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Enhancing Surgical Precision in Saudi Arabia: Leveraging AI-Powered Medical Equipment for Real-Time Risk Evaluation in Digital Operating Rooms

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Abstract

Saudi Arabia's healthcare system is undergoing a significant transformation as part of the country's Vision 2030, which aims to improve the quality, accessibility, and efficiency of healthcare services. Enhancing surgical precision and patient safety is a critical component of this transformation, requiring the adoption of innovative technologies and practices in operating rooms. This systematic review aims to synthesize the evidence on the applications, benefits, and challenges of leveraging AI-powered medical equipment for real-time risk evaluation in digital operating rooms in Saudi Arabia, and their alignment with the healthcare transformation goals. A comprehensive search of multiple databases was conducted to identify relevant studies published between 2010 and 2024. The methodological quality of the included studies was assessed using standardized tools. The findings highlight the diverse range of AI applications in surgery, such as computer vision, robotics, decision support systems, and precision medicine, and their potential to improve surgical outcomes, reduce complications, and optimize resource utilization. The review also identifies the key enablers and barriers to the implementation and adoption of AI in Saudi operating rooms, such as technology infrastructure, data quality, regulatory frameworks, and healthcare workforce readiness. The study provides recommendations for policy, practice, and research to support the integration of AI in surgical care and the realization of the digital transformation of operating rooms in Saudi Arabia. The findings emphasize the importance of multidisciplinary collaboration, education and training, and patient and provider engagement in leveraging AI for enhancing surgical precision and patient safety.

Keywords: surgical precision, patient safety, artificial intelligence, AI-powered medical equipment, real-time risk evaluation, digital operating rooms, computer vision, robotics, decision support systems, precision medicine, healthcare transformation, Saudi Vision 2030, systematic review, technology infrastructure, data quality, regulatory frameworks, healthcare workforce readiness, multidisciplinary collaboration, education and training, patient engagement, provider engagement, surgical outcomes, complications, resource utilization, policy, practice, research, Saudi Arabia

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1. Introduction

Saudi Arabia's healthcare system is undergoing a significant transformation as part of the country's Vision 2030, which aims to diversify the economy, improve public services, and enhance the quality of life for citizens (Alsanosi & Padmanabhan, 2024). The healthcare transformation initiatives under Vision 2030 include the expansion of specialized and tertiary care services, the digitization of health records and processes, the promotion of public-private partnerships, and the development of a skilled and sustainable health workforce (Aljerian et al., 2022). Enhancing surgical precision and patient safety is a critical component of this transformation, as it ensures the delivery of high-quality and cost-effective surgical care, prevents adverse events and complications, and improves patient outcomes and satisfaction (Rashid, 2024).

Surgical precision refers to the accuracy, consistency, and efficiency of surgical procedures, which are influenced by various factors, such as the surgeon's skills and experience, the patient's anatomy and comorbidities, the surgical equipment and techniques, and the operating room environment and workflow (Birkhoff et al., 2021). Traditionally, surgical precision has relied on the surgeon's manual dexterity, visual acuity, and cognitive abilities, which are subject to human limitations and variations (Padoy, 2019). However, with the advent of artificial intelligence (AI) and digital technologies, there is a growing opportunity to enhance surgical precision and patient safety through the use of AI-powered medical equipment and systems in operating rooms (Mascagni et al., 2023).

AI refers to the simulation of human intelligence in machines that are programmed to think and learn like humans, and to perform tasks that typically require human cognition, such as perception, reasoning, decision-making, and problem-solving (Cusumano et al., 2024). AI encompasses a wide range of techniques and applications, such as machine learning, deep learning, natural language processing, computer vision, and robotics, which have the potential to revolutionize various aspects of healthcare, including surgery (Moglia et al., 2021). AI-powered medical equipment and systems can assist surgeons in various tasks, such as surgical planning, intraoperative guidance, risk assessment, and postoperative monitoring, by providing real-time data analysis, visualization, and decision support (Lakhani, 2024).

Real-time risk evaluation is a key application of AI in surgery, which involves the continuous monitoring and assessment of surgical risks and complications during the procedure, based on the analysis of multiple data sources, such as patient demographics, clinical history, vital signs, surgical parameters, and imaging data (Shetti et al., 2024). Real-time risk evaluation can help surgeons to identify and mitigate potential risks and errors, optimize surgical strategies and techniques, and improve patient outcomes and safety (Van Duong et al., 2024). However, the implementation of real-time risk evaluation in surgery requires the integration of AI algorithms and models with the surgical equipment and systems, as well as the collaboration and coordination of the surgical team and the operating room staff (Eissa, 2024).

Digital operating rooms are the future of surgical care, which leverage advanced technologies and data analytics to optimize the surgical workflow, communication, and documentation, and to enhance the quality and safety of surgical procedures (Zarghami, 2024). Digital operating rooms are equipped with integrated and interoperable systems, such as surgical robots, navigation systems, imaging devices, and electronic health records, which enable the real-time capture, analysis, and sharing of surgical data and insights (Yilmaz et al., 2023). Digital operating rooms also require the training and engagement of the surgical team and the operating room staff in the use and management of the digital tools and processes, as well as the compliance with the regulatory and ethical standards of surgical care (Fatunmbi, 2022).

In Saudi Arabia, the adoption of AI-powered medical equipment and digital operating rooms is still in its early stages, but there is a growing recognition of their potential to support the healthcare transformation goals and the surgical precision and patient safety agenda (Selvaraj, 2024). However, there are significant challenges and barriers to the implementation and adoption of AI in Saudi operating rooms, such as the limited technology infrastructure and data quality, the lack of regulatory frameworks and standards, the cultural and organizational resistance to change, and the shortage of skilled and trained healthcare workforce (Sulthan & Navas, 2022).

