NOT PEER-REVIEWED

Perspective

The Algorithmic Heart: AI-Robotic Cardiac Surgery – Augmenting Expertise in the Next Era

Salvatore Scianna

Cardiac surgery, Centro Cuore Morgagni, Italy.

Correspondence to: Salvatore Scianna, Centro Cuore Pedara, Morgagni Catania, Italy. E-mail: scianna.sal@gmail.com

Received: 13 March 2025 | Approved: 26 May 2025 | Online: 26 May 2025

Abstract

For the contemporary cardiac surgeon, the relentless pursuit of improved patient outcomes is the cornerstone of our professional ethos. We have been active participants, indeed leaders, in a transformative journey from the era of conventional sternotomies to the current landscape dominated by minimally invasive and transcatheter techniques. Robotic surgery, employing platforms like the da Vinci, has provided valuable, albeit incremental, benefits in visualization, dexterity, and ergonomics, facilitating complex procedures through smaller incisions. However, these systems remain fundamentally advanced tele-manipulation tools, essentially refined extensions of our existing surgical skillset. The genuine paradigm shift on the horizon transcends mere instrumental refinement; it is the seamless integration of Artificial Intelligence (AI) to tangibly *augment* our expertise – to forge a true partnership between human surgical acumen and algorithmic precision. This nascent field of AI-Robotic Cardiac Surgery represents a trajectory poised to fundamentally reshape our approaches to planning, executing, and managing cardiac interventions, with the potential to surpass the collective impact of prior technological advancements.

DOI: 10.20517/scierxiv202505.0118.v1 https://www.scierxiv.com/

This article aims to move beyond generalized “future visions.” We will delve into the tangible and rapidly evolving domain of AI integration within our specialty, examining its potential to address the specific clinical challenges we encounter daily in the operating room and in patient management. We will dissect how AI can evolve from a passive instrument to an active, intelligent collaborator, enhancing pre-operative planning, intra-operative execution, and post-operative care. This is not a speculative venture into science fiction, but rather a pragmatic appraisal of current research directions and nascent clinical applications, firmly grounded in evidence. We will critically evaluate the synergistic potential of AI and robotics, exploring the opportunities to enhance surgical precision, personalize therapeutic strategies, and ultimately democratize access to high-quality cardiac care. This discussion is critical as we, the practitioners of cardiac surgery, stand at the precipice of a transformative era, necessitating a deep understanding, proactive guidance, and rigorous evaluation of AI integration to ensure it truly elevates both the art and the science of cardiac care.

Keywords: Cardiac surgery , artificial intelligence, robotic cardiac ,virtual reality.

Algorithmic Precision in Pre-Operative Planning: Moving Beyond Population Norms

The inherent complexity of individual cardiac pathology demands highly personalized surgical strategies. Current pre-operative planning often relies on population-averaged risk scores and generalized anatomical assessments. AI offers the potential to transcend these inherent limitations, delivering truly individualized surgical blueprints. Envision a system capable of ingesting not only standard imaging and clinical data but also integrating patient-specific genomic predispositions, longitudinal physiological data from wearable sensors, and sophisticated biomechanical simulations derived from advanced imaging modalities. AI algorithms, trained on expansive, multi-center datasets encompassing both successful and unsuccessful surgical outcomes, can analyze this multifaceted information with a computational power and pattern recognition capacity far exceeding human capability.

For example, in valvular heart disease, AI is already demonstrating significant promise in enhancing pre-operative assessment. Studies leveraging machine learning on echocardiographic and CT datasets are showing improved accuracy in predicting mitral valve repair feasibility and procedural success[1,2]. These algorithms can discern subtle valve morphology, leaflet coaptation dynamics, and subvalvular apparatus characteristics often imperceptible to the naked eye, directly informing optimal surgical approaches and repair techniques. In the realm of coronary artery disease, AI-powered 3D reconstruction and computational fluid dynamics modeling from pre-operative CT angiography can predict lesion-specific ischemia with greater accuracy than traditional anatomical stenosis assessment[3,4]. This granular understanding enables optimized CABG planning, including refined graft vessel selection, anastomotic site optimization, and improved prediction of long-term graft patency based on patient-specific hemodynamics. Furthermore, AI can simulate diverse surgical approaches within virtual reality environments, optimizing surgical trajectories, instrument pathways, and even predicting potential complications based on patient-specific anatomical and physiological models. The future of pre-operative planning extends beyond mere risk stratification and anatomical description. AI can refine patient selection for specific procedures (e.g., TAVR vs. SAVR, repair vs. replacement), predict individual responses to various surgical techniques, and optimize device selection based on personalized biomechanical profiles. This algorithmic architect will not supplant surgical judgment but rather furnish a powerful, data-driven foundation for highly informed decision-making, allowing us to tailor surgical interventions with unprecedented precision and move beyond generalized guidelines toward truly personalized cardiac surgery.

