrument channels as well as pipes for water and air. *2016 Intuitive Surgical.*

simple electrodes that heat up the tissue through the passage of currents, to harmonic scalpels—tools that convert electrical energy into mechanical motion, effectively cutting through tissue via high frequency vibrations of a blade.²⁹ For cauterisation, radiofrequency ablation systems and argon-enhanced electrosurgery allow efficient current delivery for improved outcomes and decreased operation time.^{30–31} Lasers are also sometimes used for ablating tissues or tumours. In prostatectomy, laparoscopic laser surgery causes lower morbidity compared with traditional transurethral resection of the prostate, although open surgery is sometimes still preferred.³² In fact, despite energy delivery technology being successfully used routinely, there are a number of safety considerations to take into account. Because of the limited field of view, the risk of burning the wrong area or activating the electrodes inadvertently is higher, as is the possibility of direct and capacitive coupling, which can too cause overheating and burns.

These advancements have improved the state of the art of many minimally invasive procedures, and have also allowed operations never performed endoscopically before, such as cholecystectomy through Natural Orifice Translumenal Endoscopic Surgery (NOTES), or image-guided keyhole neurosurgery for brain tumour removal.^{33–34} The potential of NOTES in particular has gained widespread attention in the clinical community, as it does not require a skin incision to access the body. However, it is limited by the restrictions imposed by the small size, large flexibility and high manoeuvrability required for endoscopic tools.³⁵ Indeed, most minimally invasive tools are much more difficult to manipulate than regular instruments.^{27–36–37} It is often complicated to achieve triangulation of the instruments, flexibility and traction, while avoiding cluttering. The tip of the instruments does not have the same degree of articulation as the human wrist, nor the same ability to grasp and manipulate objects. The need to frequently change endoscopic devices also tends to prolong operative times and may cause patient discomfort.³⁸

ROBOTICS

Robotics offers some solutions to the aforementioned problems, and has proven to be a viable option to address the limitations associated with MIS. In robotic-assisted surgery, the instruments are not moved directly by the surgeon, but through ad hoc controllers and software. The tools can be supplemented with motors and end-effectors, improving the user's ability to rotate, move and manipulate in minimally invasive procedures. By providing articulation, implementing filtering of tremors and simulating tactile sensations, the surgeon's dexterity and eye-hand coordination are enhanced, thereby subjectively improving surgical performance.^{39–40} The most successful example of surgical robotic systems is perhaps the da Vinci SP (Intuitive Surgical, Sunnyvale, California, USA), which was the first (and thus far, the only) console for teleoperated surgery to receive the approval of the Food and Drug Administration (FDA). In the past two decades, it has been adopted widely in hospitals and clinics worldwide for operations that range from urological to cardiac to abdominal surgery. Its master console is equipped with controllers through which the surgeon intuitively controls a slave unit, made of up to four robotic arms and a 3D HD camera.³⁹ The robotic arms allow mounting of custom-made tools and articulated end-effectors; actuators can also be installed to move catheters and endoscopes, enhancing the feasibility of robotic minimally invasive operations such as fenestrated stent grafting and prostatectomy.^{32–40} The new da Vinci SP offers single-port functionality and the possibility of using three fully articulated instruments through a single 25 mm cannula—a feature not implemented in previous versions, which prevented single-port access (figure 2).⁴¹

A product developed specifically for NOTES is the i-Snake (Imperial College London, UK), a surgical flexible robot that allows movement in 8° of freedom thanks to four articulating joints. Multiple tools, cameras and illumination fibres can be passed through its cylindrical body while still maintaining its flexibility and ability to steer, due to a novel tendon system and



Figure 2 The da Vinci surgical robotic platform. (1) The surgeon console. The surgeon operates through master controls, and is supplied with a high-definition, three-dimensional (3D) view of the operating space. Hand, wrist and finger movements control the tools accurately and in real time. The double console setup allows for cooperation between surgeons, and can be used for training purposes. (2) The patient-side cart, consisting of three or four robotic arms which carry the camera (usually a flexible HD 3D endoscope) and the instruments. The tools are controlled directly by the surgeon, with safety mechanisms preventing independent movements. The tip of the tools is articulated to simulate the 7° of freedom of the human wrist and fingers. Tremor reduction and motion scaling can also be implemented. (3) The vision system. Dedicated hardware and software for image processing provides detailed images of the patient's anatomy; the screen provides a view of the operating field to the whole surgical team. 2016 *Intuitive Surgical*.

