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From clinical prediction to surgical autonomy: Evolution and clinical validation of artificial intelligence in plastic and reconstructive surgery (1990-2026)

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Review

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Background: Artificial intelligence (AI) has progressively transitioned from experimental computational models to clinically applicable systems across multiple surgical disciplines. Plastic and reconstructive surgery, characterized by complex anatomy and reliance on visual assessment, represents a particularly suitable field for AI integration.

Objective: To evaluate the historical development, current clinical applications, and existing evidence gaps of AI in plastic and reconstructive surgery between 1990 and 2026.

Methods: Narrative review with structured search strategy of PubMed, Scopus, and Web of Science was performed. Studies evaluating clinically relevant AI applications were included and categorized by decade and clinical domain.

Results: Early implementations focused on neural network–based survival prediction in burn patients, reporting high internal accuracy. Subsequent developments introduced computer-assisted diagnostic systems, burn depth classification tools, and microsurgical training platforms. During the 2010s, machine learning and deep learning models achieved diagnostic accuracies exceeding 90% in facial symmetry analysis and tissue viability assessment. Since 2020, AI integration has expanded to telemedicine, free-flap monitoring, thermographic-guided perforator mapping, and large language model–assisted documentation. However, most studies remain retrospective and single-center.

Conclusions: AI currently functions as an adjunctive tool that enhances diagnostic objectivity, operative planning, and educational assessment. Prospective multicenter validation and regulatory standardization are required before widespread clinical integration.

KEYWORDS
Artificial Intelligence; Plastic Surgery; Deep Learning; Microsurgery; Burns; Augmented Reality; Predictive Models.

Artificial intelligence (AI), defined as the set of computational systems with the ability to emulate and optimize cognitive processes inherent to human beings, was formally conceptualized in the mid-20th century (1-4). For decades, its development remained confined to the purely theoretical realm. However, the substantial increase in processing capacity and the availability of Big Data have enabled its effective integration into the context of clinical medicine (5-9).

Plastic and reconstructive surgery, a field characterized by its intrinsic anatomical complexity, eminently subjective aesthetic evaluation, and imperative microsurgical precision, is an ideal terrain for the application of AI (10-13). The purpose of this review is to trace the trajectory of this technology, from its initial theoretical models to its current consolidation as a fundamental pillar of precision medicine (1,4,8,10,13,14).

HISTORICAL DEVELOPMENT

1990s and earlier: Conceptual foundations and early implementations.

Artificial Intelligence (AI), understood as the network of computer systems designed to emulate and optimize human cognitive processes, began its theoretical formalization in the 1950s. This period established the scientific foundations that would allow,

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Domain	Primary Application	AI Technique	Evidence Level	Clinical Readiness
Burn Care	Survival prediction	ANN / ML	Retrospective	Moderate
Burn Depth	Image classification	CNN	Prospective (limited)	Moderate
Facial Analysis	Symmetry assessment	SVM / DL	Observational	Moderate
Microsurgery	Skill assessment	Motion analysis	Prospective	Early
Flap Monitoring	Thermographic AI	CNN	Limited prospective	Early
Documentation	LLM	Transformer models	Experimental	Early

Table 1. Summary of major clinical domains, artificial intelligence techniques, reported performance metrics, level of evidence, and current clinical readiness in plastic and reconstructive surgery between 1990 and 2026. Most studies represent retrospective or single-center experiences with limited external validation. **Abbreviations:** AI, artificial intelligence; ANN, artificial neural network; ML, machine learning; DL, deep learning; CNN, convolutional neural network; SVM, support vector machine; LLM, large language model.

decades later, its transition from the theoretical to the applied realm (1-3,7,8).

Although the origins of AI predate this, its first clinical application occurred in the late 1980s in a robot-assisted neurosurgical biopsy procedure. Subsequently, in the early 1990s, AI began to establish its methodological foundations in medicine with the first interpretations of digital mammograms (DM). A key turning point came in 1994 with the publication of the first study documenting the implementation of AI models in clinical cardiology. This achievement spurred the expansion of these technologies into various areas of medicine, including surgical disciplines (1,7,15).

In 1996, Frye et al. published a seminal paper entitled Simulated biologic intelligence used to predict length of stay and survival of burns, in which artificial neural networks—bio-inspired computer models—were used for prognostic stratification in patients with severe burns. The study included 1,585 critically ill patients and reported 98% accuracy in predicting survival and 72% accuracy in estimating hospital stay. These findings provided early evidence of the potential of artificial intelligence as a tool to support complex clinical decision-making (6).

