IOSR Journal of Dental and Medical Sciences (IOSR-JDMS)
e-ISSN: 2279-0853, p-ISSN: 2279-0861.Volume 23, Issue 2 Ser. 6 (February. 2024), PP 37-46
www.iosrjournals.org

Recent Developments In Minimally Invasive Surgical Techniques: A Comprehensive Review Of Innovative Strategies

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Abstract:
Background*: Minimally Invasive Surgery (MIS) traces its roots first time in 19th century, with fundamental advancements including thoracoscopy in 1912. Laparoscopic techniques were greatest innovation of mid-20th century. Revolutions like laparoscopic appendectomy and cholecystectomy in the 1980s marked the start of MIS's transformative era and was major breakthrough of medical science in reshaping surgical paradigms. Robotic surgery, advanced 3D imaging and AI use has become latest innovation in MIS procedure.*
Materials and Methods*: We followed a systematic search strategy utilizing databases like PubMed, Scopus, and Web of Science. Some data was searched manually from chrome. Primary keyword combinations such as "minimally invasive surgery" and "recent advancements" were used along with secondary keywords to gather relevant literature. Inclusion criteria focused on peer-reviewed studies from the past decade, covering various aspects of MIS and related technologies. We extracted data from about 38 papers to conduct comprehensive current MIS developments across surgical specialties.*
Results*: Recent advancements in technology have revolutionized minimally invasive surgeries (MIS) and it was enhanced precision and patient outcomes. Medical advancements in MIS surgery have reduced the risks, post operative pain, hospital stays, costs, and surgeon's stress. Key breakthrough tools include robotic systems like da Vinci Surgical System, enabling enhanced dexterity and control. Artificial intelligence (AI) aids in preoperative planning and intraoperative decision-making, optimizing surgical approaches. Medical science has introduced use of advanced imaging modalities such as intraoperative MRI and 3D laparoscopic cameras for real-time visualization and using flexible endoscopes along with micro-instruments and sensors enable access to intricate anatomical structures.*
Keyword*: Robotic surgery, Artificial Intelligence, Minimally Invasive Surgery, Advanced Imaging, Micro-instruments*

Date of Submission: 12-02-2024 Date of Acceptance: 22-02-2024

I. Introduction

Minimal Invasive Surgery (MIS) is the surgery type that uses sophisticated technology to attain the internal organs or structures through small incisions or natural orifices, in contrast to traditional open surgery [1]. MIS covers various techniques and is being used in multiple surgeries. MIS procedures are accompanied by surgical tools like a laparoscope, Trocar, insufflators, and catheters that cause lesser pain, shorter hospitalizations, and fewer incidents of complications. MIS tools are selected based on the type of surgery being performed. MIS accuracy rate depends on factors like the type of surgery, equipment used, individual health or skills, and surgeons' experience. However, its accuracy rate ranges from 75 to 80% in most surgeries [2]**.**

According to projections by Next Move Strategy Consulting, the global minimally invasive surgery market experienced significant growth between 2019 and 2030. In 2019, the market was valued at approximately 20.5 billion U.S. dollars. However, by 2030, it is expected to more than double in value, reaching over 44 billion U.S. dollars. This substantial increase underscores the growing adoption and advancement of minimally invasive surgical techniques worldwide [3].

Background

The conception of minimally invasive surgery (MIS) can be traced to the early 19th century when Philipp Bozzini developed an endoscope in 1806. The developments in endoscopes were continued by Antoine Desormeaux in 1983 [4]**.** The lynchpin changes in MIS happened (was with) the emergence of thoracoscopy by Hans Jacobeus in 1912 to treat lung tuberculosis. In the 1930s and 1940s, Heinz Kalk and John Ruddock's application of diagnostic laparoscopy laid the groundwork for further research. The most significant progress in this area came from gynecologists such as Raoul Palmer and Hans Frangenheim, who advanced laparoscopic techniques in the middle of the 20th century. Kurt Semm's inventions in the 1970s, including the first laparoscopic appendectomy performed in 1980, and Erich Mühe, who invented the first laparoscopic cholecystectomy in 1985, the end of the minimal invasive surgery (MIS) era began [4]**.**