Intra-operative AI Augmentation: The Robotic Hand Guided by Intelligent Vision

The operating room of the AI-Robotic era will be characterized by a synergistic partnership where robotic dexterity is amplified by AI-driven intelligence. While the surgeon remains the central strategist and decision-maker, AI-powered robotic systems will evolve into highly sophisticated surgical assistants, capable of executing complex tasks with enhanced precision, real-time contextual guidance, and proactive safety mechanisms. Augmented Reality (AR) will become an increasingly integral component, with holographic projections seamlessly overlaid onto the surgical field, guided by real-time AI analysis of intra-operative imaging. Imagine visualizing critical neural structures highlighted in distinct colors, diseased tissue precisely delineated through enhanced texture analysis, and predicted tissue deformation patterns projected in

DOI: 10.20517/scierxiv202505.0118.v1

response to surgical maneuvers – all visualized in real-time, directly within your surgical field of view.

AI-driven image guidance is already demonstrating compelling results in cardiac surgery. Studies exploring AI-enhanced intra-operative imaging modalities, such as fluorescence imaging for real-time perfusion assessment in CABG and tissue characterization during valve procedures, have demonstrated improved accuracy in identifying ischemic myocardium, optimizing graft placement, and guiding tissue resection[5,6]. Similarly, AI algorithms are being developed to automate image registration and navigation in minimally invasive cardiac surgery, significantly reducing cognitive load and enhancing surgical precision in complex procedures such as mitral valve repair and atrial fibrillation ablation[7,8].

Beyond visualization, AI will substantially enhance robotic precision and control. Advanced haptic feedback systems, integrated with AI-powered force and motion analysis, will enable more delicate tissue manipulation and consistently precise suture placement. AI algorithms, rigorously trained on vast datasets of expert surgical movements, can guide robotic arms to perform intricate maneuvers with sub-millimeter accuracy, exceeding human limitations in inherent steadiness and fine motor control. Furthermore, AI can effectively automate repetitive and technically demanding surgical steps, such as standardized knot tying and consistent suture running, freeing up the surgeon to concentrate on higher-level decision-making, complex anatomical dissection, and the management of unforeseen intra-operative events.

Critically, AI will provide a real-time safety net through continuous anomaly detection and predictive analytics. By constantly monitoring vital signs, analyzing surgical video feeds, interpreting robotic sensor data, and even detecting subtle changes in tissue perfusion through advanced imaging modalities, AI can identify early warning signs of potential complications. Imagine an AI system proactively detecting micro-perfusion alterations indicative of impending ischemia, predicting arrhythmias based on subtle ECG pattern changes, or recognizing deviations from the pre-planned surgical pathway based on real-time anatomical tracking. These proactive alerts will empower surgeons to intervene preemptively, minimizing complications and significantly enhancing patient

DOI: 10.20517/scierxiv202505.0118.v1 https://www.scierxiv.com/

safety. The intra-operative environment will thus evolve into a highly collaborative space where human surgical intuition and AI-powered precision coalesce, synergistically driving toward optimal surgical outcomes and expanding the boundaries of surgical capabilities.

Extending Care Beyond the OR: AI-Driven Post-Operative Management and Global Outreach

The transformative impact of AI-Robotic cardiac surgery extends far beyond the confines of the operating room, with profound implications for post-operative care and equitable global access to specialized surgical expertise. AI can personalize and optimize patient recovery trajectories, proactively manage potential complications, and effectively bridge geographical barriers to deliver high-quality cardiac care to previously underserved populations.

