

Review

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Beyond diagnosis: how advanced imaging technologies are shaping modern surgery

Taner Shakir¹ , Dominic Atraszkiewicz² , Mohamed Hassouna¹, Tom Pampiglione¹, Manish Chand¹

¹Division of Surgery and Interventional Science, University College London, Charles Bell House, 43-45 Foley Street, London W1W 7JN, UK.

²Broomfield Hospital, Mid and South Essex NHS Trust, Court Road, Chelmsford CM1 7ET, UK.

Correspondence to: Dr. Taner Shakir, Division of Surgery and Interventional Science, University College London, Charles Bell House, 43-45 Foley Street, London W1W 7JN, UK. E-mail: taner.shakir.23@ucl.ac.uk

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Abstract

Traditional imaging techniques are limited by their preoperative nature, limited image resolution, and the need for radiologist interpretation. Multiple advanced imaging technologies have been developed, which may enhance surgical precision and patient outcomes.

Near-infrared fluorescence (NIRF) imaging, particularly with indocyanine green (ICG) dye, enables perfusion assessments and may help prevent anastomotic leaks. Additionally, NIRF can augment the identification of tumour growth patterns and lymphatic networks, thereby improving resection margin accuracy. Combining NIRF with radioisotope tracers allows for deep tissue navigation with high-precision dissection. In advanced disease, radioisotope scans may also enable prompt identification and excision of distally affected lymph nodes. Hyperspectral imaging (HSI) provides molecular-level information without the need for harmful contrast agents. HSI tissue vascularisation data may help shorten procedure times and reduce perioperative morbidity. Furthermore, when combined with neural networks, the technology can improve tumour detection and tissue differentiation.

Extended reality (XR) has multiple applications within surgical imaging. Augmented reality (AR) allows for intraoperative image overlays, thereby improving surgical navigation. Additionally, virtual reality (VR) may help users to visualise three-dimensional anatomical reconstructions, with applications in surgical training and patient consent. Artificial intelligence (AI) systems offer enhanced perioperative information to surgeons, such as the



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prediction of both disease progression and patient response to treatment. These benefits are compounded when paired with imaging modalities, such as HSI and XR.

Overall, advanced imaging technologies offer an exciting future for surgical practice and improved patient outcomes. Further work, including standardised protocols and ethical frameworks, is required.

Keywords: Imaging, extended reality, hyperspectral, fluorescence, artificial intelligence, surgery

INTRODUCTION

In 1901, Wilhelm Röntgen received the inaugural Nobel Prize in Physics for his discovery of X-rays and their application in medical imaging. A century later, cross-sectional imaging has progressed significantly and is now ubiquitous within the surgical landscape. A surgeon's decisions are often dictated by subtle details in shades of grey, with ultrasound scanning (USS), computed tomography (CT), and magnetic resonance imaging (MRI) mainstays of the diagnostic process. Improvements in reducing exposure to ionising radiation have helped make CT the gold standard investigation for acute abdominal pain. Additionally, MRI of the rectum can provide a preoperative assessment of pathological risk factors, thereby allowing for prognostication. The practice of taking a patient to theatre solely based upon a clinical diagnosis is a relic of the past.

Imaging provides the blueprint upon which surgery is performed. However, this is not without its limitations. Firstly, the interpretation of these images is often dependent on radiologists, who may not fully appreciate the nuances of surgery. Additionally, these images are commonly viewed preoperatively, thereby limiting intraoperative insight. Further limitations of traditional imaging techniques include limited image resolution, long acquisition times, and operator dependency. This paper, therefore, explores the benefits that advanced imaging technologies may proffer in both augmenting surgery in real time and advancing modern surgical techniques.

FLUORESCENCE-GUIDED SURGERY

In near-infrared fluorescence (NIRF) imaging, a fluorescent dye binds to a blood constituent, typically albumin, allowing it to circulate to specific target areas^[1]. The dye can be administered either intravenously or interstitially, depending on the intended target. A laser is then used to excite the dye, with the subsequent fluorescence captured as a video image using a modified infrared camera system^[2].

The use and scope of NIRF imaging have advanced significantly over the past decade, with indocyanine green (ICG) emerging as the most frequently used fluorophore. NIRF imaging enables the identification of structures that were previously imperceptible, thereby transforming surgical practice across various fields^[2]. The tool, therefore, has the potential to enhance bowel resection and anastomosis. Additional applications include assisting in the detection of tumour growth patterns and lymphatic networks, as well as ureteric visualisation^[3].