This was possible thanks to the innovation of imaging and illumination devices like the Hopkins rod lens system and solid-state cameras, both of which offered high-quality visual displays for video-assisted procedures and helped steer MIS to various surgical disciplines. MIS's evolution was characterized by an incremental transition from diagnostic to therapeutic applications, with the precondition of the development of relevant instruments and techniques geared towards reducing patient trauma and shortening recovery time, which changed surgery and patient care models in existing. The continuous transformation of MIS throughout the last two decades has resulted in the addition of numerous surgical procedures to its list and contributed to improving patient outcomes and quality of life. Nevertheless, although the method is highly effective, there are still challenges, including the risk of complications; therefore, it needs to be re-evaluated to prove its efficacy and safety [5]**.**

The objective of the Review

We aimed to investigate recent advancements, the use of robotics in surgery, and A.I. integration in minimally invasive surgical techniques, focusing on emerging innovative strategies that come up with various surgical specialties. Through a systematic examination, we intended to provide insights into the current landscape of MIS, clinical applications, challenges faced by surgeons with integrating A.I. and robotics in minimal surgical procedures, and future directions of minimally invasive surgery.

II. Material And Methods

Systematic Search Strategy

A comprehensive systematic search strategy was followed to extract data relevant to our research topic. We used electronic databases like PubMed, Scopus, and Web of Science with suitable search terms and Boolean operators. This Review also contains manual searches of relevant journals and reference lists of cited articles is provided in the end of paper.

Keyword Strategy

The keyword strategy combines relevant terms of minimally invasive surgery and its various aspects. This will include variations and synonyms of the following key terms: "minimally invasive surgery," "laparoscopic surgery," "robotic surgery," "minimally invasive oncologic surgery," and "surgical training." Boolean operators utilized to systematically combine these keywords to ensure comprehensive coverage of the literature.

Boolean Strategy

1. "Minimally Invasive Surgery" OR "MIS" AND "Recent Advancements"
2. "Laparoscopic Surgery" OR "Keyhole Surgery"
3. "Robotic Surgery" OR "Robot-Assisted Surgery"
4. "Minimally Invasive Surgical Techniques" AND " Advantages and Challenges "
5. "Surgical Training" OR "Surgical Education"
6. "Minimal Invasive Surgery" OR "MIS" AND "A.I. Use"

We carefully selected these terms using Boolean operators "OR" and "AND" which helped us to search critically on databases chosen to reach out to desired data literature on recent developments in minimally invasive surgical techniques and related topics.

Inclusion and Exclusion Criteria

Inclusion Criteria

1. Publications in peer-reviewed scientific journals and governmental sites
2. Studies conducted in the last ten years to keep our research current

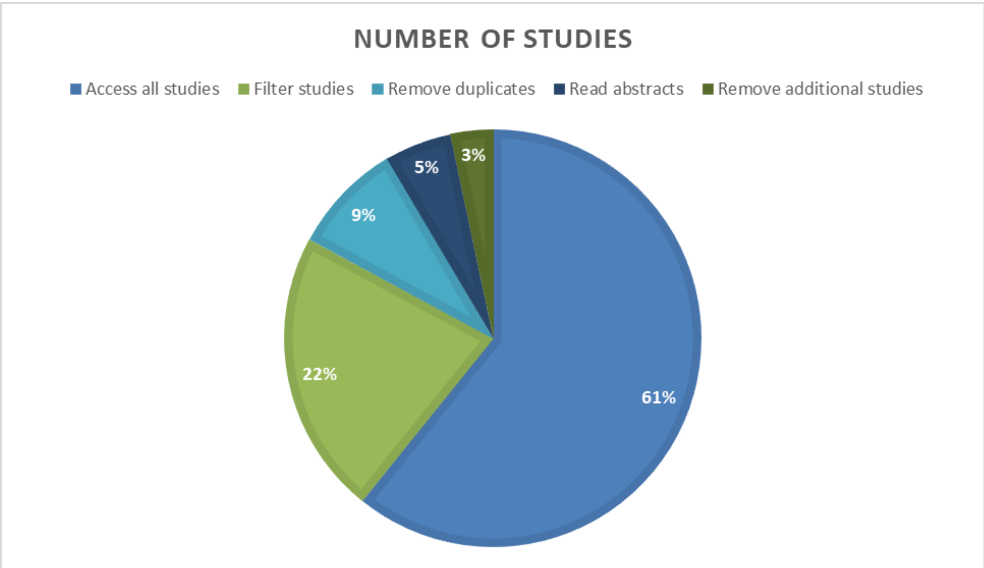
3. Articles on recent developments in minimally invasive surgical techniques such as laparoscopic, endoscopy, and robotic surgery were selected. We aimed to focus on studies discussing A.I. integration, the historical background of MIS, and other MIS procedures that were selected.
5. Studies on the efficacy and the results of minimally invasive surgical interventions in different surgical specialties.
6. Articles examine progress in surgical training and education about minimally invasive approaches.
8. Studies on patient outcomes such as pain control, postoperative complications, and long-term survival outcomes.
9. Minimally invasive surgery articles focusing on technological developments, like imaging modalities and surgical instrumentation.
10. Research focused on integrating minimally invasive procedures into multidisciplinary treatments for complex medical conditions.

