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Intelligent implants: AI-integrated microchips from neural interfaces to precision cardiothoracic surgery

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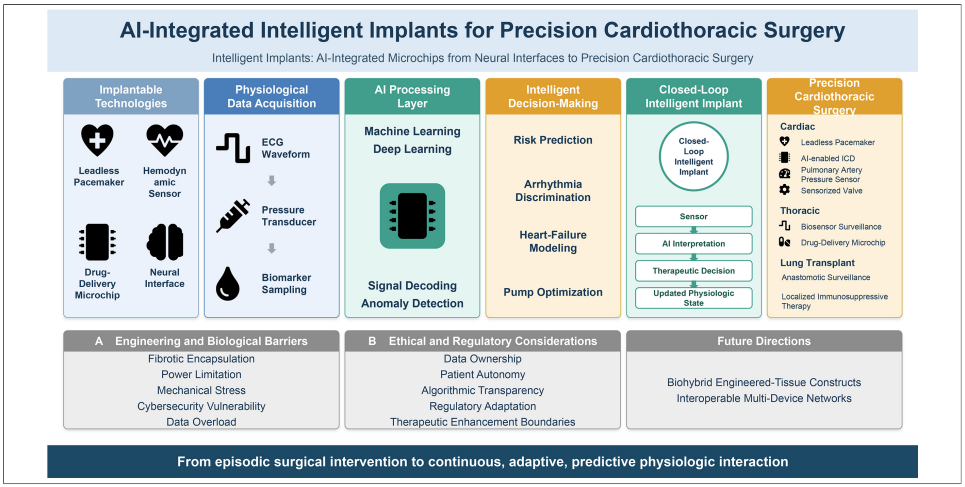

Abstract

The integration of microchips into the human body has progressed from passive identification devices to intelligent, implantable systems capable of sensing, computation, stimulation, and therapeutic delivery. Advances in microelectronics, wireless power transfer, biomaterials, and artificial intelligence (AI) have enabled the development of brain-computer interfaces, implantable drug-delivery platforms, and continuous biosensing systems. Increasingly, these technologies are reshaping cardiovascular and thoracic care. In cardiothoracic surgery, microchip-enabled systems are increasingly integrated into cardiac rhythm management, hemodynamic monitoring, mechanical circulatory support, structural heart interventions, and transplant surveillance. Implantable cardiac monitors, leadless pacemakers, pressure micro-sensors, AI-driven arrhythmia detection systems, and bioelectronic interfaces for autonomic modulation illustrate the convergence of

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microelectronics and cardiovascular therapeutics. In thoracic oncology and lung transplantation, implantable biosensors and microfluidic platforms offer emerging potential for early detection of rejection, infection, and tumor recurrence. This review examines the technological foundations of human-integrated microchips and explores their multidisciplinary applications, with particular emphasis on cardiothoracic surgery. Engineering challenges, biocompatibility constraints, cybersecurity concerns, and ethical implications are analyzed. As AI transforms these devices from passive hardware into adaptive, closed-loop therapeutic systems, the future of cardiothoracic surgery may increasingly depend on intelligent implants capable of real-time physiologic interpretation and precision intervention.

1. INTRODUCTION

The integration of microchips into the human body represents a major inflection point in modern medicine, enabling a shift from episodic intervention to continuous physiologic interaction[1]. Early subcutaneous radiofrequency identification devices have evolved into sophisticated implantable systems capable of neural recording, targeted stimulation, wireless communication, and real-time data processing[2]. Advances in semiconductor miniaturization, flexible electronics, microfluidics, and biocompatible materials have accelerated the development of devices that can function chronically within complex biological environments[3,4]. In parallel, artificial intelligence (AI) has emerged as a critical enabling layer, transforming implantable microchips from passive components into adaptive, closed-loop systems[5].

While much public attention has focused on neural interfaces, the cardiovascular system has been one of the earliest and most impactful domains of human-microchip integration. Contemporary cardiothoracic practice already depends heavily on implantable electronic technologies. These systems represent foundational examples of bioelectronic medicine - devices that sense physiologic signals and deliver targeted therapy within the body.

Recent advances extend far beyond traditional rhythm management. Indeed, new developments in implantable cardiovascular technologies reflect a broader trend toward device miniaturization, continuous physiologic monitoring, and increasingly sophisticated data analysis capabilities[6]. Modern systems integrate microelectronic sensors and computational algorithms that enable real-time assessment of cardiovascular function, remote disease management, and improved diagnostic and therapeutic precision across multiple domains of cardiac care[7].