Clinical applications and evidence

Anastomotic leak remains prevalent in colorectal surgery (CRS), resulting in significant patient morbidity and burdens on healthcare finances^[4]. Key determinants of anastomotic healing include adequate blood supply to tissues and balanced microbial gut flora^[5,6]. Traditional practice is to assess anastomotic bowel segments for pulsation, bleeding, and/or their colour. These are, however, subjective assessments and rarely provide a clear demarcation between well-perfused and non-perfused tissue. ICG can be used intraoperatively to provide objective perfusion assessments at the time of anastomosis [Figure 1]. The use of

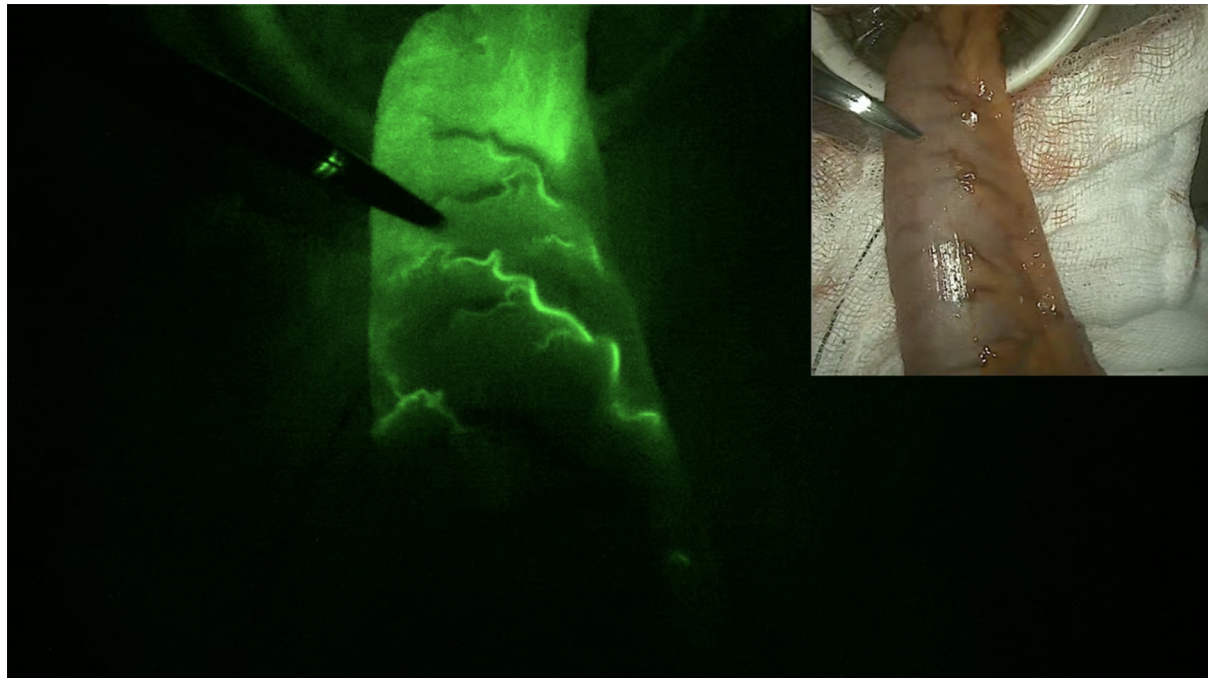


Figure 1. Indocyanine green perfusion captured using a near-infrared fluorescence camera (centre). Photograph of the same specimen in white light (top right). Original image.

ICG leads to a change of resection margins in 3.7%-19% of cases compared to standard clinical assessment^[7-9].

Multiple studies have established a role for ICG in preoperative tumour visualisation. One team reported an intraoperative tumour visibility rate of 93.8% following ICG injections into bowel wall submucosa at the distal side of tumours during preoperative colonoscopy^[10]. Another team reported intraoperative colonic tattoo visibility of 93.5% when injecting ICG into the serosal layer on the opposite sides of the tumour during laparoscopic CRS^[11]. Moreover, a study involving 199 patients who received submucosal ICG reported that tumours were easily distinguishable from their surroundings when viewed intraoperatively with a laparoscopic NIRF camera^[12]. Consequently, the team recommended that high volume and high concentration dye injections (i.e., 10 mL of solution containing 25 mg of ICG) in four separate locations near the tumour were optimal for tumour identification^[12].