Exclusion Criteria
1. Non-scientific literature includes conference abstracts, editorials, and letters to the editor.
2. Studies published to ensure relevance to the recent advancements.
3. Articles focusing only on the traditional open surgical methods without mentioning the minimally invasive approaches.
4. Research other than minimally invasive surgery or surgical training.
5. Studies need a more appropriate research design or statistical analysis.
6. Articles on outdated surgical technology or methods.
7. Research focuses only on the fundamental scientific aspects of surgical procedures without any clinical relevance.
8. Studies with a small number of samples or limited generalizability.
9. Studies focusing only on pediatric or animal models, which do not have clinical translation.

Data extraction

Data extraction entailed extracting data from chosen papers. After removing duplicates, the first abstracts were studied, and papers were selected; then, full papers were studied, and only required information was extracted. This Review includes around 38 articles that passed the strict inclusion criteria and are cited in the end, thoroughly reviewing the latest developments in minimally invasive surgical techniques in different surgical sub-specialties.

Step	Number of Studies
Access all studies.	1238
Filter studies	450
Remove duplicates.	177
Read abstracts.	105
Remove additional studies.	67
Select final studies.	30
Added manual studies.	8



III. Results

Evolution of Minimal Invasive Surgery Techniques

Development of Laparoscopy (1980s): Laparoscopy represented a major advance in minimally invasive surgery for several reasons. Benefits over traditional open surgery included shorter hospital stays and less postsurgical pain. The small-incision technique requires a laparoscope to perform surgeries, with the first laparoscopic appendectomy in the 1980s marking the beginning of this modern era [6]**.**

Emergence of Robotic-Assisted Surgery (1980s-1990s): The foundation for the idea of robotic surgery came from military projects that sought to develop remote surgical technologies. Early inventions included the ROBODOC for total hip arthroplasty and the AESOP 1000, which assisted in manipulation of a laparoscopic camera. These innovations set the stage for more advanced robots in surgery [6].

Inception of Early Robotic Platforms (1990s): In the 1990s, an array of robotic platforms appeared to aid a surgeon, such as the PROBOT for prostatectomy and the Zeus robotic surgical system that had separate arms for surgical manipulation. The Zeus system made for the first transatlantic cholecystectomy in 2001, proving that surgical procedures could be performed in such a remote manner **[7].**

Creation of the da Vinci Surgical System (2000): The da Vinci Surgical System by Intuitive Surgical revolutionized robotic surgery by offering 3D vision and EndoWrist technology for exactitude in surgical maneuvers. Its debut in the operating room began with general laparoscopic surgeries such as cholecystectomy and mitral valve replacements, establishing the device's efficacy and safety [8]**.**

Evolution of the da Vinci System (2000s-2010s): The da Vinci system continued its progress with the development of the da Vinci S, Si, and Xi models that refined its visualization, instrumentation, and overall surgical capabilities. Such advancements broadened its utilization across many different surgical disciplines, proving the effect that robotic assistance can play in minimally invasive surgery [9]**.**

Robotics Use in MIS

In robotic-assisted minimally invasive surgery, the surgeon does not operate manually using hands; instead, there are two advanced technological approaches: a direct telemanipulation system or a computer-controlled setup.

Direct telemanipulation (Such as in Da Vinci) stands for robotic surgery in which the surgeon from a control desk located away from the patient views a stereoscopic vision and remotely handles the instruments. These tools are connected to robotic arms performing the same task as in laparoscopy procedures but with small incisions for access [10]. Robotic arms are at the core of mechanical systems that allow the surgeon to extend his capabilities to tight spaces with unmatched precision, equipped for complex tasks, leading to higher surgical efficacy.