AI plays a pivotal role in this evolution. For the purposes of this review, the term "artificial intelligence" is used as an umbrella term encompassing data-driven computational approaches, primarily machine learning (ML) and its deep learning (DL) subfield[8]. Where relevant, specific architectures such as convolutional neural networks (CNNs), long short-term memory (LSTM) networks, and transformer models are discussed individually according to their clinical applications.

Modern implantable systems generate high-volume, high-frequency physiologic data streams that exceed human interpretive capacity. AI algorithms enable signal decoding, anomaly detection, predictive modeling, and dynamic therapy adjustment[9]. In cardiothoracic surgery, this convergence raises the possibility of fully closed-loop systems capable of autonomously modulating pacing, adjusting ventricular assist device parameters, or titrating pharmacologic delivery based on continuous physiologic feedback. Figure 1 illustrates the evolution of intelligent implantable systems from conventional devices to AI-enabled closed-loop therapeutics.

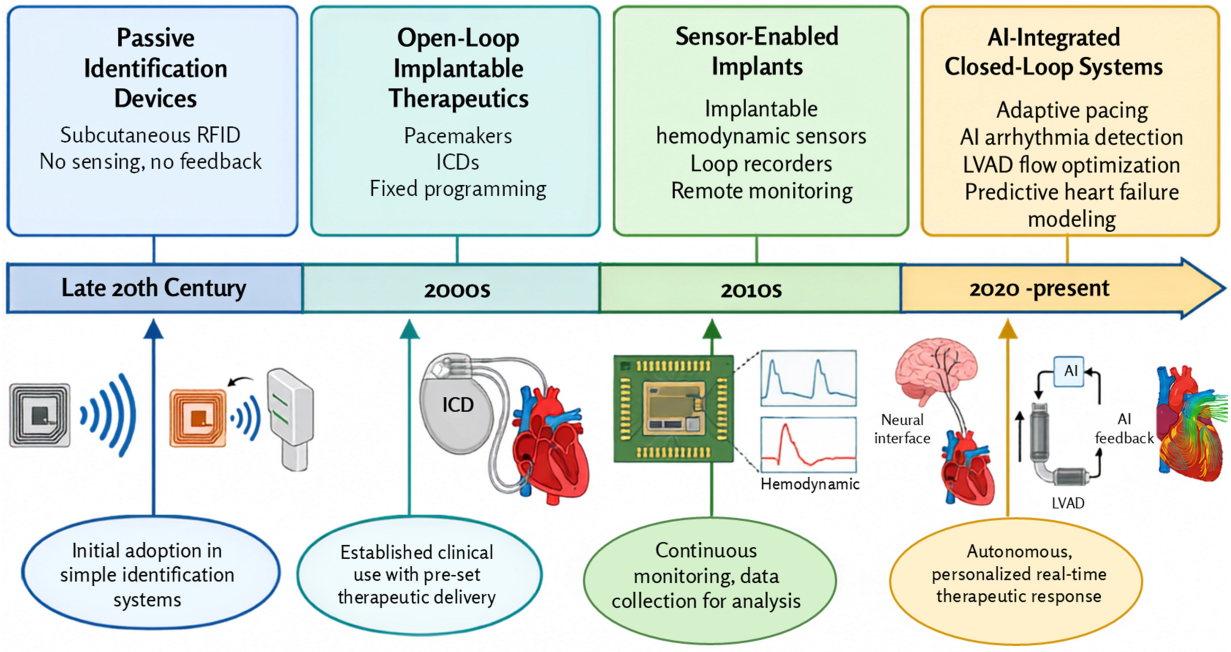

Figure 1. Evolution of human-integrated microchip systems toward AI-driven closed-loop therapeutics[2,5,10,11]. AI: Artificial intelligence; RFID: subcutaneous radio frequency identification; ICDs: implantable cardioverter-defibrillators; LVAD: left ventricular assist device.

Despite these advances, substantial challenges remain. Long-term biocompatibility, device durability in high-motion cardiac environments, power constraints, cybersecurity risks, and regulatory oversight represent critical barriers[12]. Ethical considerations, including data ownership, patient autonomy, algorithmic transparency, and the boundary between therapy and enhancement, are increasingly relevant as implantable systems gain cognitive and adaptive capabilities[13].