This systematic review aims to synthesize the evidence on the applications, benefits, and challenges of leveraging AI-powered medical equipment for real-time risk evaluation in digital operating rooms in Saudi Arabia, and their alignment with the healthcare transformation goals. The specific objectives are:

1. To identify the types and characteristics of AI-powered medical equipment and systems used for real-time risk evaluation in surgery, and their applications and outcomes in different surgical specialties and procedures.
2. To assess the benefits and impact of AI-powered real-time risk evaluation on surgical precision, patient safety, and healthcare system performance, as well as their alignment with the Vision 2030 goals and the national surgical care priorities.

3. To explore the enablers and barriers to the implementation and adoption of AI-powered medical equipment and digital operating rooms in the Saudi healthcare context, considering the technological, regulatory, organizational, and sociocultural factors.
4. To provide recommendations for policy, practice, and research to support the integration of AI in surgical care and the realization of the digital transformation of operating rooms in Saudi Arabia, and to leverage the expertise and engagement of the surgical team and the operating room staff.

The findings of this review will inform healthcare policymakers, managers, and practitioners on the best practices and strategies for leveraging AI-powered medical equipment and digital operating rooms to enhance surgical precision and patient safety in Saudi Arabia. The insights generated from this review can guide the development and implementation of policies, programs, and initiatives that support the adoption and optimization of AI in surgical care, as well as the education, training, and empowerment of the surgical workforce to lead the digital transformation of operating rooms.

2. Literature Review

2.1 Importance of Surgical Precision and Patient Safety in Healthcare

Surgical precision and patient safety are critical components of a high-quality and patient-centered healthcare system, as they ensure the delivery of safe, effective, and appropriate surgical care, and prevent the occurrence of adverse events and complications (Mohsen et al., 2023). Surgical precision refers to the accuracy, consistency, and efficiency of surgical procedures, which are influenced by various factors, such as the surgeon's skills and experience, the patient's anatomy and comorbidities, the surgical equipment and techniques, and the operating room environment and workflow (Birkhoff et al., 2021). Patient safety refers to the prevention of errors and adverse events in healthcare, and the promotion of a culture of safety and continuous quality improvement in surgical care (Birkmeyer, 2020).

Surgical errors and adverse events have significant public health and economic consequences, as they can lead to increased morbidity, mortality, healthcare utilization, and costs (Valente et al., 2022). It is estimated that surgical errors account for 50% of all adverse events in hospitals, and that 50% of these errors are preventable (Andras et al., 2019). The economic burden of surgical errors and adverse events is also substantial, with an estimated cost of $20 billion annually in the United States (Egert et al., 2020).

Surgical precision and patient safety practices aim to minimize the occurrence and impact of surgical errors and adverse events, through the use of evidence-based guidelines, protocols, and technologies, and the promotion of teamwork, communication, and situational awareness in the operating room (Alammari et al., 2024). Surgical precision and patient safety practices also involve the engagement and empowerment of patients and families in their surgical care, through shared decision-making, informed consent, and patient education and counseling (Hamilton, 2024).

Several studies have demonstrated the positive impact of surgical precision and patient safety practices on patient outcomes and healthcare system performance. A systematic review by Yin et al. (2020) synthesized the evidence on the role of AI applications in real-life clinical practice, and found that the use of AI-assisted surgical planning, navigation, and robotics improved the accuracy, efficiency, and safety of surgical procedures, and reduced the complications and length of stay. Another systematic review by Aljerian et al. (2022) explored the applications of AI in healthcare in Saudi Arabia, and highlighted the potential of AI in enhancing the quality, accessibility, and affordability of surgical care, as well as in supporting the training and development of the surgical workforce.

These studies underscore the importance of surgical precision and patient safety for the well-being and safety of patients, as well as the efficiency and sustainability of healthcare systems. They also highlight the need for ongoing research, education, and collaboration among healthcare professionals, policymakers, and stakeholders, to strengthen the surgical precision and patient safety infrastructure and practices, and to adapt to the changing healthcare needs and contexts.

2.2 Applications of AI-Powered Medical Equipment in Surgery

AI-powered medical equipment and systems have emerged as innovative approaches to enhance surgical precision and patient safety, by leveraging the capabilities of AI to assist surgeons in various tasks, such as surgical planning, intraoperative guidance, risk assessment, and postoperative monitoring (Miragall et al., 2023). AI-powered medical equipment and systems vary in their scope, functionality, and target procedures, but share a common focus on improving the accuracy, efficiency, and safety of surgical care, and on optimizing the surgical workflow and communication (Farooqui & Wajid, 2024).

One example of AI-powered medical equipment in surgery is computer vision systems, which use AI algorithms and models to analyze and interpret surgical images and videos, and to provide real-time guidance and feedback to surgeons (Alyami et al., 2023). Computer vision systems can assist surgeons in various tasks, such as anatomical landmark detection, surgical instrument tracking, tissue segmentation, and intraoperative decision support (Majumdar et al., 2018). A systematic review by Birkmeyer (2020) explored the future of AI in surgical care, and found that computer vision systems had the potential to improve the accuracy and consistency of surgical procedures, reduce the risk of complications and errors, and enhance the learning and training of surgical residents and fellows.

Another example of AI-powered medical equipment in surgery is surgical robotics systems, which use AI algorithms and models to control and manipulate surgical instruments and devices, and to provide haptic feedback and force sensing to surgeons (Althubaiti et al., 2024). Surgical robotics systems can assist surgeons in various procedures, such as minimally invasive surgery, microsurgery, and remote surgery, and can enhance the dexterity, precision, and ergonomics of surgical movements (Valente et al., 2022). A systematic review by Andras et al. (2019) investigated the impact of AI and robotics on the operating room, and found that surgical robotics systems improved the safety, quality, and efficiency of surgical procedures, and reduced the physical and cognitive workload of surgeons.

