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 disfigurement, 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 skillfulness 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 in 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...
and colonoscopes. 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. 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. Advanced laparoscopes, usually based on rod lens systems, have also benefited 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. 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. 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., 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.

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. 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. 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. 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.

**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. 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 gastrostomy and sudden anastomosis with increasing reliability, and have provided better performance compared with manual stitching or clips. 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

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**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.
Intuitive Surgical processing provides detailed images of the patient anatomy; the screen provides a view of the operating field to the whole surgical team. **2016 Intuitive Surgical.**

**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.

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. 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.

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).

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. 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 endoscopic imaging. Another example is the Flex Robotics System (Medrobotics, Raynham, Massachusetts, USA), designed for endoscopic imaging. Another example is the Flex Robotics System (Medrobotics, Raynham, Massachusetts, USA), designed for endoscopic imaging. Another example is the Flex Robotics System (Medrobotics, Raynham, Massachusetts, USA), designed for endoscopic imaging. 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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.69 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.72–76 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.69

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.75–77 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”.76 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,81 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
to provide extremely accurate and rapid classification of pulmonary adenocarcinoma or bladder cancer through cystoscopy.\textsuperscript{93} Fluorescence cystoscopy has resulted in further improvements in tumour detection.\textsuperscript{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.\textsuperscript{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;\textsuperscript{98, 99} it can also perform high-resolution scans at the cellular level.\textsuperscript{100}

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,\textsuperscript{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 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

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 camera. 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.
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?

Key references

1. Gomes P. Surgical robotics: reviewing the past, analysing the present, imagining the future. Robot Comput Integr Manuf 2011;27:261–6. doi:10.1016/j.rcim.2010.06.009

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.

Contributors All authors viewed and approved the final manuscript. MT carried out the literature review, wrote the first draft and edited subsequent version of the manuscript, editing the changes made by the other authors. He also wrote the self assessment questions, main research points and selected the key references. MHS proposed the idea of the review and acted as main supervisor during the writing process. In addition, he offered his knowledge and experience as a minimally invasive surgeon. DSE provided his expertise in medical imaging, expanded multiple sections in the imaging chapter, and performed a thorough review of the manuscript. G-ZY and AWD reviewed and corrected the final draft, suggested additional references and contributed their experience in the fields of medical engineering and surgery.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.
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