As microchip technologies mature in the era of AI, cardiothoracic surgery stands at the intersection of bioengineering and digital intelligence. The field is uniquely positioned to shape the development of intelligent implants that not only support cardiac and thoracic function, but actively interpret and respond to physiologic signals in real time. This review examines the technological foundations of human-integrated microchips, explores their multidisciplinary applications with emphasis on cardiothoracic surgery, and outlines future directions that may redefine surgical therapeutics in the age of AI.

2. HISTORICAL EVOLUTION OF HUMAN MICROCHIP INTEGRATION

The history of human-integrated microchip technologies is closely intertwined with the development of implantable cardiac rhythm management devices, with the major technological milestones and their clinical implications summarized in Table 1. The first fully implantable cardiac pacemaker was introduced in the late 1950s and represented one of the earliest clinical applications of long-term implantable electronic devices[10]. Early pacemakers relied on relatively simple circuitry and battery systems, delivering fixed-rate electrical stimulation to maintain cardiac rhythm in patients with complete atrioventricular block or severe bradyarrhythmias.

Subsequent technological advances during the 1970s and 1980s led to the development of demand-based pacemakers capable of sensing intrinsic cardiac activity and delivering stimulation only when necessary[21]. The introduction of implantable cardioverter-defibrillators (ICDs) in the 1980s further expanded the role of implantable electronics in cardiovascular therapeutics by enabling detection and termination of

Table 1. Historical progression of implantable cardiac microelectronic systems.

Era	Device type	Technological characteristics	Clinical impact
Early Era[10]	Single-chamber pacemakers	Fixed-rate pacing	Basic rhythm support
Intermediate[14,15]	ICD, CRT	Arrhythmia detection + resynchronization	Reduced sudden death
Sensor Era[16-18]	Hemodynamic sensors	Continuous pressure monitoring	Remote HF management
AI Era[19,20]	Adaptive closed-loop systems	Predictive modeling + auto-adjustment	Precision physiologic control

ICD: Implantable cardioverter-defibrillator; CRT: cardiac resynchronization therapy; HF: heart failure; AI: artificial intelligence.

life-threatening ventricular arrhythmias[14]. Cardiac resynchronization therapy subsequently emerged as a therapeutic strategy for patients with heart failure and ventricular conduction delay, demonstrating that implantable devices could actively modulate cardiac physiology to improve hemodynamic performance and clinical outcomes[15].

Throughout the late 20th and early 21st centuries, improvements in semiconductor miniaturization and battery technology facilitated the development of smaller, more durable devices capable of increasingly sophisticated sensing and computational functions. Implantable loop recorders were developed to enable long-term cardiac rhythm surveillance in patients with unexplained syncope or cryptogenic stroke[11].

More recently, a major technological transition has occurred from transvenous lead-based systems toward leadless and wireless platforms. Leadless pacemakers represent a miniaturized intracardiac device that can be delivered via catheter without the need for transvenous leads or subcutaneous generator pockets, thereby reducing infection risk and lead-related complications. Clinical studies have demonstrated high implantation success rates and favorable long-term safety profiles for leadless pacing technologies compared with conventional systems[22,23].

3. CURRENT IMPLANTABLE TECHNOLOGIES ACROSS MEDICINE

3.1. Neural and neurostimulation systems

Neurostimulation technologies represent one of the most rapidly advancing domains of implantable bioelectronics. Deep brain stimulation has become an established therapeutic intervention for neurological disorders including Parkinson disease, essential tremor, and dystonia[24]. These systems consist of intracranial electrodes connected to implantable pulse generators capable of delivering controlled electrical stimulation to targeted neural circuits. By modulating abnormal neuronal activity, deep brain stimulation can significantly improve motor symptoms and quality of life in affected patients.

Beyond traditional neurostimulation, brain-computer interfaces have emerged as a transformative technology capable of establishing bidirectional communication between neural networks and electronic systems. Implantable neural interfaces can record neuronal activity and translate neural signals into digital commands, enabling control of external devices such as prosthetic limbs or communication systems[25,26]. Conversely, electrical stimulation delivered through neural interfaces can restore sensory perception or modulate neural circuits involved in movement and cognition[27].