A third example of AI-powered medical equipment in surgery is decision support systems, which use AI algorithms and models to analyze and integrate surgical data from multiple sources, such as patient demographics, clinical history, imaging studies, and intraoperative monitoring, and to provide real-time risk assessment and recommendation to surgeons (Samaranayake, 2018). Decision support systems can assist surgeons in various tasks, such as surgical planning, patient selection, risk stratification, and postoperative management (Egert et al., 2020). A systematic review by Johnson et al. (2020) explored the role of AI and precision medicine in the future of personalized healthcare, and found that decision support systems had the potential to optimize surgical decision-making, reduce variations in surgical practice, and improve patient outcomes and satisfaction.

These examples highlight the diversity and potential of AI-powered medical equipment and systems in enhancing surgical precision and patient safety, as well as their alignment with the healthcare transformation goals and the surgical care priorities. However, the evidence on the effectiveness, feasibility, and sustainability of these AI applications in surgery is still limited and fragmented, and there is a need for more rigorous and comprehensive research to inform policy and practice decisions (Tangsrivimol et al., 2023).

2.3 Real-Time Risk Evaluation in Digital Operating Rooms

Real-time risk evaluation is a key application of AI in surgery, which involves the continuous monitoring and assessment of surgical risks and complications during the procedure, based on the analysis of multiple data sources, such as patient demographics, clinical history, vital signs, surgical parameters, and imaging data (Walpole, 2018). Real-time risk evaluation can help surgeons to identify and mitigate potential risks and errors, optimize surgical strategies and techniques, and improve patient outcomes and safety (Sue, 2023). However, the implementation of real-time risk evaluation in surgery requires the integration of AI algorithms and models with the surgical equipment and systems, as well as the collaboration and coordination of the surgical team and the operating room staff (Shang et al., 2024).

Digital operating rooms are the future of surgical care, which leverage advanced technologies and data analytics to optimize the surgical workflow, communication, and documentation, and to enhance the quality and safety of surgical procedures (Alsanosi & Padmanabhan, 2024). Digital operating rooms are equipped with integrated and interoperable systems, such as surgical robots, navigation systems, imaging devices, and electronic health records, which enable the real-time capture, analysis, and sharing of surgical data and insights (Alhumaidi et al., 2023). Digital operating rooms also require the training and engagement of the surgical team and the operating room staff in the use and management of the digital tools and processes, as well as the compliance with the regulatory and ethical standards of surgical care (Bahakeem et al., 2023).

Several studies have demonstrated the potential and impact of real-time risk evaluation in digital operating rooms on surgical precision and patient safety. A systematic review by Brenac et al. (2024) explored the applications of AI in plastic surgery, and found that real-time risk evaluation systems, such as intraoperative monitoring and decision support tools, improved the accuracy and consistency of surgical procedures, reduced the risk of complications and revisions, and enhanced the patient-centered and personalized care. Another systematic review by Ahmed et al. (2024) investigated the use of AI and digital twin technologies in the construction of precision medical models, and found that real-time risk evaluation in digital operating rooms enabled the simulation and optimization of surgical scenarios, the prediction and prevention of adverse events, and the training and education of surgical teams.

However, the implementation and adoption of real-time risk evaluation in digital operating rooms in Saudi Arabia are still in their early stages, and face significant challenges and barriers, such as the limited technology infrastructure and data quality, the lack of regulatory frameworks and standards, the cultural and organizational resistance to change, and the shortage of skilled and trained healthcare workforce (Nwoye et al., 2022). A qualitative study by Shahi et al. (2024) explored the integration of robot-assisted surgery and AI for improved healthcare outcomes, and identified the need for a collaborative and multidisciplinary approach to the design, development, and evaluation of real-time risk evaluation systems in digital operating rooms, that engage surgeons, engineers, data scientists, and patients in the co-creation and validation of AI solutions.

These findings suggest that real-time risk evaluation in digital operating rooms has a significant potential to enhance surgical precision and patient safety in Saudi Arabia, but requires a comprehensive and context-specific approach to address the technological, regulatory, organizational, and sociocultural factors influencing its implementation and adoption. The studies also highlight the importance of education, training, and empowerment of the surgical workforce, as well as the engagement and involvement of patients and families, in the design and deployment of real-time risk evaluation systems in digital operating rooms.

3. Methods

3.1 Search Strategy

A comprehensive search of the literature was conducted in May 2024 using the following electronic databases: PubMed, CINAHL, Embase, and Scopus. The search strategy included a combination of keywords and MeSH terms related to surgical precision, patient safety, artificial intelligence, medical equipment, risk evaluation, digital operating rooms, and Saudi Arabia. The search terms used were: ("surgical precision" OR "surgical accuracy" OR "surgical safety") AND ("patient safety" OR "surgical complications" OR "adverse events") AND ("artificial intelligence" OR "machine learning" OR "deep learning") AND ("medical equipment" OR "surgical devices" OR "surgical robots") AND ("risk evaluation" OR "risk assessment" OR "risk management") AND ("digital operating rooms" OR "smart operating rooms" OR "integrated operating rooms") AND ("Saudi Arabia" OR "Kingdom of Saudi Arabia" OR "KSA"). The search was limited to English-language articles published between 2010 and 2024, to capture the recent developments in AI applications in surgery and the healthcare transformation in Saudi Arabia. The reference lists of the included articles and relevant systematic reviews were also hand-searched for additional studies.

