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Augmented Reality Integration in Gastrointestinal and Bariatric Surgery: A Review of Enhanced Visualizations.

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ABSTRACT

From open surgeries to MIS was a game changer in both GI and bariatric spheres but presented a number of visualization challenges. Classical 2D laparoscopy involves inherent lack of depth perception and limited spatial orientation that, in its turn, increases the workload of surgeons performing such procedures. Objective: In this narrative literature review, we attempt to analyze the present state, scientific bases and clinical significance of AR, VR and MR applications in GI and bariatric surgeries. We performed a comprehensive analysis of peer-reviewed literature regarding advanced approaches in visualization during surgery, including intraoperative navigation, ergonomics, patient safety and clinical outcomes. Advanced technologies allow one to overcome the limitations of classical MIS techniques, providing 3D high-resolution vision with enhanced degrees of freedom. Augmented reality has a huge potential of improving patient care and simplifying complicated surgical procedures by integrating crucial anatomical data into the real world vision. Moreover, VR opens the doors for new highly effective opportunities in perioperative patient education and simulation. Although AR presents a great number of advantages, some intraoperative issues such as soft tissue deformations, peristalsis and hardware delays are still worth mentioning. The advances in visualization technology constitute a paradigm shift in the field of GI and bariatric surgery. As computer vision software and biomechanical modeling techniques develop to cope with the dynamics of soft tissues, AR and 3D robotic systems will certainly be a new normal for the operating theatre of tomorrow.

Keywords: Computer-assisted surgery, Intraoperative navigation, Surgical ergonomics, Spatial perception, Image-guided intervention, Perioperative simulation...

INTRODUCTION

The treatment approach to gastrointestinal and bariatric disorders has seen a dramatic change in the last three decades. The emergence of minimally invasive surgery has changed the entire surgical approach with proven clinical benefits including less postoperative pain, shorter hospital stays, decreased risk of infection at the surgical site, and quicker recovery (1). These clinical benefits have a great biomechanical and physiological price to pay. Minimally invasive gastrointestinal and bariatric procedures are highly complicated (2). The operating surgeon performing surgery using conventional laparoscopy has to deal with highly vital anatomy in a highly restricted 2D visual environment. This inherent problem leads to a complete loss of depth perception, spatial orientation, and hand-eye coordination due to the presence of fulcrum at the site of trocar insertion (3,4). As a consequence, the mental load placed upon the operating surgeon increases greatly as he needs to mentally construct a 3D model from the 2D monitor images and at the same time analyze preoperatively obtained radiological imaging (3). In an effort to overcome these visual and ergonomic constraints, the field of surgery has resorted to integrating advanced digital technology with advanced visualization technologies. The types of spatial computing technologies can be best categorized using Milgram's Reality-Virtuality continuum, which includes Virtual Reality, Augmented Reality, and Mixed Reality (5)..

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Virtual Reality entails the total submergence of the user into a completely synthetic and computer-generated reality, occluding the real physical world. In the context of surgery, virtual reality has been very effective in aiding procedural planning prior to operation, training of residents through simulation, and perioperative reduction of patient anxiety (6). On the other hand, Augmented Reality does not supplant the real world but enhances it with the use of computational power. In augmented reality, computer generated inputs such as three-dimensional models of anatomy obtained from computed tomography (CT) or Magnetic Resonance Imaging (MRI) of patients are overlaid onto the real world of the surgeon (7). However, Mixed Reality is a further development of Augmented Reality where the digital holograms projected can be made to interact with the physical environment such that surgeons can dissect the digital anatomical structure in physical space (5). The use of such technologies within the operating theater directly helps overcome the shortcomings of traditional laparoscopic procedures. The advanced digital technology offers remedies through the provision of 3D HD vision and better degrees of freedom (8). Modern robotic surgical systems that make use of 3D binocular vision and wristed tools have already proven their ability to bring back the sensation of depth perception and allow for precise tissue manipulation within deep anatomic cavities. Within the scope of bariatric surgery, the need for superior vision becomes particularly acute. Bariatric surgeries involving the operation on super obese patients pose an especially challenging task because of the thick abdominal wall, enlarged liver and restricted intra-abdominal working area (9). As 3D robotics reconstruct vision, while visualization on its own is frequently not enough when dealing with obscured tumor margins, abnormally situated vasculature, or distorted anatomical planes as part of revisional bariatric surgery or GI oncologic surgeries (1), here we see the true value that comes from using AR for surgical operations. With the ability to superimpose key anatomical information on top of the actual surgeon's view, there is great potential for improving the quality of both care provided and operational procedures performed (10). Using computer vision and optical tracking techniques, AR provides surgeons with what can be called "intraoperative x-ray vision," allowing them to visualize the underlying structures – be it the biliary tree or blood vessels (11). However, despite its vast potential, the incorporation of AR technology into GI and bariatric surgery is far from easy. While in neurosurgery and orthopedic procedures, the process of spatial registration through the help of AR system could use static bony landmarks as references, the abdominal cavity is an extremely dynamic environment (8). In other words, the abdominal cavity experiences constant deformation of soft tissues, respiratory movement, movements of the organs, and changes in structure caused by pneumoperitoneum. This paper provides an overview of the present state of AR, VR, and 3D visualization in GI and bariatric surgery.

2. TECHNOLOGICAL FOUNDATIONS OF SURGICAL AR

The implementation of Augmented Reality (AR) technology in the operating room requires a complex relationship between hardware elements and software processing. The basic framework for surgical AR applications can be classified into three main stages: pre-operative data capture and segmentation, intra-operative spatial registration, and real-time visualization (5). The effectiveness of such a pipeline ensures the degree of precision in superimposing the virtual computer-generated model of anatomy on the physical operating environment, a parameter that is essential for patient safety.