The relevance of neural implants to cardiothoracic medicine lies in the growing understanding of neurocardiac interactions. The autonomic nervous system plays a central role in regulating cardiac rhythm, myocardial contractility, and vascular tone. Neuromodulation strategies targeting autonomic pathways have been investigated as potential therapies for heart failure and arrhythmias[28].

These translational links become more concrete when weighed against specific, unmet needs in cardiothoracic surgical practice. Chronic post-thoracotomy and post-sternotomy pain remains common after cardiac and thoracic operations and is attributed largely to intercostal nerve injury during retraction, cannulation, or rib spreading, a problem current analgesic strategies address incompletely[29]. Closed-loop spinal cord stimulation systems, which sense evoked compound action potentials and titrate stimulation amplitude in real time, have recently been shown to operate safely alongside ICDs, illustrating a direct extension of neural-interface technology into a surgical pain problem that pharmacologic approaches alone cannot solve[30].

A second unmet need concerns neurocognitive protection during mechanical circulatory support. Acute brain injury affects up to one-third of patients supported with venoarterial ECMO, and stroke remains a major complication of left ventricular assist devices (LVADs), yet current mechanical circulatory support (MCS) control algorithms optimize pump flow and thrombosis detection rather than cerebral perfusion[31]. Continuous cerebral autoregulation monitoring, which uses near-infrared spectroscopy-derived indices to identify a patient-specific optimal blood pressure range, is a neural-interface-adjacent technology that could in principle be integrated into a closed loop with MCS controllers, adjusting flow parameters to real-time cerebral perfusion rather than systemic hemodynamics alone, a capability existing devices do not offer[31].

A third area concerns cardiac denervation after heart transplantation. Because the transplanted heart loses its afferent and efferent autonomic connections, recipients exhibit an elevated resting heart rate, a blunted chronotropic response to exercise, and loss of anginal warning of graft ischemia; sympathetic reinnervation, when it occurs, is partial, delayed by months to years, and remains incomplete in the majority of recipients[32]. Autonomic Neuromodulation strategies developed for neurocardiac disease could plausibly be adapted to accelerate or substitute for this reinnervation process, representing a concrete cardiothoracic surgical application that conventional BCI- or DBS-oriented neural interface research does not currently address.

Despite this translational potential, several limitations temper enthusiasm for neural-interface technologies in cardiothoracic applications. Electrode-tissue interfaces are subject to chronic gliosis and fibrous encapsulation, which progressively increase impedance and attenuate signal fidelity over months to years, and brain-computer interface trials report substantial variability in long-term signal stability, with some systems requiring recalibration within the first year[33,34].

It also remains unresolved how a neural interface implanted in or near the thorax would tolerate the mechanical stresses of cardiac and respiratory motion over years of use, an environment considerably more dynamic than the cranial cavity in which most existing evidence has been generated. Furthermore, established, less invasive alternatives already exist for some of the same physiological targets: catheter-based renal or pulmonary denervation achieves durable autonomic modulation without a permanently implanted neural device, and recent meta-analyses confirm meaningful and sustained blood-pressure reduction with this approach[35].

Whether an implantable neural interface can offer a clinically meaningful advantage over these established, reversible, and comparatively inexpensive catheter-based techniques, rather than simply a more complex alternative, remains an open question that the cardiothoracic surgical literature has yet to address.

3.1.1. Implantable drug delivery microchips

Implantable microchip-based drug delivery systems represent another emerging application of microelectronics in medicine. These devices typically consist of microfabricated reservoirs capable of storing pharmacologic agents and releasing them in a controlled manner through programmable electronic

triggers[36]. Microelectromechanical systems technology allows precise temporal control of drug release while maintaining extremely small device dimensions suitable for long-term implantation[37].

Programmable drug delivery microchips have been investigated for a variety of therapeutic applications including hormone replacement therapy, oncology, and chronic disease management[38]. The ability to electronically control drug release allows physicians to adjust dosing schedules remotely and may enable personalized pharmacotherapy based on physiologic monitoring data. Such technologies may have particular relevance for transplant medicine, where precise titration of immunosuppressive therapy is essential for balancing rejection risk against drug toxicity[39].

3.2. Implantable biosensors and microfluidic platforms

Implantable biosensors represent a rapidly expanding field within biomedical engineering. These devices incorporate microelectromechanical sensors capable of detecting physiologic signals such as pressure, oxygen concentration, metabolic metabolites, or inflammatory biomarkers. Advances in microfabrication techniques have enabled the development of sensors with extremely small dimensions, allowing implantation within vascular structures, organs, or engineered tissue constructs[40,41].

