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Artificial Intelligence Surgery

Review

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Transformative role of artificial intelligence in plastic and reconstructive surgery: innovations, applications and future directions

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Abstract
This review explores the current applications, benefits, and challenges of artificial intelligence (AI) in plastic, reconstructive, and aesthetic surgery. In recent years, AI has found its way into everyday life, including the healthcare sector. To deepen the understanding of the use and handling of AI in plastic and reconstructive surgery, this review provides valuable insights into modern practices, illustrated with real examples and potential future applications. While the advantages of AI are obvious, the disadvantages cannot be ignored. This review aims to highlight possible risks, dangers, and sources of error inherent in AI itself and its applications. Therefore, this paper seeks to address possible concerns and questions about AI in plastic surgery while offering a realistically neutral insight. Additionally, fundamental ethical and legal principles will be discussed, as well as possible "rules of the game" for the application and integration of AI in surgery. Innovations in this field are often hailed as miracles, making it crucial to evaluate them critically and objectively. Although progress in AI cannot and should not be halted, it is important to strengthen the trained approach and always look at the whole picture.

Keywords: Intelligent systems, smart technology, ethical concerns, optimization, prediction

INTRODUCTION

Artificial intelligence (AI) is transforming the landscape of modern medicine, offering innovative tools that enhance diagnostic accuracy, therapeutic outcomes, and clinical efficiency[1]. From machine learning (ML) algorithms that analyze large datasets to neural networks capable of image recognition, AI has begun to revolutionize various specialties, including radiology, oncology, and pathology[2,3]. In recent years, plastic and reconstructive surgery has emerged as a field where AI applications demonstrate significant promise[4].

In plastic surgery, where precision and individualized patient care are paramount, AI technologies facilitate more accurate preoperative planning, optimizing surgical techniques, and improving postoperative outcomes. For instance, AI-driven 3D imaging systems allow for more detailed preoperative simulations, while ML algorithms aid in predicting patient-specific surgical outcomes based on vast clinical datasets. Moreover, AI is enhancing patient safety through real-time monitoring and predictive analytics that foresee complications before they arise[5].

Reconstructive surgery, often dealing with complex defects and requiring meticulous planning, can also benefit from AI. From automating the design of tissue flaps to integrating robotic systems for microsurgical precision, AI contributes to improved reconstructive outcomes, shorter operative times, and reduced recovery periods. The integration of AI in these specialized procedures is driving a paradigm shift toward more personalized, data-driven surgical care[6].

This paper explores the recent advancements and applications of AI in plastic and reconstructive surgery, emphasizing the novel techniques, obstacles, and future potential. By examining how AI is reshaping these fields, we aim to highlight the role of technology in driving the next era of surgical innovation. This paper gives an overview of AI in plastic surgery, ML, and virtual reality (VR) and its pros and cons in applications.

AI IN PLASTIC SURGERY

To best illustrate its use in plastic surgery, we divided it into three categories: preoperative, intraoperative, and postoperative. In the preoperative setting, population screening, early and accurate diagnosis and statistical risk assessment can be used to create a precise surgical plan and individualized overall assessment of the patient[7]. To incorporate AI into plastic surgery, it is essential to first grasp how these tools can be utilized in the medical field[8]. Predicting surgical results, particularly in complex reconstructive procedures, is challenging and can lead to discrepancies between expected and actual outcomes for the patient and the plastic surgeon[9]. AI can be used to analyze medical images, like magnetic resonance imaging (MRI) or computed tomography (CT) scans, to ensure significantly higher and faster accuracy of diagnostic confirmation. This AI-integrated technique is more efficient than conventional techniques and shows detailed and precise visual representations of the anatomy. The benefit to the plastic surgeon is a thorough understanding of the individual's facial or body structure to assist in the preoperative planning. AI-driven 3D simulation tools enable surgeons and patients to preview possible surgery results, helping to align expectations and surgical strategies. This supports communication with the patient for the expected outcomes in the case of flap surgery, aesthetic face surgery, or breast surgery[8].