smart computer guidance.⁴² The promising results obtained with the i-Snake have set the stage for the development of the Micro-IGES platform (Imperial College London), a fully integrated endoluminal surgical platform with bimanual control and hand-assisted instrumentation designed for incision-less transanal microsurgery, integrating novel mechatronics, force and contact sensing and non-invasive structural and endomicroscopic imaging. Another example is the Flex Robotics System (Medrobotics, Raynham, Massachusetts, USA), designed for transoral procedures, which offers very similar capabilities.⁴³

Haptics

A major area of focus in the development of surgical robotic platforms is the implementation of haptic feedback. Haptics include sensations such as force, pressure, temperature and texture—all qualities that are difficult to quantify and represent in robotic and minimally invasive procedures.⁴⁴ It is hence problematic for the surgeon to judge the right amount of force to apply and make decisions based on tactile palpation. The addition of force and tactile feedback has been shown to improve learning for novices, decrease the risk of tissue damage and shorten operating times.^{45–47} The da Vinci SP does not have native haptic feedback capabilities, although attempts have been made to implement it through its dedicated research kit.⁴⁸ This has been achieved by installing force sensors on the tools, and using actuators to provide active resistance through the controllers. However, this feature is still experimental and it is not present in the commercial product used in surgical theatres. Conversely, in handheld robotic tools haptic feedback has been successfully implemented through various approaches, including vibration as well as auditory and visual cues.^{49–52} These techniques have also been applied in endoscopy, achieving good results.⁵³

Human-robot interactions

Another fertile area of research in surgical robotics is the application of machine learning algorithms for the creation of human-robot cooperative control frameworks, in which the surgeon is aided by the machine in the most critical parts of a task.⁵⁴ This can speed up the learning curve for users new to robotic technology, and would also allow to perform repetitive tasks (such as laser ablation, which needs to be performed many times over the same area) with much greater precision and reliability. Using a double console setup can thus be beneficial for training and learning purposes, both for the novice and the machine: as expert surgeons perform a physical or virtual surgical simulation, the trainees can follow their steps using another machine, while the robot can track the instruments, implementing complex algorithms in order to improve performance.⁵⁵ For example, active constraints can be applied to enhance the safety of operations by limiting the reachable space of the end-effector;⁵⁴ the surgeon's gaze can be tracked and registered with the tools in order to minimise erroneous movements;⁵⁶ visual servoing can be used to perform autonomous tissue scanning for enhanced real-time biopsies and diagnosis⁵⁷ and additional instruments can be controlled through voice commands.⁵⁸ Furthermore, motion scaling can be applied in laparoscopic procedures, to mitigate for the effects of the varying amplification of the hand movements, due to the length of the instruments and the presence of a fulcrum point.⁵⁸

Challenges and limitations

Despite the technical advantages that robotic setups can provide to minimally invasive surgeons, there is still little evidence of

significant improvements from a clinical point of view.⁵⁹ Moreover, robotic technology is still extremely expensive, for instance, a single da Vinci SP system costs about US\$1.5 million, and a robotic laparoscopic operation can require up to US \$5000 more than its traditional alternative. The high prices are due to the complexity of the technology, as well as to biocompatibility, maintenance and sterilisation issues.^{60–62} It is therefore difficult to justify such expenses for a technology that, even though it has the potential to improve surgical performance,^{63 64} does not yet seem to yield proven clinical benefits for the patients.⁶⁵ Therefore, until costs decrease, it is not realistic to imagine a widespread diffusion of robotic MIS. Moreover, because of the difficulty to prove the clinical advantages of surgical robotics, obtaining FDA approval tends to be especially lengthy and difficult.⁵⁹ This is also due to a number of ethical issues surrounding the use of robots for medical purposes, including the possibility of malfunctions and system downtimes which could harm the patient, and a lack of clear ways to define legal responsibilities if these events occur.^{66 67} Efforts should be aimed at bridging the gaps in the legislation, while continuing to improve the safety of the robotic systems and studying ways to make the technology cheaper and more accessible. On this topic, the FDA has published a report outlining the challenges and regulatory pathways for introducing robotically assisted surgical devices (RASDs) into the market. The major issues currently slowing down the approval of new RASDs are identified to be the lack of a national registry; the lack of a formal framework to describe their development stages; the lack of clarity about their actual clinical potential; the inability to assess and compare training and simulation technology and limited collaboration between stakeholders to generate and collect clinical data.⁶⁴