Towards the end of the century, in 1999, the work of Frey et al. marked a turning point in objective assessment. Using three-dimensional video capture systems with an intricate system of mirrors, it laid the foundation for quantitative analysis of facial movement. This innovation made it possible to transcend subjective assessments, introducing unprecedented metric precision in functional and aesthetic evaluation (16).

2000s: Consolidation of Emerging Systems and Assisted Diagnosis.

At the beginning of the 21st century, Artificial Intelligence (AI) transcended the theoretical realm to establish itself as a highly valuable complementary clinical tool. This period was characterized by the validation of predictive algorithms and the birth of modern medical simulation (6,7,17,18).

The validation of artificial neural networks previously used for survival prediction in pediatric trauma was used to predict survival in patients with severe burns and documented in the 2002 publication by Estahbanati and Bouduhi entitled Role of artificial neural networks in prediction of survival of burn patients – a new approach, which was a significant milestone in the consolidation of data-based medicine. Achieving accuracy levels close to 90%, these models demonstrated superior or at least comparable performance to traditional severity indices, justifying their incorporation into prognostic stratification and decision-making optimization in advanced life support. Likewise, it was shown that neural networks, as nonlinear techniques, are more suitable for addressing complex prognostic problems, since they are capable of modeling real clinical events and capturing dynamic interactions between variables, as opposed to conventional methods that focus exclusively on estimating the relative influence of isolated factors (4,6,19).

An unexpected catalyst for AI in medicine occurred in 2003, when the Accreditation Council for Graduate Medical Education (ACGME) imposed restrictions on residents' working hours to 80 hours per week. With the reduction in direct surgical exposure, there was an urgent need to develop AI-assisted simulation and training systems. These platforms made it possible to ensure the learning curve and patient safety, compensating for time constraints in the operating room through high-fidelity virtual environments (20).

Between 2003 and 2005, the introduction of Computer-Assisted Diagnosis (CAD) tools, based on fuzzy logic and neural networks, revolutionized the assessment of skin lesions. These systems automated the classification of burn depth through digital image processing, analyzing color and texture. This advance made it possible to move from a subjective assessment—dependent on the examiner—to objective diagnostic standardization (4,6).

Finally, the period between 2006 and 2008 focused on refining facial morphometric analysis. Although these systems still required manual placement of markers for data capture, they

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Figure 1. Timeline of the development and clinical implementation of AI in plastic surgery.

represented the evolutionary link toward full automation. They laid the technical foundations for contemporary three-dimensional analysis, which is essential in reconstructive surgery planning and postoperative functional evaluation (2,15,16).

2010s: Digitization, Data Mining, and the Expansion of Specialized AI.

The 2010s represented a period of consolidation for clinical digitization and the rise of data mining, marking an accelerated and highly specialized expansion of Artificial Intelligence (AI) in the medical-surgical field (5,7,8,21,22).

In 2011, Patit et al. documented the integration of advanced data mining techniques, specifically Support Vector Machines (SVM), together with decision trees (DT) and the Naïve Bayes classifier, to refine the accuracy of predicting clinical outcomes (survival/mortality) in 180 burn patients, achieving an accuracy of 96.1 to 97.8%. Simultaneously, the study by Patel et al. marked a milestone by developing algorithms for the objective evaluation of facial aesthetics using SVM on a set of 80 facial images, using characteristics extracted from reference points, achieving an accuracy of 88%, providing tools to quantify parameters that traditionally depended on subjective assessment in reconstructive surgery (6,15,21).

The analysis of facial paralysis underwent a significant transformation in 2012 with the introduction of Facegram, a standardized photography-based diagnostic tool used in numerous studies related to facial reanimation surgery. Although innovative, it still relied on manual marking of facial anatomical reference points (16).

In March 2014, the Fast Healthcare Interoperability Resources (FHIR) standards were introduced for the first time, defining the vocabulary, structure, and formats necessary to ensure interoperability between health information systems. Their implementation facilitated the integration and efficient exchange of data from Electronic Health Records (EHRs), substantially transforming the Health Information Exchange (HIE). This advance enabled the systematic use of large volumes of clinical information by structuring robust, heterogeneous, and clinically representative databases, which are essential for the training, validation, and scalability of artificial intelligence models with real applicability in healthcare settings (23).