In plastic surgery, the aesthetic outcome is very important, and by analyzing the patient's anatomy, the healthy breast in breast cancer, cultural differences, and ideal values with the help of AI, an ideal image can be generated as a template. Having a template or plan for the planned procedure improves patient safety. Traditional manual methods are often limited by human dexterity, fatigue, and the variability of complex cases. This is particularly true for tasks like tissue flap design and vascular anastomoses, which are intricate and error-prone[9].

The ability to import intraoperative imaging in the form of 3D images directly to the surgical site increases anatomical accuracy, provided that the imaging is up-to-date[10]. With regard to the intraoperative use of AI, three categories can again be defined: intraoperative guidance, operative use of robotic devices, education and training[7]. Image-guided surgery (IGS) systems improve orientation in the surgical field and, thus, patient outcomes. IGS can help the surgeon to identify anatomical structures quickly and reliably, thus reducing the duration of the operation and the workload[11]. Before IGS can be used, a precise plan must be drawn up, starting with the creation of a 3D model based on available imaging (CT, MRI). Detailed 3D planning of the prevailing conditions supports the surgical planning. VR-assisted planning uses VR to enable precise preparation for surgery using a patient-specific model. VR-based surgical navigation often combines augmented reality (AR) technology to assist during surgery by displaying additional information, such as anatomical details of the patient of the planned procedure[12]. The ability to import intraoperative imaging in the form of 3D images directly to the surgical site increases anatomical accuracy, provided that the imaging is upto-date[10]. Using VR systems such as ImmersiveView VR, surgeons can analyze 3D representations of the patient's anatomy before surgery. An algorithm detects subcutaneous fat and muscle and displays the anatomical structures[12]. All the necessary landmarks, structures, surgical steps, and positional control points are incorporated into this model or plan. These virtual landmarks are imperceptible to the naked eye and do not require physical attachment to the patient. Instead, they are digitally integrated into the 3D model[13].

The FDA-cleared AI tool "Cydar EV Maps (Cydar Medical, UK)" can use preoperative and intraoperative fluoroscopic imaging to create an anatomical map and update it in real time during surgery. This anatomical map helps to identify and address complex conditions in a more patient-specific way. Having an up-to-date picture of the situation at all times can be a huge advantage in complex and lengthy operations, as conditions can change, and preoperative images are no longer sufficient for assessment. To make this map more usable for the surgeon, it is sent to head-mounted displays or glasses. The current market-leading system is HoloLens (Microsoft Corporation, Redmond, WA, USA)[14]. Furthermore, in complex resections of facial tumors and reconstructions of the head and neck, wearing video goggles allows the surgeon to superimpose three-dimensional X-rays over the patient so that the pathology can be clearly seen and identified. This gives the surgeon more options and helps them make a better decision. Inevitably, the result is a reduction in human error[15].

Mixed reality with HoloLens

VR submerges the user completely in a virtual world, blending out the real world. AR combines the virtual and real worlds by inserting virtual content into the real image. This factor gives AR a major advantage over VR and allows it to be used in medicine. Mixed reality (MR) is a specific form of AR. MR is an environment where users can interact with both real and virtual objects in real time[14,16]. One of the leading providers of such MR devices is Microsoft, with its HoloLens[17]. HoloLens is a head-mounted display similar to typical smart glasses. It allows the user to extend their real world and interact with the virtual world using holograms[18]. HoloLens enhances surgical outcomes by optimizing the surgeon's visual-motor coordination, addressing the misalignment that currently exists between the surgeon's line of sight and hand placement caused by monitor positioning. This misalignment can be eliminated by using HoloLens glasses[19]. Another success was achieved in the differentiation of tissue layers. Using HoloLens, the individual tissue layers could be clearly labeled and identified by the surgeon[18]. Conventionally experienced surgeons differentiate the tissue macroscopically to confirm or exclude cancer cells; the incisions are sent intraoperatively to the pathologist to ensure that the resection is inside the healthy tissue border.