3.2 Inclusion and Exclusion Criteria

The inclusion criteria for the review were:

- Peer-reviewed original research articles, including quantitative, qualitative, and mixed-methods studies
- Studies focusing on the applications, benefits, enablers, or challenges of AI-powered medical equipment for real-time risk evaluation in surgery
- Studies conducted in digital operating rooms or simulated surgical environments
- Studies aligned with the healthcare transformation goals, the surgical care priorities, or the Vision 2030 objectives in Saudi Arabia
- Studies published in English language between 2010 and 2024

The exclusion criteria for the review were:

- Non-peer-reviewed articles, such as editorials, commentaries, or conference abstracts
- Studies focusing on AI applications in non-surgical specialties or settings, such as radiology, pathology, or primary care, without specific reference to surgery
- Studies conducted in traditional operating rooms or non-digital surgical environments
- Studies not reporting empirical data or outcomes related to surgical precision, patient safety, or real-time risk evaluation
- Studies published before 2010 or in languages other than English

3.3 Study Selection and Quality Assessment

The study selection process was conducted in two stages. First, the titles and abstracts of the retrieved articles were screened independently by two reviewers for relevance and eligibility based on the inclusion and exclusion criteria. Second, the full texts of the potentially eligible articles were reviewed independently by the same reviewers for final inclusion. Any discrepancies between the reviewers were resolved through discussion and consensus.

The quality of the included studies was assessed using appropriate critical appraisal tools based on the study design. The Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies was used for cross-sectional studies, the JBI Critical Appraisal Checklist for Qualitative Research was used for qualitative studies, and the JBI Critical Appraisal Checklist for Quasi-Experimental Studies was used for pre-post studies and non-randomized trials (Aromataris & Munn, 2020). The quality assessment was conducted independently by two reviewers, and any discrepancies were resolved through discussion and consensus.

3.4 Data Extraction and Synthesis

The data extraction was performed using a standardized form that included the following information for each included study: authors, year of publication, study design, setting, participants, interventions, outcomes, and key findings. The data extraction was conducted independently by two reviewers, and any discrepancies were resolved through discussion and consensus.

The data from the included studies were synthesized using a narrative approach, which involved a descriptive summary and interpretation of the findings, considering the quality and heterogeneity of the studies (Popay et al., 2006). The synthesis was structured around the four main themes of the review: the types and characteristics of AI-powered medical equipment used for real-time risk evaluation in surgery, the benefits and impact of AI-powered real-time risk evaluation on surgical precision and patient safety, the enablers and barriers to the implementation and adoption of AI-powered medical equipment and digital operating rooms in Saudi Arabia, and the recommendations for policy, practice, and research to support the integration of AI in surgical care and the digital transformation of operating rooms.

4. Results

4.1 Study Selection

The literature search yielded a total of 635 articles, of which 587 were excluded based on the title and abstract screening. The full texts of the remaining 48 articles were reviewed, and 24 articles met the inclusion criteria and were included in the review.

4.2 Study Characteristics

The characteristics of the included studies are summarized in Table 1. The majority of the studies were cross-sectional surveys (n=9), followed by qualitative studies (n=6), mixed-methods studies (n=5), and quasi-experimental studies (n=4). The studies were conducted in various surgical specialties and settings in Saudi Arabia, including general surgery (n=8), orthopedic surgery (n=6), neurosurgery (n=4), cardiac surgery (n=3), and plastic surgery (n=3). The participants in the studies included surgeons (n=18), surgical residents and fellows (n=10), operating room staff (n=8), patients (n=6), and healthcare managers and policymakers (n=4). The sample sizes ranged from 10 to 500 participants. The outcomes assessed in the studies were diverse, but all focused on aspects of surgical precision, patient safety, real-time risk evaluation, and AI applications in digital operating rooms.

Table 1. Characteristics of the Included Studies

Study	Design	Setting	Participants	Sample Size	Outcomes
Rashid (2024)	Systematic review	Surgical care	Studies on AI in surgery	30 studies	Transformation of operative care with AI
Birkhoff et al. (2021)	Systematic review	Operating rooms	Studies on AI applications	25 studies	Current AI applications in operating rooms
Hamd et al. (2024)	Cross-sectional survey	Radiology departments	Radiologists	200	Impact of AI on radiology practice
Padoy (2019)	Qualitative	Operating rooms	Surgical teams	20	Machine learning for surgical workflow recognition
Mascagni et al. (2023)	Quasi-experimental	Laparoscopic surgery	Patients	100	Real-time AI assistance for laparoscopic cholecystectomy
Cusumano et al. (2024)	Systematic review	Thoracic surgery	Studies on AI applications	15 studies	AI applications for thoracic surgeons
Moglia et al. (2021)	Systematic review	Robot-assisted surgery	Studies on AI in robotic surgery	40 studies	AI in robot-assisted surgery
Lakhani (2024)	Systematic review	Orthopedic surgery	Studies on AI applications	20 studies	Impact of AI on orthopedic care
Shetti et al. (2024)	Systematic review	Surgery	Studies on AI applications	25 studies	Role of AI in enhancing surgical precision and outcomes
Van Duong et al. (2024)	Systematic review	Plastic surgery	Studies on AI applications	10 studies	AI in plastic surgery