A significant complication of CRS is ureteral injury (UI), with an estimated incidence of 0.3% to 1.5%^[13]. Approximately 9% of all UI incidents occur during CRS^[13]. ICG has been widely used in ureter detection/visualisation during laparoscopic pelvic surgery. A study reported that, during total mesorectal excision, ICG administered retrogradely via cystoscopy enabled clear localisation of both ureters^[14]. The left ureter was reported to be protected when a transileal conduit ureteral catheter was used near sigmoid tumours during ICG NIRF laparoscopy^[14]. A 94% ureter identification rate during robot-assisted CRS was also achieved via intra-ureteral ICG cystoscopy injections^[15].

The therapeutic window of NIRF has two ranges: 700 to 900 nm (NIRF-I) and 1 to 1.7 μ m (NIRF-II). The advantages of NIRF-I are generally lower cost, lower radiation, and ease of implementation. NIRF-II allows for deeper tissue penetration and higher-resolution images. Animal studies have shown a role for NIRF-II with ICG in identifying necrotic tissue^[16] and evaluating lymphatic systems^[17]. Additionally, a team has

shown a role for NIRF-II imaging with ICG to enhance the accuracy of microsurgery^[18]. A quantitative analysis concluded that NIRF with ICG offers accurate and easy tissue perfusion evaluation, with perfusion difference/heart rate ($\Delta T/HR$) levels of ≥ 832 recommended as an intraoperative parameter to guide CRS decision making^[19].

Limitations

Though the majority of evidence suggests that NIRF imaging techniques are safe, economical, and easily reproducible, it is important to highlight some concerns and challenges. Due to the lack of high-quality prospective randomised controlled trials, there are currently no satisfactory standards or guidelines for technical aspects, such as injection site, dosage, and observation periods^[20].

The use of ICG in left-sided resections has been somewhat standardised with regard to timing (i.e., before proximal transection and after anastomosis) and, to some extent, concentration and volume. However, there is a non-quantified degree of variability in the signal characteristics of the fluorescence and, consequently, the point of bowel transection. Specifically, after assessing fluorescence, there is no guidance as to what defines “optimal perfusion”, nor at which point the transection should be made. There is subsequently limited patient stratification due to intraoperative angiography. This has not been addressed in previous work; however, several hypotheses have been proposed which may help the user. These include the rate of colour change, longevity of signal, and depth of colour^[21].

Furthermore, the learning curves of image interpretation have not been analysed. Previous studies^[7,22,23] have compared assessments by experts and non-experts using dynamic video assessment tools. However, no consistent threshold for defining expertise has been established. There is a need for standardisation of ICG image interpretation and, potentially, the development of a quantitative model to aid in clinical decision making.

Future applications

Fluorescence-guided surgery continues to be a subject of active investigation. Encouraging outcomes have been shown for the identification of tumours using organic dyes. As with any emerging scientific technology, NIRF-assisted surgery must: address unmet clinical requirements; prioritise patient safety; be cost-effective; and demonstrate superiority over conventional approaches.

HYPERSPECTRAL IMAGING

An improvement on current white light and near-infrared operative camera systems is offered by hyperspectral imaging (HSI). This fuses two imaging technologies - a digital photographic camera and a spectrographic unit - to provide both quantitative and qualitative insights into tissue composition at the molecular level without the use of potentially harmful contrast agents^[24]. Consequently, HSI enables objective differentiation of various tissue types and the distinction between healthy and pathological tissue.

HSI can identify distinct optical patterns within underlying tissue, thereby providing an ‘optical biopsy’ which can assist surgeons in the identification and removal of tumours^[25]. This is possible due to the different biological characteristics of tumour and non-tumour tissues, which result in unique HSI signatures. The technology could also provide a degree of quality assurance following the excision of tumours, ensuring that no residual disease remains.