VR and AR are of great benefit in the field of breast surgery, especially in breast reconstruction with deep inferior epigastric perforator (DIEP) flaps. These technologies allow preoperative planning by visualizing the complex anatomical structures of the perforators. One example is the visualization of blood vessels based on CT angiograms, which helps surgeons determine the optimal position for the perforators during surgery[20]. Intraoperative AR-based visualization of perforator vessels has been shown to be more reliable than traditional methods such as Doppler ultrasound[18]. Nonetheless, up to now, finding the perforator by Doppler US is a proven conventional method.

In South Korea, liposuction has been supported by AI for several years. The 365mc Motion Capture and Artificial Intelligence assisted Liposuction (M.A.I.L.) system employs advanced analytics to examine billions of movements, enabling the use of AI to identify the optimal movements for a successful procedure. Conversely, the M.A.I.L. system transmits visual and haptic (touch-based) notifications to the surgeon's hand in the event of a potentially hazardous movement, thereby enabling real-time micro-adjustments. The movements of the cannula are recorded on nine different axes to further improve ML for future interventions. With each operation performed, the system expands its database, increasing its precision and accuracy[21]. A recently developed virtual robotic system has performed significantly better than experienced surgeons in basic surgical tests on pig tissue. More broadly, this proves that AI can be trained to perform highly complex technical skills[22]. Despite these technological advances, surgical robots are not yet widely used in plastic surgery, although they could offer advantages such as eliminating tremors and scaling movements. However, reports of the use of robots in lymphatic reconstruction and free flap dissection indicate increasing acceptance[23].

One of the main applications of VR and AR technologies in upper extremity (UE) plastic and reconstructive surgery is postoperative rehabilitation, particularly for patients with phantom pain following amputation. VR is used as an alternative to mirror therapy by simulating the amputated limb to help the patient process the visual and proprioceptive sensations of the lost limb[24]. Postoperative care is equally complex, requiring close monitoring to prevent complications such as infections, tissue necrosis, or suboptimal healing[25]. Early detection of complications is crucial but often difficult to achieve with traditional methods. AI technologies have the potential to revolutionize postoperative care by offering predictive analytics based on real-time data. For example, AI-powered systems can monitor wound healing, predict the likelihood of complications, and provide timely alerts for early intervention. This not only improves patient safety but also reduces the need for revisions or secondary surgeries[26]. This can help in postoperative surveillance of microvascular flap surgery. The postoperative compliance rates for each patient can be assessed individually and an effective discharge plan can be developed in combination with discharge management. This can improve the length of stay and postoperative outcome and reduce the bureaucratic workload[27]. Discharge planning is a critical issue at a time when hospitals are chronically overcrowded and understaffed. Staff shortages, a large wave of retirements, and an ever-growing and aging population demand efficient and universal solutions. The solution can only be found through precise and accurate planning, and this is what AI offers[28].

LEARNING CURVE OF SURGEONS

Surgery is a profession that requires endless practice and training. AI offers a whole new world of training methods, from virtual tutoring to VR simulators and training robots. VR can also be used in medical education, where it is widely used as a training tool. Many commercial products are already on the market and are being used successfully in medical education[12]. Another application of VR in UE surgery is microsurgery training. VR has proven to be particularly useful for super-microsurgical procedures, such as the treatment of lymphoedema, which involves extremely small vessels and lymphatic channels.

Traditionally, training is carried out on live animals, but this is costly and not always feasible. VR-based microsurgery simulators, on the other hand, allow for cost-effective and realistic training[29]. Through ML, the skills and knowledge of surgeons can be compared and evaluated against countless others. A statistically-based assessment can then be used to make training recommendations or suggestions for improvement[30]. Medical professionals engage in continuous learning throughout their careers, but surgeons do not usually have the time to spend hours reading and evaluating publications and new literature. AI can quickly analyze large amounts of new literature and provide the most important and significant results in a summarized form[31]. The ability to compare skills with surgeons around the world and learn from other techniques and findings offers a whole new opportunity for global shared progress.