Hardware Modalities: HMDs, Robotic Consoles, and Intraoperative Displays

The hardware interface acts as the medium via which the augmented environment is provided to the operating surgeon. There are currently three main hardware interfaces used for gastrointestinal and bariatric surgery: the head-mounted display (HMD), the robotic closed console viewer, and the augmented intraoperative standard monitor. The head-mounted display such as the Microsoft HoloLens and the Magic Leap has been gaining popularity due to its advantage of untethering the surgeon from fixed monitors, thus creating an ergonomic visual experience (12). There are two types of HMDs available: the optical see-through (OST) and video see-through (VST). The OST HMD uses a semi-transparent holographic lens (waveguide) that provides the surgeons with an ability to have unobstructed visual access to the patient and the operating room environment along with the digital overlays (13). VST, on the other hand, uses outward facing cameras and projects a digitized version of the environment and overlays onto the opaque internal micro-displays. Although VST provides better control over opacity and brightness of the digital overlay, it creates inherent micro-latencies, leading to visual-vestibular mismatch, an area investigated further in human factors studies (14). Although there have been many improvements made to HMDs, the incorporation of AR in robotic surgical consoles stands out as the smoothest transition for complex GI and bariatric procedures. Stereoscopic viewer technology in systems such as the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) and Hugo Robotic-Assisted Surgery (RAS) (Medtronic, Minneapolis, MN) is extremely sophisticated and uses closed console. Since the surgeon is immersed in the digitized, high definition 3D view of the surgical field, overlaying preoperative 3D imaging, such as CT angiography showing abnormal vasculature in the liver for a complex gastrectomy, would not require any additional wearable technology (15,16). Additionally, robotic platforms inherently track camera and instrument movement in real time, providing vast amounts of data to make the spatial tracking algorithms easier (17). Alternatively, the technology of AR can be used in intraoperative screens for routine laparoscopy. In this case, the 2D/3D output from the laparoscope is passed through a processor that generates the overlay of 3D segments before projecting it onto the monitor. Though such an approach eliminates the inconvenience associated with wearing HMDs, it still does not solve the basic issue of spatial misalignment between the operation of the surgeon’s hands in one space and the projection on the monitor (18).

Software Algorithms and Computer Vision

All the computation necessary for the AR experience during surgery is done through its software stack and relies extensively on computer vision and machine learning. The first step before creating an AR overlay on the live feed is to build a personalized 3D model of the anatomical structure of the patient usually from multiphase CT and MRI images acquired prior to the procedure (19). Traditionally, the segmentation of the target organs, tumor, and vascular structure used to be an extremely tedious and manual process. However, the emergence of the deep learning architectures, especially CNN models such as U-Net has made the task of segmenting volumetric medical images almost fully automatic with highly precise 3D surface mesh results (20). Once the 3D model is created, it has to be aligned in the correct way with the real-life anatomical structure in the operating theatre, which is called registration. At the heart of the spatial computations during registration is the Simultaneous Localization and Mapping (SLAM) technique. Originating in autonomous robotics and drones, SLAM enables the AR system to create a real-time three-dimensional topological map of the intra-abdominal space while at the same time locating the exact 6-degrees-of-freedom pose of the laparoscopic camera (21). In monocular laparoscopy, the SLAM algorithm identifies key points in terms of visually distinctive features with higher contrast such as vascular patterns or tissue textures from consecutive video frames to compute depth information and estimate camera movement. The next step involves point cloud registration, where the mathematical relationship between the pre-operative imaging data and the intra-operative SLAM-derived topographical map is established. This is primarily done through the use of the Iterative Closest Point (ICP) algorithm or any probabilistic variant of the same. The ICP algorithm essentially tries to reduce the distance between two different point clouds: one representing the surface mesh of the pre-operative 3D model and another one being generated from the SLAM system during laparoscopy (22). Through constant modification of the transformation matrix, ICP ensures that the digital hologram is always aligned with the target anatomy (23).

The Challenge of Soft-Tissue Deformation

Although the above mentioned algorithms are excellent in static environment, the abdomen poses a great biomechanical challenge. There is a basic dichotomy in the implementation of AR surgery – rigid body tracking and deformable soft tissue tracking. In fields like neurosurgery and orthopedics, the target anatomy – the cranium, spine, or the femur, is made up of non-deformable bony structure. These processes are compatible with rigid body tracking in which the target anatomy does not deform between the pre-operative imaging process and intra-operative surgical procedure (24). In these rigid environments, AR technology can use bone anchored fiducial markers to attain sub-millimeter registration accuracy with minimal computational complexity (5,25). In contrast to this, rigid body tracking breaks down in the GI system because of the highly deformable properties of the abdominal organs. From pre-operative CT scan where the patient is in lying down position, at rest and in normal atmospheric pressure, to intra-operative condition, there is drastic topological deformation that occurs (26). Inflation of carbon dioxide into the body for achieving pneumoperitoneum completely alters the structure of the abdomen. In addition, positioning of the patient in extreme reverse Trendelenburg or lateral decubitus positions causes shifting of the organs such as the liver, stomach, and intestines due to the pull of gravity (27). Apart from the gross movements, there are microscopic movements that are caused by breathing of the patient, pumping of the heart, peristalsis of the intestine, and manipulation of the retractor by the surgeon (28).For the creation of AR overlays to be accurate in this harsh environment, the use of simple point cloud registration using geometry is not enough. To solve the problem of soft-tissue deformation, there needs to be more complex biomechanical modeling techniques, such as that of the Finite Element Analysis (FEA). The finite element model breaks down the organ that the surgeon intends to work on into thousands of volumetric geometric elements, and then creates a mathematical representation of how the organ behaves physically (29). Using FEA, one can calculate how the organ deforms with the application of external forces (30).When the preoperative model is infused with finite element attributes, the AR system can dynamically distort, stretch, and compress the digital image overlay according to the actual deformation of the tissue being observed by the laparoscope (31). The problem, however, is that performing very intricate calculations for complex and non-linear biomechanical equations during surgery demands enormous computing power and results in significant latency. This latency means that there will be a delay in the process of updating the AR hologram based on the movement of the tissue being observed (32). In order to minimize this latency, recent scientific studies tend to focus more on physics-informed neural networks (PINNs) and other machine learning solutions. AI algorithms are pretrained before surgery based on numerous simulations of soft-tissue deformations, so that they can instantly predict the actual behavior of the tissues during the operation without performing the whole set of calculations (33). Thus, mastering the task of soft-tissue deformation is the main challenge in surgical augmented reality.