Microfluidic technologies further enhance the capabilities of implantable biosensors by enabling continuous sampling and analysis of biological fluids. Particularly, microfluidic channels integrated within implantable devices can analyze biomarkers in blood, interstitial fluid, or lymphatic fluid, potentially enabling real-time monitoring of disease processes at the molecular level[42].

Such technologies have the potential to transform clinical monitoring by shifting from intermittent laboratory testing toward continuous physiologic surveillance. Indeed, early detection of biochemical changes may allow clinicians to intervene before the onset of overt clinical deterioration.

A recent computational framework combining IoT-enabled implantable biosensors with CNN classification demonstrated 97.2% accuracy in distinguishing cancer biomarker patterns (including HER2 and CEA), illustrating how AI-integrated sensing could extend beyond cardiothoracic applications into oncologic surveillance, though this proof-of-concept has not yet been validated in fabricated devices or patients[43].

As with neural interfaces, implantable drug-delivery microchips carry limitations that warrant explicit acknowledgment. Most current designs use a fixed drug reservoir and are single-use, requiring surgical removal and replacement once the reservoir is depleted, which limits their suitability for indefinite chronic therapy. Fibrotic capsule formation around the implanted device is a further, well-documented problem, progressively impeding drug diffusion into surrounding tissue and altering release kinetics in ways that are difficult to predict prospectively[44].

Refillable and antifibrotic-coated designs are under active development, but none has yet reached routine clinical use in cardiothoracic practice. Compared with conventional systemic pharmacotherapy, implantable microchips offer more precise, programmable, and localized dosing, but at the cost of a surgical implantation procedure, a finite device lifespan, and a substantially higher unit cost; for most cardiothoracic indications where oral or intravenous therapy remains effective, this trade-off has not yet been shown to justify routine adoption outside investigational settings[38,44].

Taken together, the neural interface, biosensing, and drug-delivery technologies described above represent the core technological building blocks from which cardiothoracic-specific intelligent implants are assembled. Neurostimulation platforms provide mechanisms for autonomic and pain modulation; implantable

Table 2. Current intelligent implant applications in cardiothoracic surgery

Application	Implant type	Timing	AI integration	Clinical objective
Rhythm management	Leadless pacemaker	Long-term postoperative management	Arrhythmia discrimination	Prevent bradyarrhythmia
Sudden death prevention	Subcutaneous ICD	Long-term postoperative management	Shock optimization algorithms	Avoid inappropriate shocks
Heart failure	PA pressure sensor	Long-term postoperative management	Predictive decompensation modeling	Early intervention
Mechanical support	LVAD embedded sensors	Long-term postoperative management	Flow and thrombosis detection	Optimize circulatory support
Transplantation	Biosensor platforms	Long-term postoperative management	Rejection biomarker detection	Early graft surveillance
Valve deployment guidance[46,47]	Sensor-integrated delivery catheter	Intraoperative	Positional/apposition feedback	Reduce malposition and paravalvular leak
Graft flow assessment[48]	Transit-time flow probe	Intraoperative	Flow/PI pattern recognition	Detect inadequate anastomosis intraoperatively
Airway anastomosis surveillance[49,50]	Implantable tissue-oximetry probe	Early postoperative surveillance	Perfusion trend analysis	Flag impending bronchial dehiscence
Esophageal anastomotic leak[51]	Peri-anastomotic microdialysis probe	Early postoperative surveillance	Lactate trend pattern recognition	Early leak warning before clinical onset

LVAD: Left ventricular assist device; ICD: implantable cardioverter-defibrillator.

biosensors provide the continuous physiologic sensing layer needed to detect deterioration before it becomes clinically overt; and programmable drug-delivery microchips provide a localized, adjustable therapeutic effector. The remainder of this review examines how these building blocks have been combined, individually and in tandem, into the cardiac rhythm management devices, hemodynamic monitors, mechanical circulatory support systems, and structural, thoracic, and transplant applications that define the current state of intelligent implants in cardiothoracic surgery.

3.3. Cardiothoracic applications

The cardiothoracic domain represents one of the most mature and clinically impactful applications of implantable microelectronic technologies across cardiothoracic surgery. Cardiac rhythm management devices remain among the most widely used implantable electronic systems. Contemporary pacemakers and ICDs incorporate advanced sensing algorithms capable of detecting complex arrhythmias and delivering targeted therapy through pacing or defibrillation[45], as summarized in Table 2. Leadless pacemakers have further reduced device complexity by eliminating transvenous leads and generator pockets while maintaining effective pacing capability[23].