However, an assistant and a nurse must constantly change the tools throughout the surgery. Da Vinci is equipped with several robotic arms that mimic surgeon movements with reasonable accuracy, providing more freedom of movement than traditional laparoscopic tools. Operated from a console offering 3D views and accurate instrument handling, a camera of high-definition and 3D visualization that significantly enhances surgical accuracy across urology, gynecology, and general surgery is it. These are beneficial to decrease surgical time and improve outcomes and recovery time. In emerging systems, Da Vinci's dominance, new players like Medtronic, Stryker, and Titan Medical come with alternatives, thus the sign of progress and more options in minimally invasive surgery [10].

The computer-based approach is the second type of robotic-based surgery. The surgeon uses a computer to command the robotic arms and their instruments, mainly made of technological components. The method might integrate telemanipulation that would allow us to communicate. This approach's most significant benefit is the possibility of conducting operations remotely, which ultimately translates to the surgeries being performed without a surgeon being physically present. At the same time, artificial intelligence can be integrated to support and eventually conduct the surgery autonomously. Robots accessed MIS use memory devices in these operations are essential to prevent disruptions by storing all detailed patient data, which may be used for an array of purposes, all aimed at maintaining the proper calibration of the robotic system and ensuring data reliability over a long duration [11]**.**

Major players in this market that are now being used for MIS include line-up players such as Intuitive Surgical, Incorporation, Stryker Corporation, Mazor Robotics Ltd., and Hocoma AG, among others, spread out around the world from the United States to Switzerland, Israel, and all around the world. The da Vinci robot by Intuitive Surgical undeniably sets the benchmark of devices used in soft tissue surgeries, with 5 thousand units in over 100 countries worldwide performing around 1 million procedures per year, mainly in urology and gynecology. The market keeps changing with the new entry of robotic systems like ALF-X, Titan, and others are intended to create a more extensive scope in surgical robotic assistance and in different specialties like cardiology with the CorPath GRX system and even hair implantation with the Artas platform [12]**.**

CorPath GRX system by Corindus achieved a significant milestone in 2018 when the FDA approved its first automated movement feature called "Rotate on Retract (RoR)," thereby paving the way for future autonomous robotic surgeries. Telemanipulators who tend to conduct surgery over long distances encounter problems like delays in image transmission, which is dangerous for patients undergoing surgery [13]**.** Yet, new developments in 5G technology are likely to alleviate the identified shortcomings, resulting in a significant reduction in delays and an improvement in image quality, which is critical for remote surgical procedures. Fourth generation minimally invasive surgery techniques involve precise manipulations, safer and more effective approach, advanced instrumentation, and innovative approaches, leading to improved outcomes and reduced recovery times [14]**.**

The progress made notwithstanding, the world still needs to improve in surgical care, produced by the lack of the necessary skills in the surgery professionals. One must recognize the introduction of appropriate technological solutions to address this gap. Still, more importantly, a collaborative effort must be made to form a global network that can enable the remote performance of surgical operations and guarantee equal access to quality medical services for all. The robotic console is the central command for robotic surgery, where the surgeon operates robotic arms with hand controls and foot pedals. The surgeon's movements are interpreted by command at the console so that they are carried out precisely within the patient. A robotic console provides a 3D high-definition view of the surgical area essential for decision-making during complex procedures [15]**.**

Robotic vision systems integrate complex algorithms to detect parts and their features while adapting to part volume and handling damage. Robotes contain "Eyes," and these vision systems eliminate the need for complex fixtures and provide flexibility to automation systems, allowing the robot to handle part variations. They consist of cameras, lighting, and software, which work together and rapidly analyze the surgical parts, providing precise position information [16]**.** For example, the SPRINT vision system by Cambridge Medical Robotics offers high-resolution, 3D imaging for minimally invasive robotic surgery. SPRINT Vision system is designed with miniature cameras and depth-sensing technology and has algorithms for better visualization of surgical sites. The vision system integrates with robotic arms, facilitating precise instrument manipulation and improving patient outcomes.

Advantages of Robotic Surgery

Precision: ROborts provides a very high level of precision beyond what human capabilities can offer. They outdo the human hands in the representation of complex operations and MIS, consequently reducing the error rate, enhancing patient outcomes, and minimizing postoperative complications [17].

Enhanced Dexterity: The robotic arms can rotate 360 degrees and duplicate that of a surgeon's hand without the tremors. It provides superior agility compared to humans. This quality benefits tight spaces where complex maneuvers must be carried out [17]**.**

Three-Dimensional Visualization: Beyond the 2D display, 3D visualization offered in robotic systems gives a depth perception and spatial awareness and is thus invaluable in navigating anatomical structures and correct instrument placement [17].