Although HSI can complement other imaging techniques, including ICG and other forms of NIRF-guided surgery, the technology offers a non-invasive, non-ionising method of imaging that does not rely on dyes to

visualise critical structures^[26]. This makes HSI highly suitable for intraoperative use. HSI can provide almost real-time images of biomarker data, such as oxyhaemoglobin and deoxyhaemoglobin, thereby enabling the evaluation of tissue perfusion by analysing the spectral properties of various tissues [Figure 2]. Following recent optical and photonic developments, intraoperative HSI may aid tissue identification and perfusion assessment across diverse surgical disciplines.

Clinical applications and evidence

HSI, when combined with advanced classification algorithms, can aid in: surgical navigation; identification of critical nearby structures; monitoring of the surgical environment; delineation of tumour boundaries; detection of residual tumour cells; and precise surgical decision making^[27]. As tumour hypoxia and microvasculature play an important role in surgical prognosis, HSI has been used to investigate real-time imaging of tissue oxygenation^[28,29]. Another study also reported that HSI has the capability to identify and track the oxygen saturation and water properties of kidney tissue during the preservation process^[30].

HSI can act as an intraoperative aid for both cancer detection and assessing tumour resection margins. An initial evaluation of the “TumorMAP system”, performed using 172 fresh tissue blocks from 115 patients’ lumpectomy specimens, compared results with gold standard pathology evaluation^[31]. The device was shown to be effective in identifying breast cancer in fresh tissue samples (sensitivity 82%; specificity 91%)^[31].

HSI has shown promise in identifying optimal sites for anastomosis during colorectal surgery. One study reported a discrepancy between CRS transection lines delineated subjectively by surgeons and border lines determined by intraoperative HSI^[32]. In 13 patients, surgeons’ resection lines were up to 13 mm too distal in the poorly perfused area, while in 11 patients, lines were positioned too deep within the better perfused area^[32].

One study incorporated intraoperative HSI along with ICG NIRF in 32 consecutive patients undergoing CRS; the two modalities performed comparably in delineating perfusion border zones and mutually enhanced each other’s capabilities^[33]. A combined system integrating both ICG NIRF and HSI has also been developed^[34]. In a cohort of 128 patients, the device was shown to synergistically utilise both technologies to provide tissue vascularisation data, thereby potentially shortening procedure times and decreasing perioperative mortality^[34]. Another study reported that HSI combined with a neural network algorithm correctly classified cancerous or adenomatous margins around central tumours (sensitivity 86%; specificity 95%)^[35].

Limitations

Though HSI has the potential as a valuable intraoperative guidance tool, several limitations have hindered its widespread adoption within theatres^[24]. Due to the challenges of miniaturising the HSI unit, spectral and spatial image resolutions are often compromised. Though previous studies^[36,37] have utilised commercially available cameras approved for human use, these systems are restricted in their applicability to open surgery. Moreover, as HSI primarily examines organ surfaces, with thermal ablation typically reserved for deeper lesions, it is challenging to envision a rapid clinical implementation of HSI. Furthermore, the majority of gastrointestinal tumours are endoluminal neoplasms, while surgeons typically have an extraluminal perspective during procedures. Presently, our team is conducting a research initiative focused on detecting endoluminal gastrointestinal tumours from the serosal perspective; initial findings are promising.