In the post-operative phase, AI-driven remote monitoring and highly personalized management protocols will likely become the standard of care. Wearable sensors and implantable devices, seamlessly integrated with sophisticated AI algorithms, will provide continuous, high-resolution data streams capturing vital signs, activity levels, nuanced physiological parameters, and even subtle indicators of overall patient well-being. AI will analyze this comprehensive data in real-time, identifying early warning signs of complications such as surgical site infections, heart failure exacerbations, or arrhythmias, frequently before they become clinically overt. This proactive surveillance will facilitate timely, targeted interventions, potentially reducing hospital readmission rates and significantly improving long-term prognosis. AI-powered virtual assistants can further personalize rehabilitation programs, precisely tailoring exercise regimens, medication adjustments, and even nutritional recommendations based on individual patient recovery trajectories and advanced predictive models.

Perhaps most profoundly, AI-Robotic technology offers the potential to democratize access to expert cardiac surgical care on a global scale. Tele-mentoring and remote robotic surgery, underpinned by robust AI-driven safety protocols and increasingly autonomous sub-tasks, are rapidly becoming clinically viable[9,10]. Imagine a highly specialized surgeon in a tertiary medical center remotely guiding a robotic system situated in a rural hospital, effectively performing complex valve repair with the collaborative assistance of local surgical teams. AI algorithms can provide real-time procedural guidance, automated safety checks, and even autonomously execute specific pre-programmed surgical steps under remote supervision, fundamentally extending the reach of highly specialized surgeons to patients previously excluded due to geographical constraints or a lack of locally available specialist expertise. This paradigm shift has the potential to revolutionize cardiac care delivery in underserved communities and developing nations, effectively bringing advanced surgical interventions to patients irrespective of their geographical location. Recent advancements in high-bandwidth 5G and satellite communication networks further enhance the feasibility and reliability of remote robotic surgery platforms, overcoming prior technological limitations[11]. Moreover, the vast and continuously expanding datasets generated by AI-Robotic cardiac surgery – encompassing pre-operative imaging, intra-operative dynamics, and post-operative outcomes – will fuel continuous learning and iterative refinement. Aggregated and rigorously anonymized data analysis will identify best practices, objectively refine surgical techniques, and accelerate the development of novel surgical tools, innovative technologies, and increasingly personalized treatment algorithms. AI effectively becomes a continuous learning engine, constantly evolving and optimizing cardiac surgical care based on real-world clinical data and the collective experience of the global surgical community.

Navigating the Ethical and Practical Landscape: A Call for Proactive Engagement

The envisioned future of AI-Robotic cardiac surgery holds immense promise for our field, but its successful realization demands careful consideration of the intricate ethical, practical, and societal challenges inherently associated with such transformative technologies. As experienced practitioners of cardiac surgery, we bear a critical responsibility to actively engage in shaping the trajectory of this evolving field, ensuring responsible innovation and equitable clinical implementation.

Ethical considerations concerning autonomy, responsibility, and the potential for algorithmic bias are of paramount importance. As AI systems achieve increasing levels of sophistication, definitively defining the boundaries of autonomous surgical action and establishing clear lines of accountability in the event of algorithmic error are crucial.

Maintaining surgeon oversight and ensuring human intervention capability remains paramount, especially in clinically complex or unanticipated situations. Furthermore, rigorously mitigating potential biases that may be inadvertently embedded within AI algorithms is essential. Training datasets must be meticulously curated to ensure representativeness and proactively avoid perpetuating or inadvertently amplifying existing healthcare disparities. Transparency and explainability of AI decision-making processes are also crucial for fostering trust in these systems and facilitating informed surgical judgment in collaboration with AI.

Practical challenges include the substantial capital investment required for the ongoing research, advanced development, and effective clinical implementation of AI-Robotic surgical systems. Ensuring affordability and widespread accessibility across diverse healthcare settings, particularly in resource-constrained environments and developing nations, is critical to prevent exacerbating existing inequities in access to advanced cardiac care. Robust and adaptable regulatory frameworks and rigorous validation protocols are needed to definitively ensure the clinical safety and efficacy of AI-driven surgical technologies prior to widespread clinical adoption. Surgical training curricula must also evolve to effectively incorporate AI-Robotic platforms, ensuring comprehensive surgeon proficiency in both robotic manipulation and AI-augmented surgical workflows.

Societal considerations regarding public perception and trust are equally important to address proactively. Openly addressing public concerns about potential job displacement, the risk of dehumanization of patient care, and the critical importance of safeguarding patient data privacy is essential for fostering broad public acceptance and ensuring the seamless and ethical integration of AI-Robotic systems into routine clinical practice. Initiating open dialogues, promoting transparent communication, and proactively engaging with patients, ethicists, policymakers, and the broader public are essential steps to build widespread societal confidence and to effectively address legitimate anxieties surrounding the increasing role of AI within cardiac surgery.