3. AR AND 3D VISUALIZATION IN BARIATRIC PROCEDURES

The use of advanced visualization technology in bariatric surgery provides an interesting example of interaction between anatomical, biomechanical, and physiological factors. With an increasing rate of severe obesity among the population worldwide, the performance of surgeries for such patients has become more and more widespread and complex. The presence of thick layers of fat, large liver size, and lack of space for operating, together with the restrictions that are associated with traditional laparoscopy, make the situation complicated (34). Under these conditions, the introduction of 3D visualization, robotic support, and virtual reality becomes not only technologically innovative but essential for safety and ergonomic sustainability of the process.

Mitigating Biomechanical Constraints with Robotic 3D Vision

In standard laparoscopic bariatric procedures, the surgeon encounters major limitations posed by the physical attributes of the super-obese patient. The very thick anterior wall of the abdomen forms a rigid fulcrum point during placement of the trocars. In order to move the laparoscopic tools in the abdominal cavity, enormous physical effort has to be made against the rigid fulcrum point, resulting in physical strain and fatigue and poor fine motor skills over extended operation times (35). In addition, the common occurrence of hepatomegaly, i.e., a hypertrophic left liver lobe, poses a significant limitation on the visualization and workspace of the gastroesophageal junction during dissection of the Angle of His and fundic mobilization (35). Robotic platforms equipped with 3D HD imaging technology completely break these limitations. Robotic 3D visualization relieves ergonomic issues by eliminating excess torque and physiological tremors for delicate tissue dissection (36). By employing RCM technology, robotic arm movements are performed through the abdominal wall trocar site, absorbing the enormous force that would otherwise exert on the shoulder and wrist joints of the surgeon (37). Meanwhile, the closed console 3D viewer gives the surgeon a magnified and binocular depth restored surgical field. This improvement in visualization especially becomes very crucial in performing complex reconstructive bariatric surgery like Roux-en-Y gastric bypass (RYGB). Performing the gastrojejunal anastomosis in RYGB involves complicated suturing in a highly narrow and deep anatomical pouch. Restoring depth perception helps in achieving proper placement of the needle bite and correct tension of tissues, which reduces the chances of ischemic mucosa and resultant anastomotic leakage (38). In the same way, during sleeve gastrectomy (SG), 3D viewing helps in identifying the pylorus and incisura angularis in order to form a uniformly non-spiral stomach while carefully avoiding the short gastric vessels, hence reducing the chance of spleen injury (36) (see table no 1).

Table 1: Applications of Enhanced Visualization Technologies in GI and Bariatric Surgery

Technology Modality	Primary Clinical Application	Key Surgical Benefit	Prototype / System Example
Augmented Reality (AR)	Endoscopic navigation & tumor excision	Superior procedural workflow and minimized safety margins (10).	HoloLens, Magic Leap
Robotic 3D Vision	Roux-en-Y gastric bypass & sleeve gastrectomy	3D depth perception, tremor filtration, reduced port torque (34).	da Vinci (Intuitive), Hugo (Medtronic)
Virtual Reality (VR)	Perioperative bariatric care packages	Reduction of surgical anxiety; enhanced anatomical education (39).	Osso VR, Surgical Theater
Fluorescence AR Integration	Anastomotic perfusion & lymph node mapping	Real-time visualization of vasculature preventing ischemic leaks (40).	Firefly technology

Augmented Reality in Revisional Bariatric Surgery

Though primary bariatric procedures have been greatly standardized in terms of operative protocols, revisional bariatric surgery stands out as one of the most dangerous frontiers in gastrointestinal surgery. A patient undergoing a revisional procedure, as a result of weight loss insufficiency, severe GERD or anastomotic complications, will present with a significantly distorted natural anatomy (41). The surgical site is usually compromised with a dense fibrosis, unclear tissue planes, and modified vascular system following the index procedure. In such conditions, the 2D or even non-enhanced 3D white light visualization will not be sufficient to locate vital structures that are hidden within the fibrous scar tissue (11). Augmented Reality plays a crucial role in the guidance of surgery in this challenging environment. Augmenting the preoperative, patient-specific 3D reconstructed image data obtained from MR enterography or contrast enhanced CT scan images, allows to pinpoint the trajectory of a concealed Roux limb or locate the position of an occult gastro-gastric fistula before proceeding with dissection (8). Also, through AR, surgeons will be able to mark out important vascular pathways like the remnants of the left gastric artery and the gastroepiploic arcades to avoid major intraoperative bleeding and one of the most feared complications, the completely avascular gastric pouch (42). With this computationally generated "X-ray vision," AR greatly reduces the immense technical challenge of revisional bariatrics.