AI has also transformed medical education. In 2015, McGoldrick et al., in their paper Motion analysis for microsurgical training: objective measures of dexterity, economy of movement, and ability, documented the use of video-based motion analysis to objectively quantify microsurgical skills, demonstrating a direct correlation between digital instrumental dexterity and surgeon experience (24,25). Subsequently, in 2016 and 2018, Heredia-Juesas et al. published studies documenting the application of multispectral imaging (MSI) and digital photography processed using ML algorithms, specifically quadratic discriminant analysis (QDA), to differentiate between viable and non-viable tissue. This technological integration significantly improved the detection of necrotic tissue susceptible to surgical debridement, optimizing therapeutic planning. At the same time, in 2018, Martínez-Jiménez et al. developed a prospective study in which they combined infrared thermography with random forest algorithms, achieving high-precision prediction of tissue viability and the need for conservative management or skin grafts. The model achieved 92% accuracy, which helped reduce uncertainty in reconstructive decision-making and strengthen objectivity in clinical evaluation (6).

It was not until 2018, with the launch of Emotrics, one of the first AI-powered tools for the objective assessment of facial symmetry. This system automated the identification and placement of facial anatomical landmarks, enabling accurate and reproducible quantitative analysis. Its implementation represented a significant advance in daily clinical practice, optimizing assessment time, reducing interobserver variability, and improving therapeutic planning in the field of facial surgery (15).

Towards the end of the 2010s, specifically in 2019, emotional recognition applications such as Affdex, developed by Affectiva, were integrated alongside the implementation of DL-based Convolutional Neural Networks (CNN). This milestone marked a turning point in automated image analysis. These architectures achieved substantial improvements in classification accuracy compared to traditional methods of manual feature processing and extraction. Complementarily, widely validated CNN

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models, such as VGG-16, ResNet-50, and ResNet-101, were applied to the automated classification of burn depth in pediatric populations, achieving accuracies greater than 91%. These results consolidated DL as the benchmark tool for image-assisted diagnosis, given its ability to identify complex, nonlinear patterns with high clinical reproducibility (6,16).

The 2020s: The Heyday of Deep Learning, Clinical Integration, and Global Expansion.

The current decade is defined by the transition of AI from experimental settings to routine clinical practice. This period is characterized by the consolidation of DL, the emergence of large language models (LLMs), and the establishment of structured scientific validation frameworks (8,16,21,26).

The COVID-19 pandemic acted as a catalyst for telemedicine and remote postoperative follow-up. Mobile applications such as SilpaRamanitor enabled autonomous monitoring of free flaps using smartphones, facilitating early detection of vascular compromise (4,5,21,24,27).

In 2021, AI's predictive capabilities reached critical milestones in burn patients, anticipating sepsis and acute renal failure up to 62 hours in advance, while Convolutional Neural Networks (CNN) achieved 91% accuracy in therapeutic stratification (6).

The year 2022 marked a milestone with the launch of ChatGPT, whose versatility enabled the automation of surgical reports and demonstrated a level of competence in medical certification exams comparable to that of resident physicians. However, systematic reviews such as that by Spoer et al., as well as studies by Sallam and Soh et al., reminded the scientific community that most applications were still in preclinical phases, underscoring the need for more rigorous future validation (7,8,17,26,28-30).

AI began to have a direct impact on surgical efficiency, with the use of infrared thermography and microsurgical planning algorithms helping to identify perforating vessels more quickly, reducing preoperative planning time by approximately two hours (24,31).

In 2024, the development of SURVAS (Surgical Validation Score) provided, for the first time, a system for categorizing the level of evidence in AI models in surgery as high, moderate, low, and very low. At the same time, the Anatomy Projector integrated augmented reality (AR) to project intraoperative heat maps, transforming anatomical guidance in real time (15,31).

By 2025, AI had expanded into pediatric craniofacial surgery, automating the production of patient-specific nasoalveolar modeling (NAM) devices, enabling their 3D printing, and optimizing the treatment of patients with cleft lip and palate. A key regulatory milestone occurred in September of that year with the FDA's approval of the Synaptix platform, which integrates predictive analytics and AR, paving the way for assisted surgical autonomy (12,32).