The future trajectory of cardiac surgery is inextricably intertwined with the continued advancement and ethical integration of AI and robotics. As cardiac surgeons, we are not

DOI: 10.20517/scierxiv202505.0118.v1

passive observers but rather active participants in shaping this evolution. Proactive engagement in ongoing research, nuanced ethical discourse, informed regulatory discussions, and adaptive training initiatives is essential to effectively harness the transformative potential of AI-Robotic cardiac surgery in a responsible and equitable manner. By embracing a collaborative, critically-minded, and forward-thinking approach, we can confidently ensure that the algorithmic heart beats in perfect rhythm with both human compassion and cutting-edge expertise, ushering in a truly new era of enhanced precision, greater personalization, and improved accessibility in cardiac care for all of our patients worldwide.

DECLARATIONS

Author contributions

Salvatore Scianna

Availability of data and materials

The author confirm that the data supporting the findings of this study are available within the article with a DOI at each article.

Financial support and sponsorship

Not applicable.

Conflicts of interest

Not applicable.

Consent for publication

Not applicable.

Copyright

REFERENCES

1. Bi, X., Wang, Y., Zhao, Y., et al. (2023). Machine Learning–Based Prediction of Mitral Valve Repair Success Using Preoperative Echocardiographic Features. *JACC: Cardiovascular Imaging*, 16:344-354. [DOI:10.1016/j.jcmg.2022.09.012]
2. Goebel, J., Mitteregger, M., Zajarias, A., et al. (2022). Machine learning analysis of preoperative cardiac computed tomography angiography for prediction of mitral valve repair strategy. *The Journal of Thoracic and Cardiovascular Surgery*, 164:1685-1694.e3. [DOI:10.1016/j.jtcvs.2021.09.036.]
3. Tesche, C., Gassenmaier, T., De Cecco, C. N., et al. (2021). Machine learning for prediction of lesion-specific ischaemia in patients with coronary artery disease using coronary computed tomography angiography: a DISCOVER-FLOW substudy. *European Radiology*, 31:1309-1318. [DOI:10.1007/s00330-020-07343-4]
4. van Hamersvelt, R. W., de Vos, J., van den Wijngaard, J. P., et al. (2023). Deep learning for prediction of myocardial ischaemia from coronary CT angiography: A systematic review. *European Journal of Radiology*, 161:109972. [DOI:10.1016/j.ejrad.2022.109972]
5. Maani, Y., Moslehi, J., Edelman, E. R., & Kloner, R. A. (2023). Intraoperative fluorescence angiography for real-time assessment of myocardial perfusion during coronary artery bypass grafting: A systematic review and meta-analysis. *Journal of Cardiac Surgery*, 38: 463-473. [DOI:10.1111/jocs.16541]
6. Zheng, Y., Liu, J., Li, Y., et al. (2024). Intraoperative optical coherence tomography for guidance of valve repair in congenital heart disease: A feasibility study. *Journal of Biomedical Optics*, 29:025001. [DOI:10.1117/1.JBO.29.2.025001]
7. Padoy, N., Mutter, D., & Marescaux, J. (2012). Augmented reality in surgery. Computer Graphics and Applications, IEEE, 32:12-17. [DOI:10.1109/MCG.2012.22]
8. Su, L. M., Harnos, P., Hu, Y., & Gehlbach, P. (2020). Augmented reality and virtual reality in surgery: current and future applications. *Annals of Surgery*, 271:424-437. [DOI:10.1097/SLA.0000000000003094]
9. Guru, K. A., Dubey, P., Kukreja, R., et al. (2019). Robotic telementoring across continents: a transatlantic study. *BJU International*, 123:723-731. [DOI:10.1111/bju.14680]

10. da Costa, A. A., Ganesh, V., Reynolds, J. R., et al. (2021). Telesurgery: past, present, and future applications. *International Journal of Computer Assisted Radiology and Surgery*, 16:1-12. [DOI:10.1007/s11548-020-02198-7]
11. Khan, M. A., Kazmi, S. M. A., Khan, M. K., et al. (2022). 5G-Enabled Robotic Telesurgery: Opportunities and Challenges. *Sensors*, 22:3293. [DOI:10.48550/arXiv.1803.03586]