Virtual Reality as a Perioperative Care Package

The influence of advanced visualization technologies in bariatric surgery transcends beyond the walls of the operating room and is essential during the psychological and educational process before and after the procedure. Bariatric surgery is distinct in the sense that the success of the procedure depends largely on life-long behavioral and dietary changes in the patient. Patient education and informed consent are thus critical in the procedure. The conventional ways of teaching patients about surgery using two dimensional images, brochures or explanations have not been effective in filling the literacy gaps of the patients regarding the drastic anatomical changes ahead (43).VR systems have proven to be useful in overcoming the problem. VR is a very powerful preoperative care package for teaching the patients and calming their nerves (44). By wearing a VR headset within the outpatient setting, a potential candidate for bariatric surgery can find themselves immersed in an interactive, 3D anatomical simulation. Through this simulation, the patient will be able to visualize the specifics of the procedures, such as the particular volume reduction of the stomach that occurs through a sleeve gastrectomy or the intestinal redirection required in a Roux-en-Y procedure. As has been established, the spatial approach to learning in this context leads to a much better understanding of the risks, expected results, and postoperative diet by patients in comparison to traditional 2D approaches to education (45). Moreover, the time right before the administration of general anesthesia is associated with high levels of psychological stress and physical arousal on the part of many patients. Preoperative anxiety correlates positively with higher anesthetic needs during the operation, as well as with pain perception and recovery after surgery (46). In terms of the bariatric perioperative care bundle, immersive virtual reality, which involves soothing computer-generated environments with guided mindfulness or cognitive behavioral audio inputs is used in the pre-operative holding area in order to distract the patient and control sensory input (45). There is evidence from neuroimaging studies that immersive VR has a strong anxiolytic effect on the mind, by reducing pain and anxiety through distracting the limited attentional resources of the brain and suppressing sympathetic nervous system activity (47). Through bringing the hemodynamic parameters of the patient into balance before intubation, VR-enhanced visualization technologies ensure the optimal physiologic starting point.

4. Intraoperative Navigation in Gastrointestinal Endoscopy and Oncology

The interface between surgical oncology and state-of-the-art endoluminal approaches is an area where a millimeter-based level of accuracy determines the radical nature of the oncologic surgery and functional preservation. In the past, the identification of hidden gastrointestinal cancers and establishing safe margin limits during resection procedures was predominantly based on surgeon’s manual feedback and estimations, which were often hampered in flexible endoscopy and rigid laparoscopy procedures. The advent of Augmented Reality (AR) in gastrointestinal endoscopy and surgical oncology offers a revolutionary navigational tool that bridges the cognitive gap between pre-operative radiographic visualization and intra-operative reality. The ability to project tumor boundaries, blood vessels, and lymphatic flow directly onto the surgeon's field of view re-defines the standards of surgical precision.

Enhancing Diagnostic and Therapeutic Endoscopy

The development of diagnostic endoscopy to a much more complex therapeutic tool, with examples being Endoscopic Mucosal Resection (EMR) and Endoscopic Submucosal Dissection (ESD), requires maximum visual acuity. More specifically, ESD requires dissection of precancerous or early neoplasm in an en bloc fashion through a very thin submucosal layer, which measures a few millimeters in thickness (48). Perforation or delayed massive haemorrhage is always a significant risk. In this setting, AR works as a very important spatial orientation aid. Modern AR systems in GI endoscopy assist in polyp detection, procedural instruction, and reduce safety margins in cases of tumor resections (10). Using modern technologies of AI and computer vision algorithms, contemporary AR endoscopy systems are capable of performing computer-aided detection (CADe) and computer-aided diagnosis (CADx) procedures on-the-spot. While navigating the colonic or gastric cavity using the endoscope, the system projects holographic bounding boxes or topographic maps on suspicious mucosa anomalies, thus helping to identify microscopic dysplasia changes (49). In the case of therapeutic resection, AR technology can superimpose a virtually marked mucosal incision along the preoperative plan, which will serve as a guide for the procedure. In this way, the endoscopist is guaranteed to have good oncosurgical margins and avoid the unnecessary loss of healthy mucosa while maintaining organ functionality and mucosal healing (50). Moreover, predictive depth markers can be applied by AR during the submucosal dissection stage, informing the endoscopist about the location of the muscularis propria and minimizing iatrogenic perforations (51).