Addressing these points is crucial, because robotics has the potential to open the doors of MIS to a higher number of surgeons by assisting them in difficult tasks. As minimally invasive procedures become more advanced and technically complex, surgical robots are the key to assist the surgeons and thus contribute to the diffusion and establishment of MIS.⁵⁹

IMAGING

Another main category of technology that provided major contributions to MIS is imaging. Since 1895, when X-rays were first discovered and their potential for medical purposes understood, radical developments in imaging techniques has led to the invention of MRI, CT, positron emission tomography and many other technologies, enabling surgeons to see inside the human body in ever greater detail and higher resolution. Minimally invasive interventions have benefitted especially from these techniques, since the target is always hidden from the surgeon's naked eye. Furthermore, it is now possible to accurately plan the operation in advance; to offer training to the surgeon in the form of virtual reality simulations; to obtain intraoperative real-time guidance; to receive valuable diagnostic information from processed image data and to perform diagnoses non-invasively.

Planning and training

Preoperative planning has been shown to be extremely helpful in order to improve the surgeon's preparation and to study the optimal strategy of intervention, leading to better performance and improved decision making.⁶⁸ In MIS, where access ports are small and paths are tortuous, accurate planning is key. Preoperative scans can be used to build 3D models of target structures and organs, or even of the whole body. These can be used by the surgeon to diagnose, plan and evaluate the outcome

of operations. CT and MRI are very commonly used for this purpose, often in combination, in a number of specialties ranging from orthopaedics to cardiac surgery.^{69–73} For the latter, for instance, CT angiography is critical to evaluate patients undergoing minimally invasive interventions: it can identify regions not apt for catheter passage and discover abnormalities of the arteries, thus avoiding possible serious complications.⁷⁴ Furthermore, preoperative imaging is often necessary to decide whether it is worth proceeding with a minimally invasive procedure or whether to opt for open surgery instead.^{75–76} Sometimes an intervention may be too risky or too difficult to be performed with non-traditional techniques. This can be especially true for very delicate operations or for patients who would not be able to withstand lengthy surgeries. In fact, clinical decision support has been identified as one of the critical areas of improvement in computer-assisted surgery.⁶³

Volumetric reconstructions from preoperative scans are also the basis for the development of patient-specific virtual reality simulations, through which the surgeon can perform procedural training before carrying out the actual intervention. Simulations have been proven to be crucial in order to steepen the learning curve for novices in MIS, and using patient-specific models can also be helpful to prepare surgeons before difficult operations.^{77–79} Moreover, lack of proper practice opportunities has indeed been identified as one of the main reasons for the slow adoption of computer-aided procedures.⁸⁰ Training is aimed at improving technical skills, and it also applies to “dealing with anatomic variations and complications, professionalism, communication skills, teamwork, leadership skills, and dealing with equipment failures”.⁷⁷ This can prove fundamental for novices, and also for more experienced surgeons who have performed traditional surgery for years, and who, for this reason, may be even slower than new trainees to assimilate new techniques. Furthermore, as suggested by Kenngott *et al*,⁶³ personalised feedback and training can potentially be enhanced through the automatic detection and analysis of the surgeon’s movements, in order to understand and improve the patterns in the workflow.

Image guidance

Another use of imaging is to offer image guidance and navigation during operations. Thanks to improved processing power and modern software, navigation has become a key part of surgical routines, allowing interventions such as aneurysm repair and stent grafting to be carried out endovascularly and thus resulting in a lower early mortality rate compared with open surgery.^{81–82} In these procedures, CT angiography is usually employed to diagnose the aneurysm, track the stent during the operation and perform follow-up checks.⁷⁴ In neurosurgery, navigation systems have existed since early times, in the form of stereotactic frames combined with MRI and CT imaging systems. Modern technology, such as the EasyGuide system developed by Wadley *et al*,⁸³ offers dynamic guidance and interactive feedback to neurosurgeons by tracking the surgical tools and showing its position on a screen overlaid onto the preoperative scans. This allows the surgeon to understand the location of the instruments intuitively and with high precision. Minimally invasive image-guided surgery has also been gaining ground for cancer diagnosis and removal, for instance, in the prostate: robotic ultrasound probes are used to improve needle localisation, diagnostic accuracy and removal precision.⁸⁴ Technology such as the C-arm, introduced in 1955, has allowed the employment of intraoperative X-rays and CT, providing huge benefits to minimally invasive spinal surgery, in which precise tracking of the instrument is vital.⁸⁵ Instruments can also be tracked