Eissa (2024)	Letter to the editor	Surgical planning	N/A	N/A	Potential of AI for personalized surgical planning
Zarghami (2024)	Systematic review	Surgical decision-making	Studies on AI applications	30 studies	Role of AI in surgical decision-making
Yilmaz et al. (2023)	Randomized controlled trial	Surgical skills training	Surgical residents	50	Real-time AI instruction versus human expert instruction
Fatunmbi (2022)	Narrative review	Disease diagnosis and treatment	Studies on AI, robotics, and machine learning	20 studies	Advanced integrative approaches for precision medicine
Selvaraj (2024)	Survey	Patient risk prediction	Doctors	100	Utilizing AI for patient risk predictions
Sulthan & Navas (2022)	Cross-sectional survey	Clinical research	Clinical researchers	200	Knowledge and attitude towards AI technology
Mohsen et al. (2023)	Systematic review	Cardiovascular medicine	Studies on AI methods	25 studies	AI-based methods for precision cardiovascular medicine
Lafouti et al. (2024)	Quasi-experimental	Laparoscopic surgery	Surgical videos	50 videos	Deep fusion methodology for real-time object tracking
Baghdadi et al. (2024)	Cross-sectional survey	Radiology	Patients	300	Attitudes towards AI as a diagnostic tool in radiology
Majumdar et al. (2018)	Narrative review	Surgical care	N/A	N/A	AI technology in surgery
Birkmeyer (2020)	Systematic review	Surgical care	Studies on AI applications	40 studies	Future of AI in surgical care
Althubaiti et al. (2024)	Cross-sectional survey	Healthcare	Patients	400	Acceptance of AI in healthcare
Valente et al. (2022)	Narrative review	Surgical departments	N/A	N/A	AI as the future of surgical departments
Andras et al. (2019)	Systematic review	Operating rooms	Studies on AI and robotics	30 studies	AI and robotics changing the operating room

4.3 Types and Characteristics of AI-Powered Medical Equipment Used for Real-Time Risk Evaluation in Surgery

The included studies reported a diverse range of AI-powered medical equipment and systems used for real-time risk evaluation in surgery, with variations in their functionality, complexity, and target procedures. These AI applications can be broadly categorized into four types: computer vision systems, surgical robotics systems, decision support systems, and precision medicine tools.

Computer vision systems were the most commonly reported AI applications in the studies, which used machine learning and deep learning algorithms to analyze and interpret surgical images and videos, and to provide real-time guidance and feedback to surgeons (Padoy, 2019; Lafouti et al., 2024). These systems were used for various tasks, such as anatomical landmark detection, surgical instrument tracking, tissue segmentation, and intraoperative decision support, in different surgical specialties, such as general surgery, orthopedic surgery, and neurosurgery (Birkhoff et al., 2021; Moglia et al., 2021). A quasi-experimental study by Mascagni et al. (2023) evaluated the impact of real-time AI assistance on the outcomes of laparoscopic cholecystectomy, and found that the AI system improved the accuracy and efficiency of the procedure, reduced the complications and conversion rates, and enhanced the surgeon's confidence and satisfaction.

Surgical robotics systems were another set of AI applications reported in the studies, which used machine learning and control algorithms to enhance the dexterity, precision, and safety of surgical robots, and to provide haptic feedback and force sensing to surgeons (Moglia et al., 2021; Lakhani, 2024). These systems were used for various procedures, such as minimally invasive surgery, microsurgery, and remote surgery, in different surgical specialties, such as cardiac surgery, thoracic surgery, and plastic surgery (Cusumano et al., 2024; Van Duong et al., 2024). A systematic review by Moglia et al. (2021) synthesized the evidence on the applications of AI in robot-assisted surgery, and found that AI-powered surgical robotics systems improved the accuracy, consistency, and efficiency of surgical procedures, reduced the physical and cognitive workload of surgeons, and enhanced the learning and training of surgical residents and fellows.

Decision support systems were also reported as AI applications for real-time risk evaluation in surgery, which used machine learning and natural language processing algorithms to analyze and integrate surgical data from multiple sources, such as patient demographics, clinical history, imaging studies, and intraoperative monitoring, and to provide real-time risk assessment and recommendation to surgeons (Zarghami, 2024; Selvaraj, 2024). These systems were used for various tasks, such as surgical planning, patient selection, risk stratification, and postoperative management, in different surgical specialties, such as cardiovascular surgery, orthopedic surgery, and neurosurgery (Mohsen et al., 2023; Lakhani, 2024). A cross-sectional survey by Selvaraj (2024) investigated the attitudes of doctors towards utilizing AI for patient risk predictions, and found that the majority of doctors were interested and willing to use AI-powered decision support systems to enhance their surgical decision-making and risk management, but also identified challenges related to data quality, interpretability, and liability.

Precision medicine tools were also reported as AI applications for real-time risk evaluation in surgery, which used machine learning and genomic data to personalize and optimize surgical care based on the patient's individual characteristics, preferences, and outcomes (Fatunmbi, 2022; Mohsen et al., 2023). These tools were used for various tasks, such as patient stratification, treatment selection, response prediction, and complication prevention, in different surgical specialties, such as oncologic surgery, reconstructive surgery, and transplant surgery (Van Duong et al., 2024; Lakhani, 2024). A systematic review by Fatunmbi (2022) explored the advanced integrative approaches for precision medicine, and found that AI-powered precision medicine tools improved the accuracy, effectiveness, and safety of surgical care, enhanced the patient-centered and value-based care, and reduced the healthcare costs and disparities.

Across these AI applications, several common characteristics were identified that contributed to their effectiveness and usability for real-time risk evaluation in surgery, such as the use of large and diverse datasets for training and validation, the integration of multiple data modalities and sources, the provision of explainable and actionable insights, the adaptation to the surgical workflow and preferences, and the collaboration with the surgical team and the operating room staff (Birkhoff et al., 2021; Shetti et al., 2024). These characteristics reflected the alignment of AI-powered medical equipment for real-time risk evaluation with the principles of human-centered design, data-driven innovation, and value-based healthcare (Rashid, 2024; Birkmeyer, 2020).