Reduced Surgeon Fatigue: Sitting in the control station instead of standing allows the surgeons to operate and lessens the physical strain. The surgeons tire less than during lengthy procedures, which would otherwise lead to fatigue. This comfort with the perfect quality of life facilitates the patient's safety and outcome [17]

Cost Effectiveness and Economic Growth: Robotic systems reduce costs in minimally invasive surgeries, promoting economic development, as evidenced by the market's projected growth from around 29 billion to over 55 billion U.S. dollars by 2030, reflecting increased efficiency and accessibility in healthcare [18].

Specialty-Wise Robotic Advancement in MIC

AI Integration in Urological Robotic Surgery in MIC

The fields of urology, AI, and robotics intersected with the breakthrough of A.I. annotations for the surgical process as they occur in real-time. This innovation is a breakthrough in urology, which makes a real-time automatic annotation of the critical surgical steps and safety measures from the operative video feeds possible. A.I. technology offers a dual advantage: enlivening surgical education through an aggressive and interactive surgical atlas and improving the quality of surgical care by delivering intraoperatively made by computerized decision support and through artificial intelligence. Both robotics and AI technologies promise to improve treatment standards significantly [19]

Robotic Nephrectomy: This method addresses the removal of the kidney, whether partial or complete, with minimal incisions, providing the necessary comfort for the patient, a shorter recovery, and a 98.6% higher success rate. Reducing the risk of postoperative complications has become the preferred choice [20]**.**

Robotic Pyeloplasty: Fixing ureteropelvic junction obstruction with great precision is what allows the return of adequate urinary flow. Its approach requires a handful of recovery days, less scarring, and less postoperative pain. Conventional procedures need weeks to heal after an open procedure. Its success rates are high, and it is now the method of choice, for it often leads to improved renal function. Robotic pyeloplasty has an overall success rate of approximately 90% for achieving complete radiographic resolution of ureteropelvic junction (UPJ) obstruction, with a symptomatic relief rate of 95%, surpassing endoscopic techniques like endopyelotomy **[21].**

Robotic Prostatectomy: The use of advanced automated systems goes a long way in the accurate treatment of prostate cancer, with a 95% exact complete cancer removal rate. This is especially important since it enables the nerve-sparing techniques vital in maintaining urinary continence and sexual function. Its minimally invasive nature results in less pain and a shorter recovery than conventional approaches [22]**.**

MIC Cardiac Surgeries for Heart Health

Robotic Coronary Artery Bypass: Transforming cardiac surgery permits the capability of precise revascularization with small incisions, thus minimal chest trauma and a shorter recovery with a 95% success rate of surgery. Robotic talent is such that accurate suturing and grafting are achieved, leading to superior outcomes [23]

Robotic Mitral Valve Surgery: Taking the repair or replacement of the mitral valve to an unparalleled standard of precision, as it is associated with much less blood loss and trauma, thus enabling an earlier return to normal activities with improved valve function [23]**.**

Robotic Atrial Fibrillation Ablation: Uses mechanical precision to treat atrial fibrillation by ensuring effective lesion creation and mapping – reducing complications and leading to quicker recovery with less need for repeat procedures [23]**.**

Orthopedic Surgery: Precision-Driven Implant Placement

Robotic Total Knee Arthroplasty (TKA): Changes how knee replacement is performed by tailoring surgical plans to position implants with sub-millimeter precision, resulting in greater longevity and patient satisfaction with less wear [24].

Robotic Total Hip Arthroplasty (THA): Increases the accuracy of hip replacement by optimizing the position of implants to reduce the complications that can be associated with them. This leads to better joint function and fewer revision surgeries [25]**.**

Robotic Spinal Surgery: Places implants with exceptional precision in procedures like spinal fusion. For example, Mazor X is a great new tool for the spine surgeon that allows less invasive access options with small incisions, less tissue disruption, and faster recovery [26]**.**

Head and Neck Surgery: Minimally Invasive Approaches to Complex Regions

Transoral Robotic Surgery (TORS): Cancers of the head and neck are handled with minimal surgery by Penn surgeons; TROS is the world's first surgery that completely removes begins and malignant tumors. This new approach allows head and throat areas that are difficult to access and is associated with a better recovery, and Da Vinci's surgical system is used. It has the potential to improve speech and swallowing outcomes [27].