through optical means—for instance, using infrared receivers and emitters—or electromagnetic systems. The latter are especially useful in MIS, because they do not require the tool to be in the line-of-sight of the detector, and can be used to track catheters and laparoscopic tools. However, they can be susceptible to interference from metallic objects or external electromagnetic fields.

Next-level guidance can be provided through augmented reality: an ‘image-enhanced operating environment’⁸⁶ is created by overlaying a visual representation of the subsurface anatomy and critical structures, and integrating it with the video feed from the camera. The rendered images are obtained from volumetric scans of the patient, and are therefore faithful representations of the real structure. This approach can alleviate the problems arising from the loss of depth perception and obstructed vision encountered in MIS, by showing anatomical information of targets that would otherwise be hidden to the eye.^{51–52–86} Current setups have the possibility of offering ‘on-demand’ augmented reality overlaid directly on the video feed of the operative screen, using a transparent screen or a separate device such as a tablet PC.^{87–88} Current research is focusing on relieving the surgeon from the pressure of deciding when visual input is needed, employing machine learning algorithms and analysis of surgical workflows to automate and improve the augmented reality systems.⁸⁹

While image guidance has indeed become an integral part of many minimally invasive interventions, the difficulty in registering soft tissue and modelling its deformation has slowed its adoption.⁹⁰ It is of paramount importance to use advanced engineering techniques to model the deformation of organs and tissue and implement it in real time in order to provide accurate information to the surgeon. These methods, however, tend to be computationally expensive and may not always be a good fit for real time. Requirements of processing and computational powers should therefore be a prime concern when developing new technology for image-guided surgery. Alternatively, live imaging techniques such as ultrasound can be used instead of preoperative models for augmented reality and navigation purposes. In this case, the position of the instruments is registered in real time directly with the ultrasound scan, eliminating the need for complex rendering and modelling (figure 3).⁸⁶

Optical imaging

Minimally invasive surgeons also benefit greatly from the opportunity to perform diagnoses on the spot through optical imaging. This technology uses visible, infrared and ultraviolet light to obtain biochemical and molecular information about the target tissue, and has a number of advantages compared with other imaging techniques. First, the energy deposited in the body is much lower than for radiative imaging and does not lead to genetic damage; second, multiple optical approaches allow differentiation between soft tissues at good spatial resolution. Diffuse optical tomography, for instance, can offer an alternative to X-rays in diagnosis and image-guided removal of breast cancer, as it eliminates the risk of damage to delicate tissue through radiations.⁹¹ The standard laparoscopes can also be augmented with imaging systems that are able to detect fluorescence, multispectral scattered light, Raman or the polarisation properties of tissue. Moreover, the instrumentation is less bulky than for alternative techniques, and can be easily attached to minimally invasive instruments. The implementation in MIS currently remains limited to a subset of procedures, but it is of major importance in order to perform diagnoses, biopsies and check-ups.⁹² For example, fluorescence imaging has been proven