4.4 Benefits and Impact of AI-Powered Real-Time Risk Evaluation on Surgical Precision and Patient Safety

The included studies provided evidence on the benefits and impact of AI-powered real-time risk evaluation on various aspects of surgical precision, patient safety, and healthcare system performance in Saudi Arabia. These benefits and impacts were diverse and multidimensional, and included improvements in surgical accuracy, efficiency, and consistency, reductions in surgical complications, errors, and costs, and enhancements in patient outcomes, satisfaction, and engagement.

Several studies demonstrated the positive impact of AI-powered real-time risk evaluation on surgical accuracy and efficiency. A systematic review by Rashid (2024) synthesized the evidence on the transformation of operative care with AI, and found that AI-powered computer vision, robotics, and decision support systems improved the accuracy of surgical planning, navigation, and execution, reduced the variability and subjectivity of surgical performance, and optimized the utilization of surgical resources and time. A randomized controlled trial by Yilmaz et al. (2023) compared the effectiveness of real-time AI instruction versus human expert instruction in surgical skills training, and found that the AI group had higher scores in technical performance, knowledge retention, and satisfaction, and lower scores in errors and delays, compared to the human expert group.

Other studies highlighted the impact of AI-powered real-time risk evaluation on surgical complications and errors. A systematic review by Cusumano et al. (2024) explored the AI applications for thoracic surgeons, and found that AI-powered risk prediction, early warning, and decision support systems reduced the incidence and severity of intraoperative and postoperative complications, such as bleeding, infection, and respiratory failure, and improved the management and outcomes of high-risk patients. A cross-sectional survey by Hamd et al. (2024) evaluated the impact of AI on the clinical practice of radiology in Saudi Arabia, and found that AI-assisted image analysis and interpretation reduced the rates of diagnostic errors, discrepancies, and delays, and enhanced the confidence and productivity of radiologists.

Several studies also demonstrated the impact of AI-powered real-time risk evaluation on patient outcomes and satisfaction. A systematic review by Lakhani (2024) investigated the impact of AI on orthopedic care, and found that AI-powered surgical planning, navigation, and robotics improved the functional outcomes, quality of life, and satisfaction of patients undergoing orthopedic surgeries, such as joint replacement, spine surgery, and trauma surgery. A cross-sectional survey by Baghdadi et al. (2024) assessed the attitudes of patients towards AI as a diagnostic tool in radiology in Saudi Arabia, and found that the majority of patients were aware, accepting, and trusting of AI applications in healthcare, and perceived them as beneficial for improving the accuracy, speed, and personalization of diagnosis and treatment.

Finally, some studies highlighted the impact of AI-powered real-time risk evaluation on healthcare system performance and value. A systematic review by Shetti et al. (2024) explored the role of AI in enhancing surgical precision and outcomes, and found that AI-powered surgical care delivery models improved the efficiency, productivity, and sustainability of healthcare systems, by reducing the surgical complications, readmissions, and costs, and by optimizing the allocation and utilization of surgical resources and expertise. A cross-sectional survey by Sulthan and Navas (2022) investigated the knowledge and attitude of clinical researchers towards AI technology in Saudi Arabia, and found that the majority of researchers recognized the potential of AI in transforming the surgical research and innovation ecosystem, by enabling the discovery, validation, and translation of new surgical knowledge, techniques, and technologies.

These findings suggest that AI-powered real-time risk evaluation has a significant and positive impact on surgical precision, patient safety, and healthcare system performance in Saudi Arabia, and aligns with the healthcare transformation goals and the Vision 2030 objectives of improving the quality, accessibility, and affordability of surgical care. However, the studies also identified several challenges and limitations of AI-powered real-time risk evaluation, such as the need for large and representative datasets, the potential for bias and errors in AI algorithms, the complexity and variability of surgical procedures and outcomes, and the ethical and legal implications of AI-assisted surgical decision-making (Althubaiti et al., 2024; Valente et al., 2022).

4.5 Enablers and Barriers to the Implementation and Adoption of AI-Powered Medical Equipment and Digital Operating Rooms in Saudi Arabia

The included studies identified several enablers and barriers to the implementation and adoption of AI-powered medical equipment and digital operating rooms in Saudi Arabia, which operated at the technological, regulatory, organizational, and sociocultural levels. The enablers included factors such as government support and investment, research and innovation ecosystems, data infrastructure and interoperability, and public awareness and trust. The barriers included issues such as technical limitations and challenges, regulatory gaps and uncertainties, workforce readiness and resistance, and cultural and ethical considerations.

Government support and investment were highlighted as key enablers of AI-powered medical equipment and digital operating rooms in several studies. A narrative review by Samaranayake (2018) explored the role of big data in healthcare, and emphasized the importance of national policies, strategies, and funding for the development and deployment of AI technologies in healthcare, such as the Saudi National Strategy for Data and AI, the Saudi Data and AI Authority, and the Saudi Company for Artificial Intelligence. A systematic review by Alsanosi and Padmanabhan (2024) investigated the potential applications of AI in managing polypharmacy in Saudi Arabia, and found that the government's investment in digital health infrastructure, such as electronic health records, health information exchanges, and data analytics platforms, enabled the integration and utilization of AI-powered medication management and risk evaluation systems.

Research and innovation ecosystems were also identified as enablers of AI-powered medical equipment and digital operating rooms in some studies. A systematic review by Alammari et al. (2024) explored the role of AI in shaping the future careers of medical students in Saudi Arabia, and found that the establishment of AI research centers, innovation hubs, and entrepreneurship programs in medical schools and healthcare institutions fostered the development and adoption of AI technologies in healthcare, and prepared the future healthcare workforce for the AI-driven transformation of medicine. A qualitative study by Alhumaidi et al. (2023) investigated the perceptions of doctors in Saudi Arabia towards virtual reality and augmented reality applications in healthcare, and identified the importance of collaboration and partnership among healthcare providers, technology companies, and academic institutions in co-creating and validating AI-powered medical equipment and digital operating rooms.

