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Artificial Intelligence Surgery

Review

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Artificial intelligence applications in free flap microvascular reconstruction: preoperative planning, intraoperative assessment, and postoperative monitoring

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Abstract

Reliable planning, execution, and postoperative monitoring in microvascular free flap reconstruction are essential to optimize clinical outcomes. Artificial intelligence has demonstrated value in several applications to clinical medicine and surgery, including image analysis and simulation, outcomes modeling, and evaluation of large datasets. Within microvascular reconstruction, artificial intelligence has been increasingly applied to preoperative planning, intraoperative decision making, and postoperative monitoring. The present paper aims to review salient applications to each. The authors conclude by suggesting areas suitable for future analysis.

Keywords: Artificial intelligence, free flap, microvascular reconstruction, anastomosis

INTRODUCTION

Reliable preoperative planning, intraoperative assessment, and postoperative monitoring in free flap microvascular are essential to guarantee successful long-term reconstructive outcomes[1,2]. Clinical examination during the pre-, intra-, and postoperative periods remains the gold standard of assessment for free flap reconstruction. In the preoperative period, this includes physical examination of patient anatomy, including close evaluation of donor site fitness[3], recipient site reconstructive need, and patient past medical history[4]. During the intra- and postoperative periods, clinical monitoring primarily relies on physical examination, including serial arterial and venous signal evaluations, as well as clinical characteristics, such as flap color, capillary refill, temperature, and caliber.

The advent of artificial intelligence has yielded improvements in clinical medicine[5], including but not limited to genetics and personalized medicine[6], cardiovascular health[7], and pulmonary/critical care[8]. Within surgical subspecialties, artificial intelligence has been applied to clinical outcomes in orthopedic surgery[9], vascular surgery[10], plastic surgery[11], and craniofacial surgery[12-14].

In the present paper, the authors aim to review the salient literature and studies regarding the applications of artificial intelligence to augment planning, assessment, and monitoring for free flap microvascular reconstruction [Table 1]. While this review aims to provide a broad overview of artificial intelligence applications across microvascular reconstruction, it should be noted the studies highlighted have nuances that render results more or less applicable to specific anatomic regions, types of procedures, and certain subpopulations of patients. Despite the nuances or focuses of each article, the generalizable principles of these studies provide a future avenue for broader artificial intelligence research and investigation.

PREOPERATIVE PLANNING

Preoperative planning has played an increasingly important role in free flap microvascular reconstruction[15]. Factors including patient selection, donor site fitness, and recipient site evaluation continue to play an essential role in overall success and outcomes[16]. The advent of artificial intelligence has provided a welcome opportunity for further evaluation of factors most important in preoperative planning and predicting overall outcomes.

Vascular mapping has become increasingly employed prior to flap dissection and reconstruction, and this has been an area fit for applications with artificial intelligence[17-19]. A recent study by Lim *et al*. focused on the accuracy of artificial intelligence models in evaluating computed tomographic angiography (CTA) data for preoperative flap planning, and the team assessed the ability of different large language models to evaluate these preoperative CTA data for DIEP flap planning[20]. When attending plastic surgeons assessed AI-generated CTA evaluations, they found that these models could provide a general summary of relevant CTA data but lacked important nuances that the surgical team desired for preoperative planning[20]. This can be applied for preoperative evaluation and flap selection, which is dependent on patient-specific factors and defects for reconstruction. There may also be applications for determining flap volume appropriateness for defect reconstruction, though this has not yet been described in any current studies.

Other studies aim to apply artificial intelligence to clinical datasets to predict overall outcomes following flap microvascular reconstruction. Within head and neck surgery[21], machine learning successfully leveraged patient characteristics to predict flap complications and loss[22]. Models predicting total flap loss exhibited accuracy of 0.63 to 0.98, with significant identified factors including gender, smoking status, use of vein graft, hypertension, and laryngectomy[22]. Similar machine learning models have created decision trees to predict free flap complications based on preoperative demographics[23]. Such research has important applications to preoperative patient selection, family counseling, and clinical shared decision making[22]. Moreover, the trainability of predictive machine learning models allows for generative growth and accuracy improvement over time. Another systematic review study protocol describes a study in process that aims to summarize artificial intelligence applications in predicting flap outcomes[24].

Table 1. Salient studies applying AI to microvascular reconstruction

Author, year, journal	Aim	Implications
Asaad *et al.*, 2023, *Annals of Surgical Oncology*[22]	Determine factors predictive of head and neck microvascular flap failure	Machine learning models determined predictors of flap complications, most commonly smoking, flap type, and vein graft
Kuo *et al.*, 2018, *Oncotarget*[35]	Use neural networks to predict surgical site infection after head and neck free flap reconstruction	Neural networks were more predictive than logistic regression for surgical site infections after head and neck microvascular reconstruction
Kim *et al.*, 2024, *JAMA Network*[33]	Develop an AI-based automated free flap monitoring system via evaluation of clinical photography	An AI-based flap monitoring system may reduce postoperative clinician burden and workload
O'Neill *et al.*, 2020, *Annals of Surgical Oncology*[34]	Develop a machine learning model that can predict flap failure from a large clinical dataset	Machine learning model identified high-risk patient factors including obesity, comorbidities, and smoking

INTRAOPERATIVE ASSESSMENT

Intraoperative assessment and decision making are fundamental parts of reliable and repeatable microvascular surgery. Artificial intelligence not only has roles in intraoperative monitoring, but has recently been applied to intraoperative decision making for troubleshooting complications.