Precision Navigation in Surgical Oncology: Gastrectomy and Colectomy

Mapping AR navigation from the endoluminal surface into the peritoneal cavity creates an additional level of anatomical complexity, especially in major oncological resections, for example, radical gastrectomy and total mesorectal excision (TME) in colorectal cancer. For instance, in gastric oncology, a complete D2 lymphadenectomy demands precise dissection of the celiac trunk along with its numerous branches (52). Any accidental injury to the aberrant vessels within the liver or splenic vessels may lead to severe hemorrhagic complications or ischemic damage. Static preoperative 3D CT angiography can help to assess the patient-specific anatomy; nevertheless, mapping this static 3D picture to a dynamic operating field becomes quite problematic. With the use of AR, it is possible to overlay this patient-specific 3D angiographic image directly on the serosa of the stomach and retroperitoneum. With the help of this technology, it is possible to mark the course of the left gastric artery, common hepatic artery, and splenic artery under the visceral peritoneum before performing any incisions (53). In this way, the surgeon is able to safely dissect the vascular pedicles and excise the desired lymph node stations. Likewise, in the procedure of laparoscopic/robotic colectomy, AR guidance is critical to preserve the important retroperitoneal landmarks. The ureters and gonadal vessels, which are usually hidden behind the Toldt's fascia, are likely to be moved from their natural positions by bulky tumors or desmoplastic inflammatory reaction (54). AR visualization can mark the anatomical path of the ureters as a continuous “keep-out” safety zone on the mesocolon. During the surgical oncological procedure, the ability to see will allow the surgeon to make curative margins wide enough to save all the autonomic and urogenital systems of the body intact and thus avoid potentially fatal postoperative problems like neurogenic bladder or erectile dysfunction (55).

Overcoming Intraoperative Visual Artifacts

Despite the beauty of the theory behind AR navigation, the actuality of the intraoperative setting often undermines it. The surgical field for GIs is intrinsically disruptive, marked by constant perturbations. For AR projections to stay clinically meaningful, the algorithms used for computer vision should be able to deal with artifacts associated with intraoperative conditions including blurring, blood and smoke from energy devices (10). Energy devices used during surgery include monopolar electrocautery, bipolar vessel sealer and ultrasonic scissors and produce high density of smoke and aerosols from water vapor generated during the process of cutting the tissue. At the same time, minor bleeding into capillaries may collect in the dependent parts of the abdominal cavity, thus disrupting the contrast and texture that are essential for optical tracking algorithms (56) (see figure no 1).

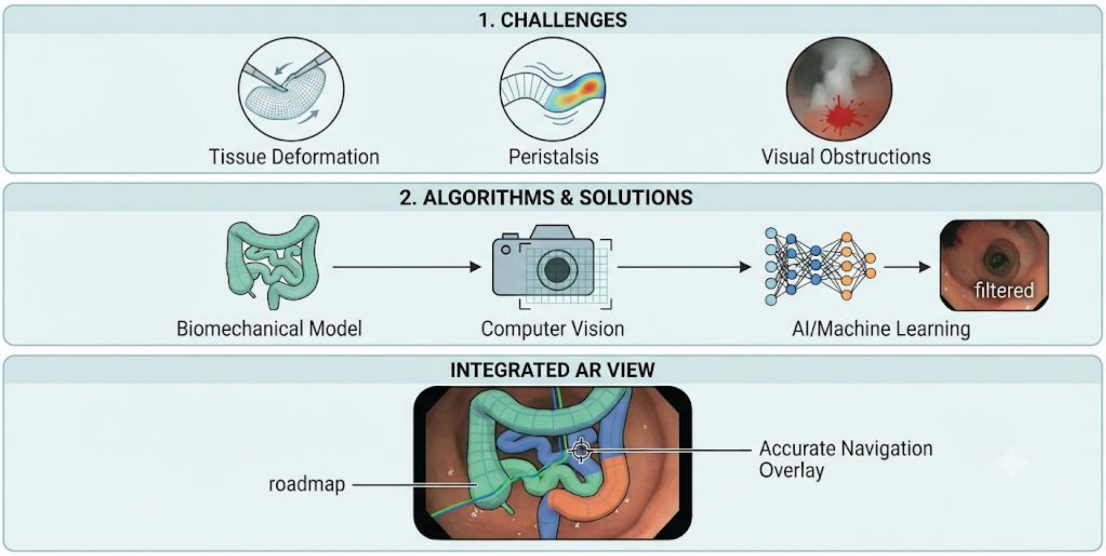

Figure 1: GI AR navigation challenges and solutions. The figure shows some of the important intraoperative variables such as tissue deformation, peristalsis, and visual obstructions due to smoke and blood that need sophisticated computer vision and biomechanics algorithms.

In case of obscuration of the field of operation, feature-based algorithms are unable to detect anatomical structures and result in loss of registration of AR projection (57). In order to solve these problems, future generations of augmented reality systems for surgery rely on advanced deep learning methods, like Generative Adversarial Networks (GANs) and spatiotemporal convolutional neural networks, which can filter surgical video in real-time (58). Image dehazing can be used to computationally remove surgical smoke by taking into account the light scattering effect between subsequent video frames, thus enabling the video restoration in advance of AR display (59). The same applies to tracking methods which can ignore the presence of pooling fluid and blood splatters and focus on structural elements instead.

Fluorescence-Enhanced Augmented Reality

One of the ground breaking achievements in surgical navigation is the complementary combination of Augmented Reality technology with NIR fluorescence visualization, thus enabling the formation of the multimodal, biological visual overlay. Indocyanine green is a sterile, water-soluble compound that binds tightly to plasma proteins after being injected into the patient's body and fluoresces under the influence of the specific laser wavelength (60). Traditional NIR visualization depicts the fluorescence either in a form of a monochrome or false color map on another screen, which means that the surgeon needs to constantly switch his attention from the traditional white light image to the fluorescent one. Contemporary AR systems unite both types of visualization within one integrated image. One of the key issues in colorectal surgery is the prevention of an anastomotic leakage – one of the deadly complications due to insufficient oxygen supply. With the help of ICG fluorescence AR integration, the surgeon can see the contrast image of microvascular perfusion overlapped on the bowel wall (61). In addition, the AR overlay depicts the exact dividing line between well-perfused and ischemic tissue, thus directing the surgeon to the ideal location to cut and minimizing postoperative leaks significantly (62). Moreover, ICG AR navigation technology is transforming the way lymphatic mapping in cases of gastric and colorectal cancer surgery is done. With the peritumoral endoscopic administration of ICG, the contrast agent travels through the lymphatic vessels to reach the sentinel lymph nodes. The AR navigation technology overlays this fluorescent map of the lymphatics on the normal surgical field, thereby helping in the visualization of hidden tumor-draining lymph nodes deeply seated within the mesenteric fat (63).