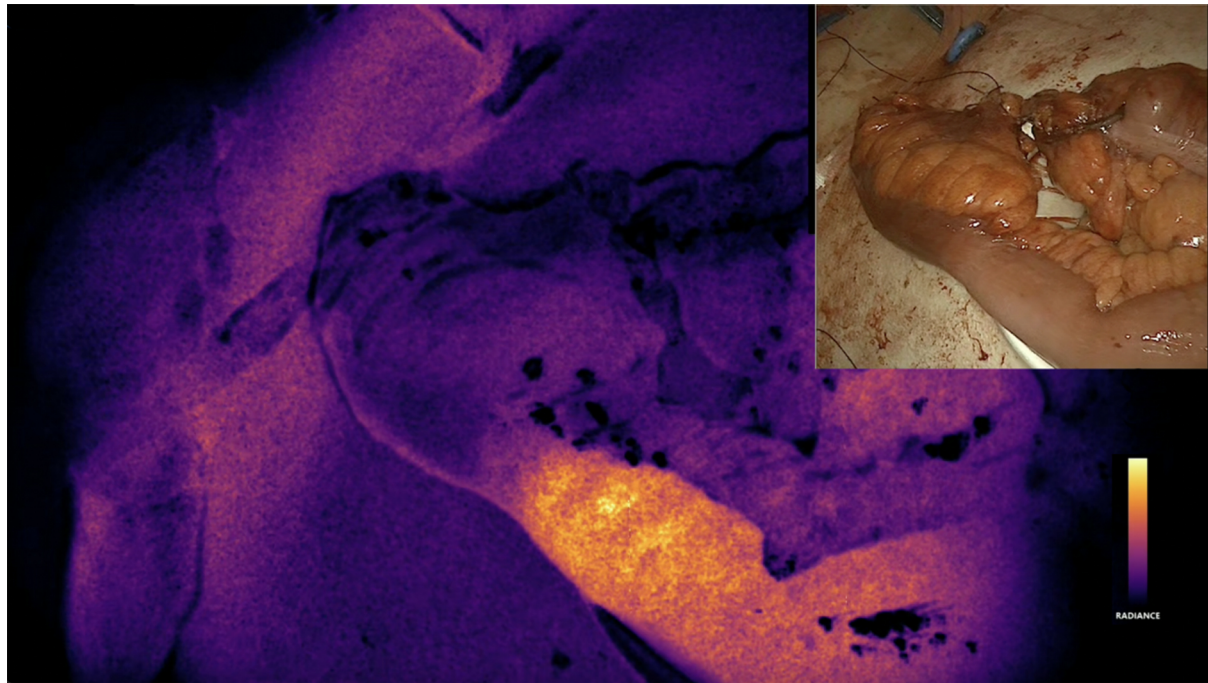


Figure 2. Hyperspectral image showing small bowel perfusion (centre). Of note, a cutoff in radiance can be seen within the middle of the small bowel loop. Corresponding white light photograph (top right). Original image.

Future applications

Multidisciplinary, well-designed, large research setups are necessary to determine the spectral characteristics necessary for diagnostic inquiries and to comprehensively ascertain which tissue types can be consistently differentiated using HSI. To streamline image acquisition and data processing, only predefined target features of the spectrum should be captured, facilitated by deep learning. Furthermore, we predict that tailored data extraction algorithms will minimise the time elapsed between image acquisition and data availability^[24].

RADIOISOTOPE SCANS

The modern imaging techniques discussed in the previous sections are already changing how we practice surgery. However, the technologies rely upon the electromagnetic spectrum, which has poor penetration through most human tissues. Radioisotope-guided surgery involves the injection of a radioactive tracer into tissues where it is transported into the lymphatic system. During surgery, a probe can then be used to measure radioactivity, with peak levels indicating the location of lymph nodes. Radiation emitted from radioisotopes has much better penetration through human tissues and, as such, can be detected from greater distances. Probes, however, have a poor resolution. Furthermore, the results are a numerical count rather than a visually highlighted area. Interpretation and use are, therefore, more challenging.

Combining NIRF imaging with radioisotope-guided surgery should allow for the strengths of each technology to placate their weaknesses. By injecting both a radioisotope and fluorescence tracer around pathology, radioisotope-guided surgery can help the surgeon navigate through deep tissues to reach a target, while NIRF can be subsequently utilised for detailed, delicate dissection.

Clinical applications and evidence

ICG and a radioisotope combined detection have already been used for lymph node mapping in several abdominal cancers^[38]. The technology has particular benefits in pelvic cancer surgery, where lymph node drainage fields may extend beyond the immediate surgical field. For example, in vulval cancer, where the surgical pathology is in the perineum, lymphatic dissection is performed in the groin to access the inguinal lymph nodes.

A study reported that the technique correctly identified sentinel nodes in all patients with early-stage vulval cancer ($n = 12$; median nodes 2; range 1-3)^[39]. A larger study using ICG and technetium-99m for 113 endometrial cancer patients reported a 96% detection rate for pelvic lymph nodes^[38]. Dual radio-fluorescence has also been applied to early-stage gastric cancer; fluorescence intensity demonstrated good concordance with intraoperative radioisotope values^[23]. Other small studies have investigated this combination in oesophageal and laryngeal cancers^[40,41].