Robotic Thyroidectomy: In this case, the thyroid gland is removed in a less invasive manner. This way allows for minimal incisions and improves cosmetic outcomes [27]**.**

Robotic Parathyroidectomy: Robotic parathyroidectomy through a transaxillary approach is the latest and most feasible approach for those patients with primary hyperparathyroidism and preoperatively localized disease. The automated transaxillary approach can be performed safely with excellent cosmesis without creating scars in neck regions. The latest advances and new technology in surgery are improved safety, enhanced precision, 3-dimensional (3D) magnified dissection for parathyroid surgery without the need for CO2 insufflation, and a better cosmetic outcome due to the presence of an invisible scar in the axillary region or retro auricular region [27].

Other general Robotic-Assisted surgeries

Expanded Robotic-Assisted Cholecystectomy: Robotic systems have revolutionized gallbladder removal. The latest robotic systems provide the surgeon with unrivaled precision and augmented reality visualization that allows the safe navigation of the confined spaces of the abdomen, minimizing risk to vital structures and providing patient benefits such as minimal incisions, reduced postoperative discomfort, and a quicker recovery [28]**.**

Enhanced Robotic-Assisted Hernia Repair: This procedure now offers advanced robotic surgery coupled with real-time image and tissue mapping, facilitating placement of mesh and hernia repairs with an unprecedented level of precision and with significantly lower recurrence rates. Patients have benefited from smaller incisions, less postoperative pain, and a speedier recovery to a normal lifestyle [28]**.**

Improved Robotic-Assisted Appendectomy: Leveraging the newest robotic and imaging technology, appendectomies are performed with minimal invasiveness. This has resulted in markedly less tissue trauma and postoperative pain, yielding a quicker patient recovery and significantly shorter hospital stays [29]**.**

Breakthroughs in Gynecological Surgery

State-of-the-Art Robotic-Assisted Hysterectomy: The combination of robotic surgery with the latest imaging and precision instruments has transformed hysterectomy procedures. Technological advancements assure minimal incisions and, therefore, minimal scarring, ultimately less time in the hospital and a quicker recovery with less postoperative pain and a rapid return to normal activities [30]**.**

Robotic-Assisted Ovarian Cystectomy with Unparalleled Precision: The leaps forward in minimally invasive surgery, specifically robotic-assisted ovarian cystectomy with unparalleled precision, has been remarkable in gynecological procedures. New sophisticated surgical tools and techniques have arisen that provide heightened accuracy and have little to no impact on the patient. Robots, for instance, allow surgeons to operate in tiny spaces with better control. Moving away from the invasive ways of the past, this truly is a new day for patient care and surgical efficiency.

Robotic-Assisted Myomectomy Ushers in a New Era: Robotic-assisted myomectomy marks the dawn of a new era where science and technology have converged, and more advances are being introduced. Myomectomy revolutionary tools and instruments use complicated algorithms and A.I. software for automation and precision where uterine fibroids are being rapidly removed with incredible accuracy, causing little to no tissue damage and giving immeasurable benefits to patient recovery [30]**.**

Artificial Intelligence in Robotic Surgery

Human intelligence is simulated and processed in a machine called AI. AI has now become able to make decisions and guide and monitor surgical operations accurately [31]**.**

Surgical Planning and Simulation: Advanced software tools are being developed to enable surgical planning and simulation. These tools incorporate AI to improve decision-making by providing predictive analysis based on thorough digitized patient data, including images, physicochemical data, and medical histories [31]

Advisory Systems: AI-driven advisory systems have also been introduced to provide real-time guidance during surgery. These systems analyze the information available from its database on current and past surgeries, reports of individual surgeons, and textual diagnostic data, and they provide both specific recommendations and alerts, thereby further improving surgical precision and safety.

A.I. in Diagnostic and Analytical Processes: The integration of A.I. during the diagnostic phase is critical for MIS. A.I. algorithms can build precise treatment models for individual patients by digitizing and analyzing images, physicochemical data, and medical histories. Such models are the most critical element for optimizing the outcome of MIS [31]**.**

Physical Modeling and Computer Simulations: It is also essential that software applications utilize A.I. for the physical modeling and computer simulation of a surgical operation. Such applications allow for the virtual planning of surgical operations to permit the change and optimization of surgical strategies and to pre-plan the measures necessary for dealing with the complications most likely to arise [31]

Image Analysis and Augmented Reality through A.I.