5. IMPACT ON SURGICAL ERGONOMICS AND COGNITIVE LOAD

The operational success of advanced gastrointestinal and bariatric surgery is intrinsically linked to the human factors governing the operating surgeon. Traditional minimally invasive surgery imposes extraordinary biomechanical and psychological demands, frequently resulting in a high prevalence of work-related musculoskeletal disorders (WMSDs) and cognitive fatigue among surgical specialists (64). As procedures extend over multiple hours, the physical strain of maneuvering rigid laparoscopic instruments against the abdominal wall, combined with the mental exertion of interpreting a 2D operative field, accelerates surgeon exhaustion (65). The introduction of 3D displays and Augmented Reality (AR) technologies fundamentally alters this human-machine interface, presenting both profound ergonomic benefits and novel physiological challenges, particularly concerning visual fatigue and cognitive bandwidth.

Physical Ergonomics: From Console Comfort to Cervical Strain

The physical ramifications of advanced visualization technologies are highly dependent upon the chosen hardware modality. Surgical robotic platforms equipped with closed-console 3D stereoscopic viewers currently form the benchmark for ergonomic surgical procedures. Through decoupling of the surgeon's hands from the abdominal wall of the patient and enabling the surgeon to work in an ergonomically correct sitting position, such consoles have solved the problem of muscle fatigue and joint stress inherent to traditional laparoscopic surgery (66). The immersive 3D visualization interface allows alignment of the surgeon's visual and manual axes, thereby eliminating the proprioceptive mismatch and substantially decreasing incidences of chronic neck and back pain (67). However, usage of AR technology through head-mounted displays (HMDs) presents a contrasting ergonomic profile. Although HMDs free surgeons from fixed monitors and allow working in a natural head-up position, the weight of the hardware itself represents an important obstacle to its prolonged usage (68). Contemporary HMDs, like the Microsoft HoloLens 2, weigh about 560 grams. In case of continuous usage of the headset for several hours of complex gastrointestinal resection, such anterior shift of the center of mass of the surgeon's head results in significant loading of the cervical spine and paraspinal muscles (69). In time, this continuous bending of the neck will cause problems like tension in the neck, tension headaches, and reduced operating endurance; hence, there is a need for continued miniaturization of this HMD device technology.

Modulating Cognitive Bandwidth and Inattentional Blindness

The cognitive load of a surgeon during the critical operations in an operating theatre is immense owing to the fact that cognitive load in surgical education entails three categories of mental burden: the intrinsic load (difficulty level of the operation itself), the extraneous load (effort expended on processing suboptimal information delivery), and the germane load (the effort expended on learning and schematic development) (70). The conventional laparoscopic surgery entails huge extraneous cognitive load since the surgeons have to continually do mental rotation to map out 3D anatomical representation of the surgical area from the 2D images and integrate MRI or CT scan images which appear on monitors far from the surgery area (71). With AR technology, however, the extraneous cognitive load is significantly reduced since the relevant anatomical information about the patient is superimposed on the operating field directly. This colocation of the information and physical anatomy makes it possible to avoid what is called the "switch cost," i.e., the cognitive cost involved when surgeons switch their attention from the surgical field to a monitor located outside of it (72). With this spatial alignment, it enables the surgeon to allocate more of his/her cognitive load to making important decisions and manipulating the tissues. Nevertheless, there is always the possibility that using AR without calibration may lead to cognitive overload. Overloading may be brought about by projecting too much, opaque, and cluttered anatomical overlay images onto the live surgical field, causing the problem known as "inattentional blindness" (73). This is a condition whereby the surgeon will be so overloaded with the digital hologram that he/she cannot detect the unforeseen events in the real world, including capillary bleeding and unintended heat spread from the energy device. In this case, good AR interface design should be minimalistic and context aware, meaning only those vascular or oncologic structures of relevance to that stage of the dissection will be shown (74).

Visual Fatigue and Simulator Sickness

In addition to musculoskeletal and cognitive overload, the use of stereoscopic 3D and AR displays for long periods presents its own set of ophthalmologic problems. The most notable problem in this category is the vergence-accommodation conflict (VAC) (75). Naturally, in humans, both vergence and accommodation are neurophysiological coupled ocular reflexes (the former refers to the process of converging one's eyes to see near objects, and the latter is changing the shape of one's lens in order to maintain sharp focus). However, in the case of HMDs and 3D robotic consoles, the surgeon's eyes are continuously accommodating to the fixed focal distance of the physical display (which is a few inches away), while at the same time converging onto virtual 3D images that are apparently situated in the depths of the patient's abdomen (76). Rapid uncoupling of natural processes quickly leads to asthenopia, visual fatigue, and depth perception impairment during long operations. Moreover, any difference between the movement of the surgeon's head and updates of digital overlay with a few milliseconds latency may cause visual-vestibular discrepancy (77). Where the visual sensory signals being received through the AR headset differ from those of the inner ear's proprioceptive and vestibular sensory signals, surgeons have a high probability of experiencing "simulator sickness" also known as cybersickness. Cybersickness manifests itself through symptoms of nausea, dizziness, sweating, and disorientation, which could greatly affect the surgeon's performance during surgery and jeopardize the safety of the patient (78). To surpass these human factors constraints, low latency tracking and dynamic varifocal display systems need to be developed.