Limitations

There are two main limitations of radioisotope and NIRF combined technology. Firstly, radioisotopes require special licensing and protocols. However, breast cancer surgery has shown that most centres have the facilities to perform basic radioisotope administration for lymph node detection. Nevertheless, as with any new technology, there remains a need for a proven use case.

Secondly, as this is an emerging technology, the exact mechanism of lymphatic drainage is not yet predictable. Therefore, the dosage and location of administration are not yet known. In particular, malignant nodes can vary in their ability to transport the radioisotope and may generate a false-negative result.

Future applications

We predict the technology will be used in a greater variety of cancers, particularly in the abdomen. Applications in rectal cancer surgery are yet to be explored. The technology has the potential to help visualise distal lymph nodes affected in advanced disease. Intravenously administered radioisotope and fluorescence markers are in development. This removes the requirement for direct injections, which tend to be less standardised in technique, painful, and often limited by tumour disruption of lymphatic channels.

EXTENDED REALITY

Extended reality (XR) is an umbrella term for several immersive technologies, namely augmented reality (AR), virtual reality (VR), and mixed reality (MR). These have shown exciting promise as novel techniques for interpreting surgical imaging.

AR involves a digital image overlaid on top of real-world information. The technology has been utilised intraoperatively for a variety of procedures. CT images have been used to generate three-dimensional (3D) images and delineate vascular anatomy when used with an AR headset; precise and efficient localisation of vasculature was observed^[42]. Moreover, 3D reconstructions of liver vasculature have been shown to enable precise navigation of structures during hepatobiliary surgery^[43].

Contrastingly, in VR, a subject is fully immersed in a virtual world and is completely disconnected from the real world. The applications of VR within surgical imaging are predominantly preoperative. Similar to AR, 3D reconstructions of CT or MRI images can be displayed on a head-mounted display. This stereoscopic view is not to be underestimated – no other platform allows for 3D visualisation. However, a direct

correlation with real-life anatomical structures is not possible.

MR combines both technologies, allowing users to interact with both the physical and digital worlds. MR is a developing field, with very limited evidence presently with regard to surgical imaging.

Clinical applications and evidence

Applications of AR involving artificial intelligence in the form of deep learning have shown significant promise. During neurosurgical procedures, CT images formed a foundation for machine learning whereby, with translation to an AR overlay, the system was able to accurately predict the location and trajectory for extra-ventricular drainage (accuracy 99.9%; specificity 95.7%)^[44]. This example of active surgical navigation is an exciting development in the field of image-enhanced surgery, propelled by artificial intelligence.

A trial utilising VR for hepatobiliary vascular anatomy relative to liver tumours showed that a mean period of 14 min of preoperative VR assessment improved understanding, identification, and recall of structures^[45]. Applications of VR are not limited to preoperative planning; the technology also improves patient education and consent. Radiological images, in the form of 3D reconstructions, were shown to help patients contextualise treatments and improve understanding^[46]. In addition to improving subjective measures (e.g. patient satisfaction), objective benefits (i.e. reduced heart rate and blood pressure levels) were also observed among patients during the consent process^[46].

Limitations

A significant limitation of AR systems is that static images are used as source data; therefore, the technology is not capable of accurately rendering deviations in anatomy. This is especially pertinent when trying to manipulate soft tissue in 3D space. Whether this can be addressed with further technological advancements remains to be answered.

Conversely, motion sickness and eye strain can be troublesome issues for VR users. Moreover, stereoscopic 3D effects are limited in certain groups with pre-existing ophthalmic conditions. With advancing technology, we may see improvements. Cost can also be prohibitive to implementation, with headsets typically ranging from €300 to €1,000.

Future applications

AR and VR offer exciting and novel methods of improving surgical training. Utilising these technologies for systems, such as surgical robots, would negate the need for in-person training. Feedback can be objective, constructive, and delivered in real time. An AR-guided walkthrough of setup could serve as part of the certification process for surgical competence. This would additionally have many socioeconomic benefits, widening access to surgical training, and allowing trainees to study at a time of their convenience rather than relying upon the availability of a field trainer.

VR systems may also lead to the implementation of virtual multidisciplinary meetings. Users could dial remotely and see radiological images in one portion of their vision, with the other parts free to view pathology or endoscopy reports. Moreover, advancements in VR technology may improve wearability and user comfort, with prolonged use for daily activities becoming the norm.