AI also enables the objective analysis of each surgeon's results, offering individualized training programs and suggestions for improvement. To be prepared for this emerging technology, a certain basic knowledge of mathematics, computer science, ethical considerations and risks should already be included in the university education of every medical professional[32]. The basic prerequisite for this is the promotion and approval of this technology in the training curriculum of every surgeon.

AI, ML AND DEEP LEARNING

ML enables computers to recognize patterns and learn from them. These are not explicitly programmed for a specific use, but the program itself structures and categorizes the input using algorithms. The distinction between supervised and unsupervised learning depends entirely on the intended goals. Supervised learning should be used to work toward a specific goal or direction, as to specify certain guidelines externally. Decision trees can be used to clearly define the criteria for analysis. Unsupervised learning is mainly used to analyze large amounts of data for patterns[33]. Another category of ML applications is where a program is given a task to perform. The program simulates and tries all possible scenarios until the task is completed, learning from its own successes and failures[34]. ML algorithms can be used to predict the results of aesthetic procedures, such as rhinoplasty or breast augmentation[35]. Another advantage of ML is that multiple ML programs can be combined and work together to make predictions and decisions that are far superior to normal statistical models in terms of accuracy and precision[36].

ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANNs) are systems based on the biological nervous system, which can be seen as a subset of ML and the basis of all AI. In ANNs, the input is evaluated by the smallest units and distributed to other units with different weights. The more input and information, the more accurate and reliable the result[26]. In terms of prediction rates, ANNs, sometimes in combination with MLs, have been able to outperform traditional risk assessment tools with impressive superiority[37]. ANNs are utilized in planning body contouring procedures, such as liposuction, by analyzing patient-specific data and predicting how fat can be removed or redistributed for optimal aesthetic results. The network helps ensure that the contours created are as smooth and symmetrical as possible[35].

DEEP LEARNING

Deep learning (DL) has established itself as a leading method in ML, particularly for image pattern recognition. It adds many different layers between the input and output layers, creating a complex network of connections. It also incorporates hidden layers that significantly influence the result. It allows the combination of supervised and unsupervised algorithms to solve large, complex problems and data sets[38]. It uses deep convolutional neural networks (DCNNs) to automatically learn data representations through multi-layer neural networks. DCNNs extract relevant features from the training data by adjusting their weights using backpropagation. No manually designed features are required. With sufficiently large and representative training sets, the automatically learned features often outperform the manually designed features due to their high selectivity and invariance. This autonomous learning process analyzes an enormous number of cases, outperforming human experts. If the training data are sufficiently diverse, DL can cover a wide range of case variations[39]. The application of DL can be used in breast reconstruction surgery, focusing on how DL models can help predict the best flap type and forecast aesthetic outcomes. The structure of AI [Figure 1] shows the steps from a simple DL network to a complete AI. AI uses and combines the processes of DL, ANN, and ML networks. This enables comprehensive data analysis and has the great potential to deliver the most accurate and appropriate solutions.

BIG DATA AND DATA PROTECTION

Big data is the foundation of AI, providing the raw material with which AI works. AI draws its knowledge from huge databases[41]. It is not just the amount of data or its size that defines big data, but rather the enormous complexity and diversity of the information. The information in these databases can be structured, semi-structured, or unstructured. In the healthcare sector, modernization has resulted in an almost infinite amount of patient data that do not all conform to the same categories or standards due to local differences. These databases are, therefore, ripe for big data[42].

One challenge presented by big data is ensuring the privacy and proper handling and protection of patient-related data. The best possible protection of patient data can only be achieved through cooperation between patients, medical staff, administrators, the legal system, and the government. General resources, rules, and conditions for data protection and data handling must be established and enforced[43]. Probably the most important requirement for big data is the complete anonymization of patient data. In this context, the term "anonymized" is used to describe data that cannot be identified as belonging to a particular person, either on its own or in combination with other data. This is achieved by taking into account all potential means that could reasonably be used to identify an individual. The process of anonymization forms the basis for the protection of personal data[44,45].