6. CLINICAL OUTCOMES, ECONOMICS, AND TRAINING

However, the proof of any novel surgical technology should not only be found in the technical aspects of the technology itself but also in how it can contribute to better patient care, more efficient health care expenses, and faster learning of the surgery by trainees. The efficacy of AR, VR, and 3D robotic visualization technologies when shifting from being a prototype to being incorporated into gastrointestinal and bariatric surgery has to be evaluated according to standard laparoscopic parameters (79). It is now apparent that better visualization provides clinical benefits; however, it requires a huge economic investment.

Measurable Clinical Outcomes: EBL, Complications, and Conversion Rates

Immediate effects of improved 3D and AR visualization on intraoperative safety are clearly seen in terms of reduction of estimated blood loss (EBL) and prevention of life-threatening complications after operation (80). In complicated bariatric procedures such as revisional Roux-en-Y gastric bypass, precise visualization of occluded vascular pedicles and dense adhesions via stereoscopic depth perception proves directly associated with a decreased number of vascular injuries (81). Thus, according to systematic reviews, robotic-assisted bariatric procedures are characterized by comparable or substantially reduced EBL compared to laparoscopy (82). Additionally, implementation of AR overlays, especially those which are supplemented with near-infrared fluorescence, solves one of the most dangerous problems in GI surgery: anastomotic leak. Anastomotic leaks are a frequent complication of bariatric and colorectal operations (their occurrence ranges between 1% to 5% of all cases) and lead to severe morbidity (83). The use of AR for assessing perfusion reduces the risk of anastomotic leaks significantly due to construction of GI anastomosis only within verified perfused areas, excluding any subjectivity from the surgeon's assessment of the area via mucosal coloring and arterial pulsation (84). An important measure for determining the safety of surgery in cases of GI oncology is the rate of conversion to open laparotomy, which always entails the development of prolonged hospitalization, increased postoperative pain, and an increased likelihood of developing incisional hernias (85). The use of AR and 3D robotic technology allows surgeons to operate in a difficult anatomical environment like the narrow fibrotic pelvis in total mesorectal excision or large hepatomegaly in super-obese bariatric patients (86). Such anatomical mapping greatly reduces the necessity of open surgery, allowing to retain all advantages of the minimally invasive technique (82). Yet, the influence of AR on the total duration of surgery poses a rather contradictory problem. Although 3D imaging allows to speed up complicated repetitive motor actions like knot tying and multilayer suturing, the existing versions of surgical AR systems usually take more time at the beginning of the surgery (87). Equipment preparation, calibration of the head-mounted display, and soft tissue registration will all take an additional 15 to 30 minutes of surgery time (88). Although quicker stitching could compensate for this time loss, operation times will be longer in general while working on the experiment stages of AR implementation. As soon as computer vision algorithms and automated registration techniques are improved, this disadvantage will reduce with time, making the surgery easier and more efficient (89).

Health Economics and Financial Viability

The ubiquitous adoption of enhanced visualization technologies remains severely impeded by health economic issues of great difficulty. The financial issue is two-fold, consisting of both the prohibitive capital investment cost and considerable recurring costs (90). A state-of-the-art robotic surgery system with enhanced 3D visualization capabilities and the capability of AR could cost more than 1.5-2 million USD, with optical see-through AR head-mounted displays adding additional costs in hardware amounting to 3,000-5,000 each (91). However, beyond capital investment, health facilities are expected to incur considerable recurring costs. Such costs include disposables robotic tools, annual service contract costing more than 150,000 a year, and software licensing fees for rendering in cloud computing and 3D image segmentation prior to operation (92). Moreover, the utilization of AR in surgery presently requires dedicated clinical engineering support. Creation of high-quality patient-specific 3D model and solving of the problem of failure of registration process during the procedure are required for success of AR in surgery and entail hidden labor costs as well (93). Justification of such extravagances would entail moving towards value-based healthcare by comparing initial costs against clinical savings (94). ROI for augmented reality and robotics is achieved through savings from the prevention of complications that arise postoperatively. The cost associated with the treatment of a single case of severe bariatric anastomotic leak, which entails admission into the ICU, total parenteral nutrition, and repeat surgery, can easily be above 50,000 to 100,000 (95). Even a minimal percentage saved in terms of preventing this rare event will quickly pay off any initial investments in technology with the aid of perfusion imaging and 3D perception provided by AR (96). Furthermore, reductions in length of stay and readmissions provide additional leverage on the economic scale for these visualization technologies, although complete cost neutrality still evades lower volume community hospitals (97).