MR could offer significant benefits in aiding intraoperative visualisation of anatomy and localisation of pathology. However, significant developments in the field are needed, as are XR protocols.

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) - defined as the ability of machines and computers to execute tasks which ordinarily require human intelligence - is rapidly growing within the field of medicine. Key facets of AI include: machine learning, which develops algorithms to learn from data patterns; deep learning, a subset of machine learning using artificial neural networks for complex data analysis; computer vision, enabling machines to interpret images; and natural language processing, which processes human language. Building upon these foundations, AI can allow for automated detection and diagnosis, thereby increasing the efficiency of highlighting urgent pathological findings. From a surgeon's perspective, the advent of AI in radiological diagnoses is crucial as it directly influences preoperative planning, intraoperative guidance, and surgical decision making. These are key opportunities to ultimately optimise patient management.

Clinical applications and evidence

The application of AI within radiological diagnoses of surgical pathology demonstrates promise across various body systems. Within the Hepatobiliary system, AI algorithms have been shown to achieve high accuracy in segmenting the liver, scoring > 90% relative to radiologists^[47]. AI has also been reported to perform comparably to experienced radiologists in characterising focal liver lesions with CT imaging; this included differentiating hepatocellular carcinoma^[48]. For pancreatic cancer, AI can differentiate between CT scans with and without the disease with high sensitivity (89.7%) and specificity (92.8%), outperforming human radiologists in predicting lymph node metastasis. Within colorectal surgery, AI can aid in detecting polyps during CT colonography and also in detecting metastatic lymph nodes on MRI with comparable accuracy but reduced reading time compared to radiologists^[49]. Furthermore, applications to pelvic MRI show promise in accurately staging rectal cancer and predicting patient response to neoadjuvant treatment. AI has also shown applications in inflammatory bowel disease by automatically evaluating inflammation in Ulcerative Colitis (UC) and Crohn's disease using endoscopic images^[50]. The accuracy of UC severity classification was comparable to that of experts^[51]; the detection of small bowel Crohn's ulcers on capsule endoscopy is a further application. Moreover, endoscopic detection and diagnosis have made great strides^[52,53]; RCTs have described novices reaching expert levels when utilising AI^[51].

Limitations and challenges

The integration of AI within imaging systems creates several technical and ethical hurdles that may limit its widespread adoption. First, there is a lack of standardised imaging protocols. Additionally, variability in data quality across institutions may compromise the reliability and generalisability of the technology. Furthermore, AI algorithms can only be as good as their training datasets and the annotators that have been utilised. This can potentially lead to inaccurate outcomes. Moreover, the resources required may prohibit AI accessibility. Ethically, concerns around patient privacy, data security, and the necessity of informed consent are paramount. Challenges also remain regarding how AI can be integrated into clinical user systems, some of which are primitive in public healthcare settings. Finally, concern exists regarding the legal and regulatory aspects of AI, which are presently not well defined.

Future applications

Personalised medicine is an exciting field in which AI has the potential to advance further. Predictive analytics, i.e., utilising AI's capacity to analyse large amounts of data, is one application. This may facilitate forecasting disease progression, predicting response to neoadjuvant treatment, and assessing the risk of recurrence. This will enable the tailoring of management strategies more effectively and proactively. This may be further optimised by analysing patient genotypes and phenotypes. AI paired with other advanced imaging modalities, such as HSI, could offer enhanced information to surgeons. Integration of AI into image analysis and XR could further augment surgical planning and intraoperative guidance^[54]. The continued evolution of AI may reshape surgical practice and contribute to significant improvements in patient care.

DISCUSSION

Advanced imaging includes numerous technologies with various perioperative applications [Table 1]. One of the most commonly used and readily available modalities is NIRF with ICG; this is utilised within laparoscopic and robotic systems. While ICG dye has a relatively low cost and a good safety profile, its interpretation can be ambiguous. Limitations include subjectivity, of which fluorescence intensity is acceptable, and a variable time prior to washout. This lack of standardisation requires further research to better define these variables.

Radioisotope imaging can provide functional and metabolic information, which is valuable for sentinel lymph node biopsy; this may help localise lesions with greater accuracy. However, hardware is constrained by poor image resolution and significant patient exposure to radiation. Implementation requires specialised hardware (i.e., gamma cameras, Positron Emission Tomography, Single-Photon Emission Computed Tomography) and facilities capable of utilising radioactive materials.