Objective data on intraoperative flap perfusion can help identify perforasomes and guide clinical decision making. Specifically, indocyanine green fluorescence angiography has been increasingly employed to assess intraoperative flap perfusion[25]. A recent study leveraged artificial intelligence-based applications to review and assess intraoperative videos of flap perfusion with indocyanine green fluorescence angiography (Singaravelu 2024). The authors found over 99% validation and testing accuracy with the need to retain or excise peripheral flap portions[26]. The study also identified a threshold of regions with fluorescence intensity less than 22.1 grayscale units that were significantly more likely to be predicted as "excise" by these models[26]. Such models may be beneficial in corroborating intraoperative decision making regarding flap perfusion and the extent of peripheral tissue included in the flap[26].

Another study evaluated the efficacy and accuracy of artificial intelligence models in providing intraoperative guidance during deep inferior epigastric perforator flap surgery[27], in which artificial intelligence responses were evaluated by board-certified plastic surgeons on several objective, quantitative scales[27]. Prompts included a broad range of intraoperative scenarios such as iatrogenic damage to perforator vessels or acute arterial thrombosis[27]. The study found that while answers generated by artificial intelligence were generally accurate, they lacked nuance specific to individual patient factors and were more comparable to resident knowledge level than to experienced attending surgeons[27].

Critically relevant to trainees, artificial intelligence has also demonstrated utility in microsurgery education. Groups have trialed the intraoperative use of augmented reality overlays in free fibula harvest, allowing surgeons and trainees to visualize bony anatomy and vascular paths in real time[28,29]. Others have utilized technology to digitize preoperative imaging and project vascular anatomy into the surgical field during anterolateral thigh free flap procedures, thus improving vessel identification with impressively high accuracy and sensitivity[30]. Similar applications of augmented reality headsets during microvascular anastomosis performed by resident trainees demonstrated improved visualization and ergonomics[31]. These technologies, although in their infancy, can assist residents not only during simulated microsurgery but also during the intraoperative setting. Utilizing artificial intelligence technology prior to even entering the operating room may yield improvements to surgical understanding, trainee dexterity, and procedure safety.

POSTOPERATIVE MONITORING

Much of the discussion and research centered on artificial intelligence and machine learning in microvascular reconstructive surgery has been dedicated to postoperative flap monitoring, given the importance of early identification of postoperative complications and timely return to the operating room[32].

A recent study in the JAMA network described the development of a cellphone-based application for postoperative free flap monitoring[33]. The authors leveraged artificial intelligence to develop models sensitive to venous and arterial insufficiency, based on over 11,000 unique clinical photos[33]. The models were 97.5% sensitive in recognizing arterial insufficiency and 92.8% sensitive in recognizing venous insufficiency based on clinical photographs alone (Kim *et al.* 2024). Such models may aid clinicians in the early identification of flap failure and may be especially useful in regions, or units, typically naïve to postoperative flap monitoring[33]. This particular initiative may also encourage postoperative monitoring with clinical photographs at regular postoperative intervals, which may allow clinicians to remotely monitor free-flap postoperative progression[33].

Other groups have applied artificial intelligence methods to large datasets to analyze postoperative risk factors for flap failure[34]. Colleagues in Toronto conducted a clinical study of over one thousand patients undergoing microvascular free flap breast reconstruction. Among the twelve patients who experienced flap failure, the authors identified significant predictors including obesity and smoking[34]. While these risk factors have been previously described, the application of artificial intelligence to large datasets may aid clinicians in predicting more nuanced outcomes for patient cohorts undergoing a diverse range of free flap reconstruction. As additional data or images are accrued, artificial intelligence can be trained and broadened to more accurately calculate risk or outcome occurrences.

FUTURE APPLICATIONS

Future endeavors should aim to build upon previously established work to expand the depth, breadth, and accuracy of applications. This may involve the application of artificial intelligence to preoperative flap imaging. With a predictive model, clinicians could envision artificial intelligence predicting and selecting the most viable vascular perforators for a reconstructive flap; however, this type of data should be leveraged in the context of patient-specific anatomy and surgeon experience. Intraoperatively, additional opportunity exists for refining artificial intelligence-generated support of intraoperative decision making, which may be especially useful in lower-resource settings or single-provider practice models. Augmented reality driven by artificial intelligence could augment surgical dissection in a real-time manner to help identify critical structures, vascular anatomy, or hazardous surgical maneuvers. Finally, postoperative monitoring may be supported by systems leveraging artificial intelligence to aid in automating flap monitoring to generate additional real-time data that may reduce the time from flap complication identification to return to the operating room.

CONCLUSIONS

Artificial intelligence has had an undeniable impact on clinical medicine and surgery; within microvascular free flap reconstruction, artificial intelligence continues to impact patient selection and prediction of preoperative outcomes, intraoperative assessment, and postoperative monitoring. While artificial intelligence will augment our ability to plan, implement, and monitor free flap reconstruction for our patients, clinicians and surgeons should continue to rely on in-person physical examination to corroborate data from emerging technology to yield the most optimal clinical outcomes. Based on the potential impact and implications of this work to patients and clinicians alike, we believe future research in this arena to be a worthwhile pursuit.

DECLARATIONS

Authors' contributions

Involved in critically drafting and editing this manuscript: Villavisanis DF, Elhage SA, Crystal DT, Terry P, Serletti JM, Percec I

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