Surgical Training and the Learning Curve

Traditionally, surgery training is conducted using the Halstedian model of apprenticeship, where trainees develop procedural skills through intraoperative exposure to the operating procedure on actual patients. Yet, the difficult learning curves entailed in the advanced minimally invasive GI and bariatric procedures pose serious ethical and clinical dilemmas (98). It takes the learning curve of 50 to 100 cases to become proficient at performing the robotic Roux-en-Y gastric bypass procedure (99). Virtual reality and augmented reality significantly break down the traditional teaching approach by transferring the process of developing the basics of surgical technique and anatomy skills to the laboratory setting (100). Using VR simulation programs provides a realistic, yet safe way for surgical trainees to perform bariatric procedures repetitively (99). Contemporary VR simulators provide detailed data on the metrics of a particular procedure performed—time taken to complete the task, economy of movement, total length of instrument path, tissue tension used, and errors made (101). By doing this, trainees attain proficiency in performing techniques on the steep part of the learning curve without even approaching live patients, thereby making the process safe for patients and alleviating the ethical dilemma posed by the traditional "see one, do one" model (102). In addition, pre-procedural "warming up" with VR tools right before a live operation has been found to sharpen cognitive attention and decrease technical mistakes made within the first 30 minutes of the procedure (103). Augmented reality also contributes significantly to groundbreaking developments in telementoring and live proctoring during surgery. With the use of optical see-through headsets or augmented operative monitors, an attending surgeon can watch a colleague perform surgery from an entirely different geographical location with no latency at all (104). The mentor is able to virtually draw annotations such as the lines where the mucosa should be incised in order to conduct an endoscopic submucosal dissection and the safety zone around the biliary tree (105). With this telementoring approach based on AR technology, this process becomes safe and much faster, ensuring that there is greater democratization and access to expert knowledge in bariatrics and oncologic surgery (106).

7. FUTURE DIRECTIONS, ETHICAL CONSIDERATIONS, AND CONCLUSION

Augmented reality (AR) and advanced visualization technologies used in the current age for gastrointestinal and bariatric surgery are but just the beginning of an immense technological advancement process. With advancements in computing abilities and the increasing sophistication of machine learning techniques, AR in surgeries can evolve into a totally self-sustained predictive environment. This would involve crossing many technological barriers and overcoming some major ethical and medico legal challenges.

Future Directions: AI Integration and Edge Computing

By far the most important frontier in the evolution of surgical AR technology is how well it is integrated into Artificial Intelligence (AI). At present, almost all AR technology provides only static passive overlays in the form of anatomical maps that need to be updated manually by the surgeon (107). The future, however, belongs to dynamic AI-based predictive surgical overlays. By using deep learning architecture algorithms based on large libraries of surgical videos, next-generation AR tools will not only show the anatomy but also predict the next steps in surgery (108). For example, during a complex revision of a bariatric procedure, an AI-based AR tool could automatically process the textures of tissues, marking the best plane for adhesiolysis or showing the surgeon where his/her instrument is about to harm some critical structures such as common bile duct while being moved too quickly towards it (109). Technologically, to solve problems with latency and weight of the AR headset, new paradigms of edge computing and 5G integration will be required. Presently, the high computational load related to soft-tissue finite element modeling requires tethering of AR headsets to bulky server towers placed in the operating room (110). Through use of 5G edge computing, the large amounts of data produced by the laparoscopic camera would be transmitted to the cloud where they would be processed through neural networks, and then sent back to the lightweight, wireless smart glasses within a few milliseconds (111). This would enable the separation of the display equipment from the processor, making it possible to create ultralight holographic visors, which would entirely solve the issue of cervical strain experienced using current HMDs. In addition, the future developments in markerless tracking through use of spatial-temporal convolutional neural networks would soon make current registration procedures obsolete, enabling the overlay to instantly “snap” to the patient’s anatomy upon insertion of the laparoscope into the abdomen (112).

Ethical Considerations and Medico legal Liability

With increased integration of advanced visualization tools into the surgical procedure flow, numerous ethical and medico legal issues arise. First and foremost, the problem of patient data privacy and security raises its head (113). Creation of 3D holograms of patients necessitates transmission of extremely sensitive un-anonymized radiological imaging (CT/MRI) scans and intraoperative video feeds to cloud servers of third parties or software vendors. It is crucial to be HIPPA and GDPR-compliant in this case (114). Medical institutions have to use quantum-resistant encryption technology to ensure no leaks of PHI can occur (115). Another issue to be considered is the problem of medico legal liability in case an adverse surgical outcome occurs due to an issue with an AR tool. In case an AI-driven AR tool incorrectly registers the deformation of the vascular pedicle in soft tissue and the surgeon cuts the vessel based on incorrect registration, then the situation becomes very complicated in terms of liability (116). Is the blame to be placed on the operating surgeon for failing to recognize the visual-spatial discrepancy, the software programmer for failing to factor in the physical distortion of tissue, or even the hospital for calibrating their equipment incorrectly? The black box dilemma of AI and AR in surgery is an issue that does not fit well within the conventional frameworks of medical malpractice (117). Standardized regulatory rules, such as the ones currently being developed by the FDA for “Software as a Medical Device” (SaMD), are vital. In addition, the surgeons have to retain the skills necessary for switching over to non-augmented traditional surgery in case of a technology failure.

CONCLUSION

The implementation of Augmented Reality, Virtual Reality, and 3D robotic visualization into gastrointestinal and bariatric surgery represents a true paradigm shift. By overcoming the limitations in terms of depth perception inherent in the 2D system of traditional laparoscopic surgery, this technology ensures a higher degree of surgical dexterity and mitigates serious ergonomic issues. Furthermore, the visualization of blood vessels, tumor borders, and even tissue perfusion in real time on the operative field during bariatric and GI oncologic surgery is of immense importance for the precision and safety of the procedure. Although several significant challenges exist mostly in relation to the issue of dynamic soft-tissue deformation, current hardware limitations, and high costs associated with the implementation of this technology, there is little doubt that rapid advances in the field of computer vision and biomechanics will enable us to overcome these obstacles in the very near future. The evolution of spatial computing technologies and their seamless combination with predictive artificial intelligence will make enhanced visualization a standard part of any surgical procedure.

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