HSI may negate the issues pertaining to dye injection and radioisotopes. However, disadvantages include the high initial start-up costs of hardware systems and the additional requirements needed to integrate the technology within existing systems.

XR is a more readily accessible technology, with several headsets already commercially available. Integration of new and existing software has shown promise with respect to preoperative planning and intraoperative 3D visualisation. Despite high initial costs, the role of XR may expand due to potential impacts on carbon footprint. Coupling this with the integration of artificial intelligence could also play a factor. Additionally, the adoption of AI into the radiological diagnostic process has shown its own merit. However, ambiguities remain regarding ethical implications and responsibilities.

These advanced imaging technologies have demonstrated varied degrees of effectiveness and potential. Future directions within advanced surgical imaging will likely require a lack of fluorophore for visualisation and assessment. Newer imaging technologies will likely build upon perfusion assessment and may be able to detect serosal margins, such as in cancers associated with inflammatory bowel disease. Enhanced integration with AI may allow for more robust algorithms that are capable of aiding intraoperative decision making. We may see percentage probabilities of different disease processes based on their interpretation via advanced imaging modalities. It is likely that the hardware itself will become smaller, cheaper, and more accessible. Solely software-based pathology detection may negate the requirement for additional hardware components.

Table 1. Comparison of advanced imaging technologies

Imaging modality	Advantages	Disadvantages	Applications	Future directions
Near-infrared fluorescence (NIRF)	Real-time imaging; intraoperative tissue visualisation	Requires specialised camera systems; limited depth of penetration; lack of standardised guidelines; user-dependent image interpretation	Vascular surgery (perfusion assessments); oncological surgery (tumour sites and resection margins); hepatobiliary surgery; urology	NIRF-II for greater tissue penetration; targeted contrast probes; augmented reality (AR) integration; quantitative image analysis models
Hyperspectral imaging (HSI)	Non-invasive; real-time imaging; no radiation exposure; intraoperative tissue visualisation	High start-up costs; bulky hardware units; limited depth of penetration	Neurosurgery (tumour identification and tissue metabolism); breast surgery (tumour margin evaluation)	Smaller HSI units; streamLined data processing, possibly with integration of deep learning; improved spectral and spatial resolution

Table 1 (continued)

Radioisotope imaging	Good tissue penetration; target-specific probes; widespread assessment	Poor image resolution; limited interpretation as results are a numerical count; exposure to radiation; specialised licensing and protocols required	Minimally invasive surgery; sentinel node mapping; pelvic cancers (lymphatic drainage); perioperative cancer staging	Intravenous radioisotope injections; integration with NIRF; improved resolution; image generation, possibly via AI integration; protocol development
Extended reality (XR)	Three-dimensional image visualisation; adjunct to surgical training; improved intraoperative navigation	Implementation costs; headgear discomfort; limited mixed reality technologies; difficulty integrating with healthcare systems; lack of standardised protocols	Surgical training; intraoperative navigation; patient consent process; perioperative planning	XR integration into surgical training; improved user comfort; advancements in mixed reality technologies; cost reduction; protocol development
Artificial intelligence (AI)	Automated image interpretation; improved diagnostic accuracy	Lack of standardised protocols; ethical considerations; regulatory challenges	Diagnostic processes; intraoperative guidance; perioperative planning (prediction of disease progression, patient response, and risk of disease recurrence)	Integration with advanced imaging modalities; development of AI protocols; ethical and regulatory frameworks established

CONCLUSION

Imaging is a fundamental part of surgical practice. Over recent decades, multiple advanced imaging technologies have been developed, including: HSI; NIRF and ICG; radioisotope scans; XR; and AI. These tools enable surgeons to visualise significantly greater levels of detail and to contextualise images within a 3D space. Standardised protocols and ethical frameworks are key areas for future development. Advanced imaging, in combination with the digital surgical revolution, offers an exciting future for a rapidly changing surgical landscape.

DECLARATIONS

Authors' contributions

Data acquisition: Shakir T, Atraszkiewicz D, Hassouna M, Pampiglione T

Final manuscript writing: Shakir T, Atraszkiewicz D, Hassouna M, Pampiglione T

Manuscript supervision and approval: Chand M

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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