The application of image analysis and augmented reality are among the leading A.I. techniques. Refined using AI-driven technologies, image analysis provides surgeons with an immersive, high-definition, 3D visualization of the surgical field. Surgically relevant digital information, such as vital structures, is visualized by augmented reality (A.R.) technologies driven through the lens of A.I., which overlay this information onto the real-world view of the surgical site. Concomitant with dramatic advances in minimally invasive surgical techniques, the fusion of A.R. with telemedicine now enables surgeries and consultations to be conducted from remote sites. Perhaps most exciting of all, telementoring in surgical education, where AI-driven 3D and A.R. visualizations are increasingly brought to bear, is democratizing surgical students' training opportunities. Telemedicine is beginning to address some barriers to surgical care, particularly in low- and middle-income regions, by delivering healthcare from a distance.

Another towering impact of AI in surgery is through big data analytics [32]**.** The application of AI to analyze enormous datasets from prior surgeries (Big Data) underpins the ability to create predictive models and define best practices to improve surgical procedure outcomes continuously. Progress towards fully autonomous surgical robots also depends on advances in A.I. A.I. will be embedded in robots on two or multiple levels for decision-making and operational execution. Specific gear systems such as sensors and algorithms are used to operate several particular tasks without a human being. For this, they will be well-trained to face the forces and the changing scenarios that occur during their operation in the clinic [32]**.**

Advances in Imaging Technologies

Integration of Medical Imaging: Medical imaging (e.g., endoscopy, x-ray fluoroscopy, computed tomography (C.T.), ultrasound, magnetic resonance imaging (MRI), etc.) have not only evolved from purely diagnostic instruments to essential ones that directly support interventional diagnostic and therapeutic procedures, but this evolution has been driven by some of the first efforts in MIS, as surgeons realized that the condition for which they were operating was not visible. Minimally invasive surgery is synonymous with precision, minimal access, and more rapid recovery time for the patient [34]**.**

Real-time Image Guidance: The transformation from purely static-to-patient imaging to image guidance in real-time is foundational to the rise of interventional radiology and minimally invasive procedures. Real-time imaging during an interventional procedure enables more accurate planning, guidance, intervention monitoring, and control, all of which can provide improved patient outcomes and reduced management costs [34]

Cost-Effectiveness: Minimal-invasive surgeries (MIS) have many advantages over traditional open surgeries. These advantages include shorter hospital stays, fewer complications, and the potential for improved healthcare capacity use. These benefits are not limited to patient recovery but expand to a more efficient healthcare system, especially during times of heightened demand like the COVID-19 pandemic. MIS can significantly reduce costs by shortening the length of hospital stays and optimizing staff and facility utilization. In addition, by reducing the time patients are in the hospital, MIS also reduces the risk of hospital-acquired infections such as COVID-19.165 [36]

Advancements in Imaging Modalities:

X-Ray Imaging and Fluoroscopy: Essential for real-time guidance, though challenged by radiation exposure risks and limited by projection views [35]

Computed Tomography (C.T.): Provides slice-by-slice anatomical views for precise localization and planning; widely used for diagnostic biopsies and percutaneous procedures; hampered by ionizing radiation and lack of physiological parameter sensitivity.

Ultrasound: Real-time capability and cost-effectiveness make it the modality of choice for biopsy guidance, including visualizing adjacent vascular structures before biopsy needle placement; it is also exceptional for fluid management despite being less committed than CT/MRI [35]**.**

Endoscopy: Revolutions in endoscopic videos allow high-resolution, complete natural color surface visualization, which, when integrated with MRI, provides outstanding anatomical context understanding.

Magnetic Resonance Imaging (MRI): The optimal tissue discrimination, lack of ionizing radiation, and the ability to monitor and guide interventions through the characterization of functional and physiological parameters, and with rapid acquisition protocols, the possibility of real-time imaging makes it a technology that enhances vascular and intravascular procedure guidance, improving safety and efficacy [35]**.**

Table: Advances in Imaging Modalities_ Advantages and challenges

Imaging Modality	Applications	Advantages	Challenges/Limitations
X-Ray Fluoroscopy	Vascular interventions	Real-time guidance	Ionizing radiation exposure, projection image limits **National**
Computed Tomography (C.T.)	Planning/guiding interventional procedures.	Geometric accuracy, detailed visualization	Ionizing radiation, less physiological sensitivity
Ultrasound	Guiding biopsies, fluid management	Real-time imaging, no ionizing radiation, cost-effective	Image quality and resolution
Endoscopy	Minimally invasive surgery	High-resolution, natural color imagery	Primarily surface visualization.
Magnetic Resonance Imaging (MRI)	Guiding, monitoring, and controlling interventions	Superior tissue contrast, functional imaging, no ionizing radiation	High cost, environmental constraints, MRI-compatible tools needed.
Thermal Surgery and MRI	Thermal ablation procedures	Precise and controlled interventions, real-time monitoring, and control	Requires advancements in MRI technology and procedural integration **National.**

This table synthesizes critical information about the advances in imaging modalities for minimally invasive surgery, focusing on their unique contributions to clinical practice. It also acknowledges the challenges that must be addressed to further enhance their utility and effectiveness.