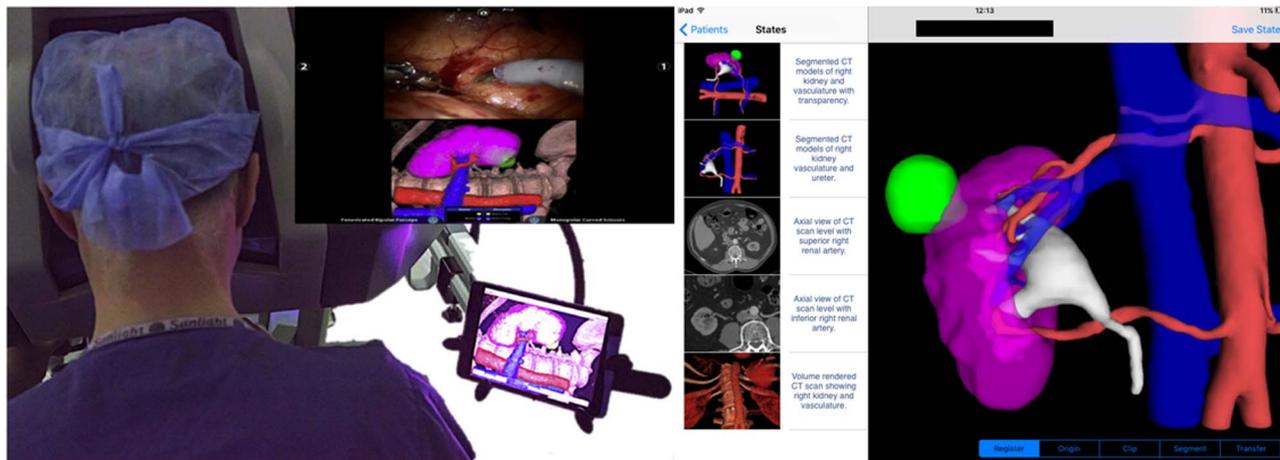


Figure 3 A navigation setup based on augmented reality, in use with a da Vinci SP console. Left: the real scene is augmented with virtual images showing a reconstruction of the target's anatomy. The same scene, or a different one, can be seen on a tablet positioned next to the console. *Image adapted with permission from Hughes-Hallett et al.*⁸⁶ 2014 Elsevier. Right: examples of navigation images available on the tablet. The surgeon can choose to view the raw scans (such as MRI or CT), or the three-dimensional reconstructions. Registration software makes sure that the position of the tools relative to the anatomy is always known. *Image courtesy of Philip Pratt, Imperial College London.*

to provide extremely accurate and rapid classification of pulmonary adenocarcinoma or bladder cancer through cystoscopy.⁹³ Fluorescence cystoscopy has resulted in further improvements in tumour detection.^{94–95} This technique uses blue light to detect an agent that was previously injected near the target site, a fluorescent derivative of which accumulates in damaged tissue. Other extensively employed techniques that take advantage of the fluorescent properties of tissues include confocal endomicroscopy—used to obtain optical biopsies of endoluminal surfaces (eg, in prostatectomy) with high spatial resolution—and fluorescence lifetime imaging, used for instance to detect polyps in the colon.^{96–97} Many promising results have also been achieved through 3D optical coherence tomography, a scanning method that allows to create depth maps of the tissue only using light and thus can be incorporated well in endoscopy;^{98–99} it can also perform high-resolution scans at the cellular level.⁹¹

An issue with fluorescence-based techniques is that they often require the injection of fluorescent agents. While this may still be a less harmful option than being exposed to radiations, it is still undesirable to expose the body to external substances. Moreover, optical techniques have a reduced imaging depth, due to high absorption and scattering of light in tissue. For this reason, they are often combined with other diagnostic tools in order to get more complete information and better axial resolution. Multimodal imaging is in fact a common approach to integrate the strength of different techniques while overcoming their limitation,¹⁰⁰ and is especially valuable in MIS, where size constraints make it more difficult to employ bulkier imaging systems such as CT, PET or single-photon emission computed tomography, effectively ruling out valuable methods for intraoperative data collection. Improving the integration and registration of images between different modalities is therefore vital in order to take full advantage of imaging technology. Recent efforts have focused on developing robotically actuated tools to achieve intraoperative multimodal fusion. For instance, endomicroscopy and ultrasound imaging have been combined in order to scan large areas of tissue in real time and perform 3D reconstruction of complex structures during an intervention.^{101–102}

CONCLUSIONS

This review has demonstrated the role that technological advancements have played in the development and diffusion of

MIS in the past decades. Some of the latest developments in vision, instrumentation, robotics and imaging have been illustrated, investigating the limitation of current practice and identifying key points of improvement that need to be addressed in the future.

Modern cameras can provide 3D images in HD and offer a vision of the operative field comparable to open surgery, making up for the loss of stereovision and representing a definite improvement over fibre optics. Flexible videoscopes allow the surgeon to reach hidden targets even through tortuous paths, and have permitted the emergence of novel techniques that exploit the body's natural openings. Efforts should be aimed at providing a more natural visualisation of 3D scenes, as well as at increasing the resolution of the images while reducing the size of the cameras. In addition, video images can be enhanced with virtual models of structures and tissues, creating an augmented reality environment that has been proven to improve the performance of the surgeon. These models, also used to create completely virtual scenes for surgical preparation and training, are rendered from volumetric data that are obtained from pre-operative scans. Through imaging technology it is indeed possible to plan operations and train the surgeon in advance; to provide guidance and navigation during the intervention, enhancing the confidence of the surgeon and the safety of the operation; to perform accurate diagnoses, biopsies and postoperative check-ups in a minimally invasive way.