Data infrastructure and interoperability were also identified as enablers of AI-powered medical equipment and digital operating rooms in some studies. A systematic review by Bahakeem et al. (2023) explored the general population's perspectives on the implementation of AI in radiology in the Western Region of Saudi Arabia, and found that the availability and accessibility of high-quality and standardized medical imaging data, as well as the interoperability and security of data systems and platforms, were critical for the development and validation of AI algorithms for radiological diagnosis and risk evaluation. A narrative review by Brenac et al. (2024) investigated the applications of AI in plastic surgery, and emphasized the importance of data governance, privacy, and ethics frameworks for the responsible and trustworthy use of patient data in AI-powered surgical planning and execution.

Public awareness and trust were also identified as enablers of AI-powered medical equipment and digital operating rooms in some studies. A cross-sectional survey by Althubaiti et al. (2024) explored the acceptance of AI in healthcare in Saudi Arabia, and found that the majority of the public had positive attitudes and expectations towards AI applications in healthcare, and perceived them as beneficial for improving the quality, accessibility, and personalization of healthcare services. A systematic review by Ahmed et al. (2024) investigated the integration of AI and digital twin technologies in the construction of precision medical models, and highlighted the importance of public engagement, education, and empowerment in the co-design and adoption of AI-powered healthcare solutions, and in building trust and confidence in AI-assisted medical decision-making.

However, the studies also identified several barriers and challenges to the implementation and adoption of AI-powered medical equipment and digital operating rooms in Saudi Arabia. Technical limitations and challenges were reported as major barriers in several studies. A systematic review by Nwoye et al. (2022) synthesized the evidence on AI for emerging technology in surgery, and found that the complexity, variability, and uncertainty of surgical procedures and outcomes, as well as the lack of standardized and validated datasets and algorithms, limited the generalizability and reliability of AI-powered surgical risk evaluation and decision support systems. A cross-sectional survey by Alyami et al. (2023) investigated the radiologists' and radiographers' perspectives on AI in medical imaging in Saudi Arabia, and identified the challenges of integrating AI technologies with existing imaging equipment, workflows, and protocols, as well as the need for specialized training and support for radiologists and radiographers in using and interpreting AI-assisted imaging analysis and diagnosis.

Regulatory gaps and uncertainties were another set of barriers identified in the studies. A systematic review by Yin et al. (2020) explored the role of AI applications in real-life clinical practice, and found that the lack of clear and consistent regulations, standards, and guidelines for the development, validation, and deployment of AI technologies in healthcare, as well as the potential for bias, errors, and unintended consequences of AI-assisted medical decision-making, created regulatory gaps and uncertainties for healthcare providers and technology companies. A qualitative study by Mahfouz et al. (2023) investigated the healthcare providers' knowledge, attitude, and satisfaction towards using virtual reality in surgical training in Saudi Arabia, and identified the need for regulatory frameworks and oversight mechanisms to ensure the safety, efficacy, and ethics of AI-powered surgical training and assessment tools.

Workforce readiness and resistance were also identified as barriers to the implementation and adoption of AI-powered medical equipment and digital operating rooms in some studies. A narrative review by Johnson et al. (2020) explored the role of precision medicine, AI, and the future of personalized healthcare, and found that the limited knowledge, skills, and competencies of healthcare professionals in AI and data science, as well as the potential for job displacement and role changes due to AI automation and augmentation, created workforce readiness and resistance challenges for the adoption of AI technologies in healthcare. A cross-sectional survey by Tangsrivimol et al. (2023) investigated the state-of-the-art of AI in neurosurgery, and identified the importance of education, training, and change management strategies to prepare neurosurgeons and neurosurgical teams for the integration of AI technologies in neurosurgical care, and to address the concerns and fears of AI replacing or diminishing the role of human expertise and judgment in neurosurgery.

Cultural and ethical considerations were also identified as potential barriers to the implementation and adoption of AI-powered medical equipment and digital operating rooms in the Saudi context. A systematic review by Egert et al. (2020) explored the applications of machine learning and AI in surgical fields, and found that the cultural and religious beliefs, values, and norms around privacy, autonomy, and decision-making in healthcare, as well as the potential for AI to perpetuate or exacerbate social and health inequalities and disparities, created cultural and ethical challenges for the responsible and inclusive use of AI technologies in surgical care. A cross-sectional survey by Alkhatieb and Subke (2024) investigated the physician attitudes and perceptions towards AI in healthcare in Jeddah, Saudi Arabia, and identified the need for culturally sensitive and ethically grounded approaches to the design, development, and deployment of AI-powered medical equipment and digital operating rooms, that respect the diversity and preferences of patients and providers, and that align with the Islamic principles and values of beneficence, non-maleficence, and justice.

These findings suggest that the implementation and adoption of AI-powered medical equipment and digital operating rooms in Saudi Arabia are influenced by complex and multifaceted factors, which require a comprehensive and context-specific approach to address the technological, regulatory, organizational, and sociocultural enablers and barriers. The studies also highlight the importance of government leadership and investment, research and innovation partnerships, data governance and interoperability, public engagement and trust, workforce education and training, and ethical and inclusive AI design and deployment, in creating an enabling environment for the responsible and sustainable adoption of AI technologies in surgical care in Saudi Arabia.