Ethical and practical considerations for AI use

There are chances of getting higher stakes while doing minimally invasive surgeries (MIS) when A.I. and robotics enter the scene. The prime concern among the many discomforting situations is the threat to safety. This comprises not only the physical health of the human bearer but also the regulation of decisions directly affected by A.I., among other aspects of ethical standards related to the responsibility in which it is involved.

Safety aspects, such as building in reliance on artificial intelligence-based decisions or opening algorithmic processes for people included, are included as well [33]. The safety issues in robotic surgery are associated with preventing cybersecurity malfunctions and errors. Such a situation becomes even more challenging as the operating systems outside A.I. become more integrated and raveled. Preserving patient data with a focus on privacy and system integrity is as indispensable as other types of medical information technologies, ensuring their protection from breach and further development. In general, research on this subject area shows that bringing A.I. to MIS is a big step in technology, with the ability to improve the precision of surgery, optimize patient outcomes, and democratize the delivery of the standard of quality surgical care [33]**.** Sophisticated software applications, AI-driven advisory systems, and the development of autonomous surgical robots are progressing the state-of-the-art in MIS. However, the movement of this technology into practice necessitates careful consideration of appropriate ethical standards, safety protocols, and cybersecurity to facilitate and ensure the technology's full potential while preventing harm to patients.

Challenges, Training Education, Ethical Considerations, and Future Directions

The transformative impact of robotics, artificial intelligence (A.I.), and advanced imaging in minimally invasive surgical techniques is matched by the transformation in the training, education, and practice of surgeons driven by these technologies. There are essential differences between robotics-as-surgery, tele-surgery, and simulated surgery, and effective implementation of these technologies requires strategies to overcome the crucial limitations of each. For example, true interoperability will be necessary to eliminate the current absence of haptic feedback in robotic surgery and the complete integration of the visual, chemical, and tactile sensibilities as are required for anatomic, biological, and surgical imaging. On the other hand, the reliability and transparency of A.I. algorithms in a surgical, in vivo context will need to be continuously validated to protect surgeons from liability and patients from unsafe decision-making. This will require the development of comprehensive curricula that include simulation-based training and virtual reality experiences. It will require the creation of a comprehensive program for the maintenance of certification. It will require the development of rigorous criteria for privileging and credentialing. However, these professions will only meet their full potential if regulatory and ethical guidelines join them to ensure that all future patients can benefit from these critical technologies' safe, effective, and efficient use. Looking to the future, several new trends and innovations promise to revolutionize surgical practices further further. The fusion of augmented reality (A.R.) and mixed reality (M.R.) in surgery is envisioned to help enhance precision and spatial awareness. The trajectory towards fully autonomous surgical systems is intended to improve efficiency and expand access to surgical care. With keen AI-powered personalized surgical planning and analysis for patient-specific anatomic variants and 5G-ready, seamless remote surgery poised to democratize high-quality surgical care. Navigating technical constraints, training, education, and regulatory and ethical concerns while embracing these future trends will be critical to the continued evolution and integration of advanced technologies within minimally invasive surgery [37]**.**

IV. Conclusion

The combination of robotic surgery, artificial intelligence, advanced imaging and micro-instruments has significantly augmented the accuracy and ease of minimally invasive surgeries (MIS). The robotic systems offer unparalleled dexterity and manipulation; the artificial intelligence (AI) assists in planning and decision-making to ensure optimum outcomes; while the advanced imaging technologies provide real-time visualization of anatomical structures allowing the surgeon to navigate with great precision. The micro-instruments are able to reach intricate areas, which greatly reduces tissue trauma and hence recovery and reduces postoperative complications. The combined advancement of these technologies has transformed MIS, making the processes vastly safer, more efficient and far less invasive, and thus improving patient outcomes and the overall quality of surgical care.

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