AI IN OTHER MEDICAL FIELDS

One of the primary applications of AI is in radiology. In a 2016 study, an artificial learning model was used to analyze mammograms, addressing common issues such as overdiagnosis, lack of time, and inaccuracy in current diagnostic methods[46]. In another study from Heidelberg, Germany, an AI network trained with 12,378 open-source dermatoscopic images for melanoma image classification outperformed 136 of 157 dermatologists regardless of their experience levels[47]. These results underscore the substantial learning capacity of AI and its ability to leverage massive databases effectively.

ETHICAL AND LEGAL ASPECTS

One of the biggest challenges at present is the uncertainty of the underlying data on which these systems are trained. The sources from which the data are drawn cannot be verified for timeliness, reliability, accuracy, and validity due to their sheer volume. In addition, these sources are not exclusively related to plastic surgery or the required specialty. Due to the lack of control over the quality and relevance of this training data, there is a risk of producing information that is not based on scientific evidence[48]. Generally, AI relies on existing data to make suggestions. As a result, it is essential to ensure the quality of the data and to select appropriate data sets for specific patient groups. In addition, the data collected must be permitted for use and anonymized to fully protect individual privacy before being included in the dataset. A data use agreement is required[5]. Patient data have to be protected against misuse, with clear limitations established on the scope of AI applications.

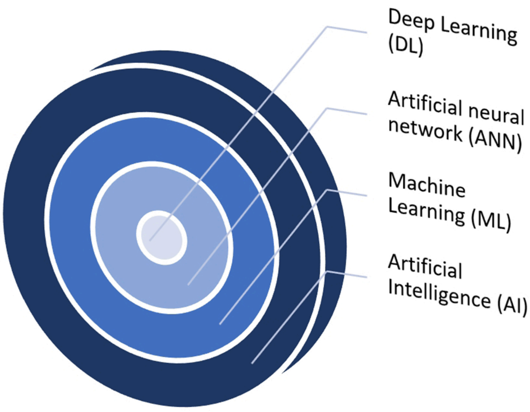

Figure 1. The structure of AI (adopted and modified from[40]). AI: Artificial intelligence.

To ensure that AI is accessible and properly used in healthcare, clinicians need to define future healthcare goals and work closely with computer scientists to develop clinically relevant and interpretable AI algorithms. Data should be collected robustly, digitized, and made usable for AI. Cost-effectiveness, security, and privacy frameworks are critical. Companies must use secure and confidential data, and high ethical standards must be maintained to ensure long-term benefits for healthcare systems. Algorithms must be validated and evidence of their safety and effectiveness must be widely available. AI results depend on accurate and unbiased data. Biased data lead to unreliable predictions, especially for underrepresented groups such as racial minorities and women. Relying solely on AI can compromise patient autonomy. The human element in healthcare remains essential. Autonomous robotic surgery requires further development, so AI is likely to assist the doctor, but not replace them[49]. AI has the potential to relieve doctors of time-consuming paperwork and other non-medical tasks, such as bureaucratic duties. However, it is important to recognize the limitations of AI. Firstly, it is not currently possible for AI to completely replace doctors in diagnosis and decision making. In many cases, AI is currently only used under certain restrictions, and the results of the algorithms are often merely an association. It is long overdue that general guidelines for the use of AI in medicine are developed[50].

The introduction of AI in plastic surgery raises ethical issues, particularly in relation to the objective assessment of attractiveness. Discrimination based on ethnicity and gender is possible. AI in plastic surgery could encourage racial differences and standardize images of people. AI-powered photo-editing applications create unattainable standards of beauty, which may lead to more cosmetic procedures and mental health problems. Cosmetic surgeons should consider the mental health of their patients when making decisions about surgical procedures[15].