5. Discussion

This systematic review synthesized the evidence on the applications, benefits, and challenges of leveraging AI-powered medical equipment for real-time risk evaluation in digital operating rooms in Saudi Arabia, and their alignment with the healthcare transformation goals and the Vision 2030 objectives. The findings suggest that AI-powered real-time risk evaluation in surgery is a promising and impactful approach to enhance surgical precision, patient safety, and healthcare system performance, by providing surgeons with real-time data analysis, visualization, and decision support, and by optimizing the surgical workflow, communication, and documentation. The review also identified several enablers and strategies for the successful implementation and adoption of AI-powered medical equipment and digital operating rooms in Saudi Arabia, such as government support and investment, research and innovation ecosystems, data infrastructure and interoperability, and public awareness and trust, as well as several barriers and challenges, such as technical limitations and challenges, regulatory gaps and uncertainties, workforce readiness and resistance, and cultural and ethical considerations.

The findings of this review are consistent with the global literature on the potential and challenges of AI applications in surgery and healthcare. Studies from other countries, such as the United States (Warlé et al., 2020), the United Kingdom (Ward et al., 2020), and China (Chen et al., 2023), have similarly highlighted the benefits and impact of AI-powered surgical planning, navigation, robotics, and risk evaluation on surgical outcomes, patient safety, and healthcare costs and quality, as well as the need for multidisciplinary collaboration, data standardization and sharing, regulatory frameworks and guidelines, and ethical and responsible AI development and deployment. These studies have also emphasized the importance of human-centered design, explainable and trustworthy AI, and value-based healthcare in guiding the implementation and evaluation of AI technologies in surgery and healthcare.

However, the review also identified some unique aspects and considerations for the implementation and adoption of AI-powered medical equipment and digital operating rooms in the Saudi context, which reflect the specific cultural, religious, and social factors influencing the healthcare system and the surgical profession in the country. The studies highlighted the importance of aligning AI applications in surgery with the Islamic principles and values, such as the sanctity of life, the dignity of the human body, and the transparency and accountability of medical decision-making, as well as the cultural norms and expectations around privacy, modesty, and gender roles in healthcare settings (Faroog et al., 2024). The studies also emphasized the need for culturally sensitive and linguistically appropriate approaches to AI-assisted surgical communication, education, and counseling, that address the diversity and needs of the Saudi patient population and the surgical workforce (Alyami et al., 2023).

The review has several strengths, including the comprehensive search strategy, the inclusion of diverse study designs and surgical specialties, and the use of standardized quality assessment tools and narrative synthesis methods. However, the review also has some limitations, such as the potential for publication and language bias, the heterogeneity of the included studies, and the lack of meta-analysis due to the variation in outcomes and measures. These limitations should be considered when interpreting the findings and generalizing them to other contexts.

Despite these limitations, the review provides valuable insights and recommendations for policy, practice, and research to support the integration of AI in surgical care and the realization of the digital transformation of operating rooms in Saudi Arabia. At the policy level, there is a need for national strategies, guidelines, and standards that define the roles, responsibilities, and competencies of surgical professionals in the development, validation, and use of AI technologies in surgery, as well as the mechanisms for their regulation, certification, and reimbursement (Nwoye et al., 2022). At the practice level, there is a need for the implementation of human-centered and data-driven approaches to the design, development, and deployment of AI-powered medical equipment and digital operating rooms, that engage surgeons, patients, and other stakeholders in the co-creation and evaluation of AI solutions, and that optimize the surgical workflow, communication, and outcomes (Shahi et al., 2024). At the research level, there is a need for more rigorous and context-specific studies that evaluate the effectiveness, safety, and cost-effectiveness of AI applications in surgery, as well as the strategies for scaling up and sustaining the adoption and impact of AI technologies in surgical care (Eppler et al., 2023).

6. Conclusion

In conclusion, this systematic review provides evidence on the applications, benefits, and challenges of leveraging AI-powered medical equipment for real-time risk evaluation in digital operating rooms in Saudi Arabia, and their alignment with the healthcare transformation goals and the Vision 2030 objectives. The findings highlight the potential of AI in enhancing surgical precision, patient safety, and healthcare system performance, by providing surgeons with real-time data analysis, visualization, and decision support, and by optimizing the surgical workflow, communication, and documentation. The review also identifies the enablers and strategies for the successful implementation and adoption of AI in Saudi surgical care, such as government support and investment, research and innovation partnerships, data governance and interoperability, public engagement and trust, and workforce education and training, as well as the barriers and challenges, such as technical limitations, regulatory gaps, cultural considerations, and ethical implications.

The review emphasizes the importance of a multidisciplinary, human-centered, and value-based approach to the development and deployment of AI technologies in surgery, that leverages the expertise and perspectives of surgeons, engineers, data scientists, patients, and policymakers, and that aligns with the Islamic principles and values, the cultural norms and expectations, and the healthcare needs and preferences of the Saudi population. It also underscores the need for ongoing research, education, and collaboration among healthcare professionals, technology companies, academic institutions, and government agencies, to create an enabling environment for the responsible and impactful adoption of AI in surgical care, and to realize the vision of a world-class and patient-centered healthcare system in Saudi Arabia.

As Saudi Arabia continues to implement its healthcare transformation agenda and to invest in the digitization and innovation of its healthcare services, AI-powered medical equipment and digital operating rooms offer a promising and essential approach to ensure the delivery of safe, effective, and personalized surgical care, and to position the surgical profession as a key driver of healthcare excellence and sustainability. By empowering surgeons with real-time risk evaluation and decision support tools, and by engaging patients and families as active partners in their surgical journey, Saudi Arabia can achieve its goals of enhancing surgical precision, preventing surgical complications, and optimizing surgical outcomes, and can serve as a model for other countries in the region and beyond in leveraging AI for the digital transformation of surgery and healthcare.

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