Lastly, the advantages and shortcomings of tools for MIS have been analysed. A number of traditional instruments have been engineered to fit through laparoscopic trocars and other small tubes, so that many procedures can now be carried out with similar or better outcomes than open surgery. The limitations of minimally invasive instrumentation can be found in the loss of articulation compared with the human wrist; complexity of making them long and flexible without losing traction; prolonged operative times due to difficult manoeuvrability. For this reason, robotics have shown promise to optimise surgical performance and minimise human errors. Tools can be articulated, computers may be employed to aid the surgeon and complex software can enhance the safety and accuracy of the system. Nevertheless, the limitations of robotic systems are still numerous. Progress must be made on bridging the gap between surgeons and machines, accelerating the learning curve and

reducing operative times and costs. Training programmes must be implemented for this purpose, improving on the existing systems for virtual reality and simulations and allowing both novices and experienced surgeons to adapt to robotic and

minimally invasive surgical systems. Haptic feedback, loss of eye-hand coordination and lack of depth perception are also still major issues that have not been completely overcome yet, which should be the focus of future research in order to allow the discipline of MIS to grow and spread.

Main messages

- ▶ Rapid growth in the popularity of minimally invasive surgery has been possible due to developments in medical technology, which minimised many problems traditionally associated with minimally invasive techniques.
- ▶ High-resolution miniaturised cameras provide a detailed view of targets inside the body, as well as stereo vision and optimal lighting.
- ▶ Imaging technology is used for planning and real-time navigation during the intervention, increasing precision, speed and safety.
- ▶ Training and guidance can be offered through virtual and augmented reality systems, using realistic patient-specific simulations and rendering of anatomical structures.
- ▶ Robotics allows to increase the surgeon's dexterity through articulated tools, sensors and human-robot collaborative platforms.
- ▶ A number of issues still need to be addressed, including a lack of proven clinical benefits of robotic platforms; the high cost of technology and steep learning curves for both novices and expert surgeons.

Current research questions

- ▶ Can robotic technology provide proven clinical benefits in minimally invasive surgery?
- ▶ How can the costs of surgical technology be reduced in order to increase the diffusion of minimally invasive surgery?
- ▶ What can be done to ensure that surgeons undertaking minimally invasive interventions are trained to use the latest technology available?

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Self assessment questions

1. In video-assisted minimally invasive surgery, which of the following does NOT provide any benefits to the surgeon?
 - A. Stereoscopic vision.
 - B. A permanent, static overlay of a rendered hidden structure.
 - C. Haptic feedback through visual cues on the screen.
 - D. Articulated tools.
2. What is one of the chief reasons for the limited spread of robotic surgical systems?
 - A. No surgical robot has received Food and Drug Administration approval yet.
 - B. The advantages of using robots are only applicable to open surgery.
 - C. They are extremely expensive.
 - D. They are difficult to customise, hence there is currently little research done to improve them.
3. Which of the following statements is correct regarding the training of surgeons?
 - A. Experienced surgeons need little training to learn how to use minimally invasive and robotic technology.
 - B. The learning curve is steeper for minimally invasive surgery than for open surgery.
 - C. Navigations systems should not be used in the early stages of training to avoid confusing the surgeon.
 - D. Virtual reality simulations are useful both to prepare before an intervention and to train novices for minimally invasive procedures.
4. Which of the following pairs is most likely to increase the dexterity of the surgeon in laparoscopy and reduce the operative time?
 - A. Articulated tools with robotic actuators and a three-dimensional high-definition camera.
 - B. A rod lens scope and an electromagnetic tracker
 - C. Rigid tools and a binocular eyepiece.
 - D. An ultrasound scanner and a xenon light.
5. True or False: Thanks to further advances in technology, it is extremely likely that minimally invasive surgery will eventually replace traditional techniques for the vast majority of interventions.

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Answers

1. B
2. C
3. D
4. A
5. False