In principle, the law distinguishes between three categories according to which AI is to be assessed: (1) responsibility; (2) liability; and (3) culpability. In the case of surgical robots, the responsibility lies with the developers or the healthcare institution using the technology. If AI causes harm during surgery, the surgeon or the hospital or even the developer might be held accountable for damages. Culpability is the most difficult to assess, because it is not yet clear how to attribute blame to an AI system. Unlike humans, these technologies do not have intent, making it hard to apply traditional legal concepts of culpability. In the future, surgical robots will perform routine operations under the supervision of a human surgeon. This poses the same problem as self-driving cars in terms of responsibility and the surgeon's role. The surgeon must be able to intervene quickly at any time and act for the benefit of the patient[51]. This highlights the complexities in determining legal and ethical responsibility when AI takes on roles traditionally managed by humans, especially when patient safety is involved.

FUTURE PROSPECTS

The future of medicine is increasingly focused on precision medicine, and precision can only be achieved with large amounts of data and comparator material. The vast datasets generated by AI enable this precision to be achieved quickly and efficiently[52]. Today's systems are still very simple and are not yet capable of performing complex surgical procedures autonomously. However, as the technology develops, significant advances in autonomy and AI capabilities will become apparent. The recovery time for patients will be reduced as the efficiency and effectiveness of the surgical procedure will be increased, primarily by reducing the operating time. In addition, this progress opens up the possibility of providing better care for patients in underserved medical areas where surgeons and resources are scarce. The use of robots in the military sector is also conceivable, as surgical procedures often take place far from medical infrastructure. Rapidly deployable robots can save both time and human resources in these situations[53].

At a time when medical care is expensive and not widely available, but smartphones are ubiquitous, AI is increasingly enabling telemedicine. For example, photos and apps can be used to quickly and easily assess injuries and medical conditions. This saves time and money and makes patient care easier. Patient compliance decreases dramatically with the distance between the healthcare facility and the patient's home, so telemedicine could support compliance[15].

However, there is a critical need for training and education in the application of AI in healthcare, both for general use and for implementation in specialized contexts. Investment in human resources and financial support is essential for acquiring equipment and training surgeons, because the effectiveness of any new technique depends on the surgeon's ability to master it.

CONCLUSION

AI has shown significant promise in revolutionizing the field of plastic and reconstructive surgery. This paper offers a brief glimpse of the future. At the forefront is the need to improve the well-being of patients and the working conditions of healthcare professionals. This can only be achieved by increasing efficiency[54].

AI can support the efficient use of time through more accurate planning, greater precision, and statistically validated results. However, it is not just time management that will be optimized, but also the precision of the surgical work. Robot-assisted surgery supports new possibilities. Diseases associated with poor outcomes may now be successfully treated thanks to the latest AI-driven technology. AI enhances diagnostic analysis, offering precise 3D models and simulations that improve surgical outcomes and patient satisfaction[10,48].

However, integrating AI into clinical practice presents several challenges. Ensuring data privacy, overcoming current AI algorithm limitations, and addressing ethical concerns are vital. Establishing standardized protocols and conducting robust clinical trials to validate AI applications are crucial for wider acceptance and implementation[51]. These applications do not replace patient care provided by doctors; instead, they serve as adjuncts to optimize safety. It is the questions of ethics, data security, regulatory and legal judgment, or rather the answers to them, that will determine the successful integration of AI into everyday hospital practice[49].

In summary, AI has the potential to greatly enhance the capabilities of plastic and reconstructive surgery, improving efficiency, accuracy, and patient-centered outcomes. Ongoing research and collaboration between technologists and medical professionals will be key to fully realizing the potential of AI in plastic and reconstructive surgery. Further research in plastic surgery is necessary to fully assess the potential advantages and address the risks associated with this emerging technology.

DECLARATIONS

Authors' contributions

Conceptualization: Radtke C, Fast A, Novotny MJ
Design of the work: Novotny MJ, Fast A, Radtke C
Investigation, writing original draft: Novotny MJ, Fast A
Writing - review and editing: Fast A, Radtke C
Supervision: Radtke C
All authors have read and agreed to the published version of the manuscript.

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Consent for publication

Not applicable.

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