Currently, in 2026, AI has become established in the automated assessment of pathological scars and in multimodal decision support systems. The immediate future is projected to lie in hybrid education models, where AI acts as a co-instructor in Extended Reality (XR) environments, offering real-time feedback with near 100% accuracy (20,26,29,33).

Immediate projections suggest that artificial intelligence (AI) is moving from being a peripheral tool to becoming an integral cognitive partner (26,32). This evolution will redefine the boundaries of reconstructive medicine through three fundamental pillars:

The technical horizon points toward the execution of procedures with increasing levels of independence. A prime example is the STAR (Smart Tissue Autonomous Robot) platform, which in preclinical settings has surpassed human dexterity in highly complex tasks such as suturing and soft tissue anastomosis. The long-term goal is not to replace the surgeon, but to delegate repetitive, high-precision tasks to minimize human error and optimize surgical times (4,33).

Emerging research explores integration of AI with robotics, augmented reality, and digital simulation platforms. Although early preclinical data suggest potential benefits in surgical precision and workflow optimization, these technologies remain investigational and require robust clinical validation before routine implementation. Below is a brief overview of these technologies (10,13,31,32,34).

The implementation of personalized digital twins is anticipated. These dynamic virtual representations integrate anatomical, physiological, and genomic data, allowing surgeons to rehearse multiple surgical strategies in a zero-risk environment. By simulating a patient's specific biological response before making the first incision, the practice moves from standardized medicine to absolute precision medicine (10,13).

The synergy between robotics, AI, and immersive technologies (XR) will create a smart operating room. The superimposition of tissue perfusion maps, predictive viability analyses, and anatomical guides using augmented reality (AR) will allow surgeons to “see” beyond the surface, transforming intraoperative decision-making from a reactive model to a predictive and adaptive one (10,31,32,34).

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Discussion

This review demonstrates that AI in plastic and reconstructive surgery has evolved from isolated predictive algorithms to clinically oriented decision-support tools. While early applications focused primarily on prognostic modeling in burn care, contemporary systems increasingly support image-based diagnostics, flap monitoring, operative planning, and structured surgical training (5,6,21).

Despite promising diagnostic accuracy metrics, several limitations restrict widespread adoption. The majority of available studies are retrospective, frequently single-center, and based on relatively small or homogeneous datasets. Reported high performance may reflect internal validation rather than reproducible real-world outcomes. Furthermore, algorithmic bias, limited explainability of deep learning systems, and regulatory uncertainty continue to represent barriers to integration into routine surgical workflows. (11,20,24,31).

Importantly, AI should be conceptualized as a clinical adjunct rather than an autonomous decision-maker. Its greatest current value lies in enhancing objectivity in visually dependent assessments, reducing interobserver variability, and supporting perioperative risk stratification (8,10,13,15,29,34-36). Future research must prioritize prospective validation, external reproducibility, standardized reporting frameworks, and measurable clinical outcome improvement. However, sustainable implementation will require prospective validation, external reproducibility, and clearly defined ethical and regulatory standards (2,10,17,37-40).

Future developments are likely to focus on multimodal systems integrating imaging, clinical, and language-based data streams. Emerging applications in orbitofacial pathology, advanced prognostic modeling, and robotic-assisted platforms suggest increasing integration of AI into operative workflows. The next stage will likely involve structured human–AI collaboration models in which decision-support systems enhance, rather than replace, clinical judgment (21,41-45).

Conclusion

Artificial intelligence represents a meaningful advancement in plastic and reconstructive surgery, with measurable impact on diagnostic objectivity, operative planning, and surgical education. Its evolution from early predictive models to contemporary multimodal systems reflects progressive integration into clinical workflows.

However, the current body of evidence remains predominantly retrospective and single-center, with limited prospective multicenter validation. This discrepancy between technological advancement and high-level clinical evidence underscores the need for standardized validation frameworks, external reproducibility testing, and transparent model development.

AI should be understood as an augmentative tool rather than a replacement for surgical expertise. Sustainable integration into practice will depend not only on algorithmic performance but on demonstrable clinical benefit, ethical oversight, explainability, and regulatory clarity.

Future progress requires rigorous prospective evaluation to ensure that innovation translates into safe, equitable, and reproducible improvements in real-world surgical outcomes.

Conflicts of interests

The authors declare that there are no financial, personal, or institutional conflicts of interest that could have influenced the work reported in this manuscript.

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