AI has increasingly been integrated into arrhythmia detection algorithms to improve diagnostic accuracy[52,53]. CNNs and LSTM networks have been among the most widely adopted deep-learning architectures for this task, extracting both morphological features (e.g., QRS width, intracardiac electrogram amplitude, and slew rate) and temporal features (e.g., RR-interval dynamics and heart-rate variability), to distinguish pathologic ventricular arrhythmias from supraventricular rhythms or benign electrical noise[54-56]. Transformer-based architectures, which apply multi-head self-attention to capture long-range dependencies across the full signal window, have recently emerged as a promising next-generation approach for long-sequence rhythm classification, with several recent studies reporting improved performance in complex arrhythmia classification[52,57].

Another important milestone in implantable microelectronics has been the emergence of remote physiologic monitoring systems. Wireless pulmonary artery pressure sensors enable continuous hemodynamic

surveillance in patients with heart failure by transmitting pressure measurements from an implanted sensor directly to clinicians. In the pivotal CHAMPION trial, this pressure-guided management strategy reduced heart failure hospitalizations by 39% compared with standard care over a mean follow-up of 15 months, and subsequent large real-world post-approval registry data have confirmed a similarly substantial reduction in hospitalization rates outside the trial setting[16-18]. Continuous hemodynamic surveillance enables earlier identification of physiologic deterioration, allowing proactive therapeutic adjustments before overt clinical decompensation and hospitalization occur.

Mechanical circulatory support systems also incorporate extensive microelectronic integration. Modern LVADs rely on embedded sensors and control algorithms to regulate pump speed, maintain physiologic flow conditions, and detect abnormal operating states such as suction events or thrombosis[58,59]. These systems represent an early example of closed-loop bioelectronic therapy in cardiovascular medicine.

Emerging applications extend into structural heart interventions. Sensor-integrated prosthetic valves and grafts are being investigated as a means of monitoring hemodynamic performance and detecting early structural deterioration[60,61].

Beyond post-implant surveillance, intelligent implants are also beginning to inform the surgical act itself. Sensor-integrated delivery catheters that combine intravascular ultrasound or impedance sensing with the valve-deployment mechanism can provide real-time positional and apposition feedback during transcatheter valve implantation, complementing angiographic guidance and potentially reducing malpositioning and paravalvular leak, which remain among the most common intraprocedural complications of transcatheter valve replacement[46].

Intraoperative graft assessment represents another distinctly surgical, rather than cardiological, application. Transit-time flow measurement is used at the time of coronary artery bypass grafting to quantify mean graft flow, pulsatility index, and diastolic filling, allowing the surgeon to identify technically inadequate anastomosis or graft spasm before chest closure, when revision is still straightforward. Embedding this flow-sensing capability directly into the graft or anastomotic site, with automated pattern recognition to flag values associated with early graft failure, would extend a well-established intraoperative quality-assessment tool into a continuous, AI-supported perioperative monitoring system[48].

Thoracic surgery and transplant medicine are also entering a phase of rapid technological evolution driven by advances in implantable bioelectronics. Implantable sensing platforms capable of monitoring biochemical and physiologic signals may enable earlier identification of complications such as graft dysfunction, infection, or tumor recurrence[8,62]. In parallel, implantable microfluidic technologies are being explored for localized therapeutic delivery, potentially allowing more precise administration of immunomodulatory or anticancer agents[63,64]. Future biohybrid approaches may combine engineered tissues with integrated sensing technologies, creating constructs capable of continuously assessing tissue function and viability after implantation[65].

Two further surgical scenarios illustrate the translational gap that intelligent implants could close. First, healing of the bronchial anastomosis has long been considered the Achilles' heel of lung transplantation: the donor bronchus loses its systemic arterial supply at the time of transplant, and airway complications, including anastomotic dehiscence, affect a substantial proportion of recipients, most often in the first weeks after surgery when bronchoscopic surveillance remains the primary monitoring tool[66]. Continuous microvascular perfusion sensing technologies developed for free-flap monitoring in reconstructive surgery, such as implantable or attached tissue-oximetry probes[50], represent a directly analogous engineering

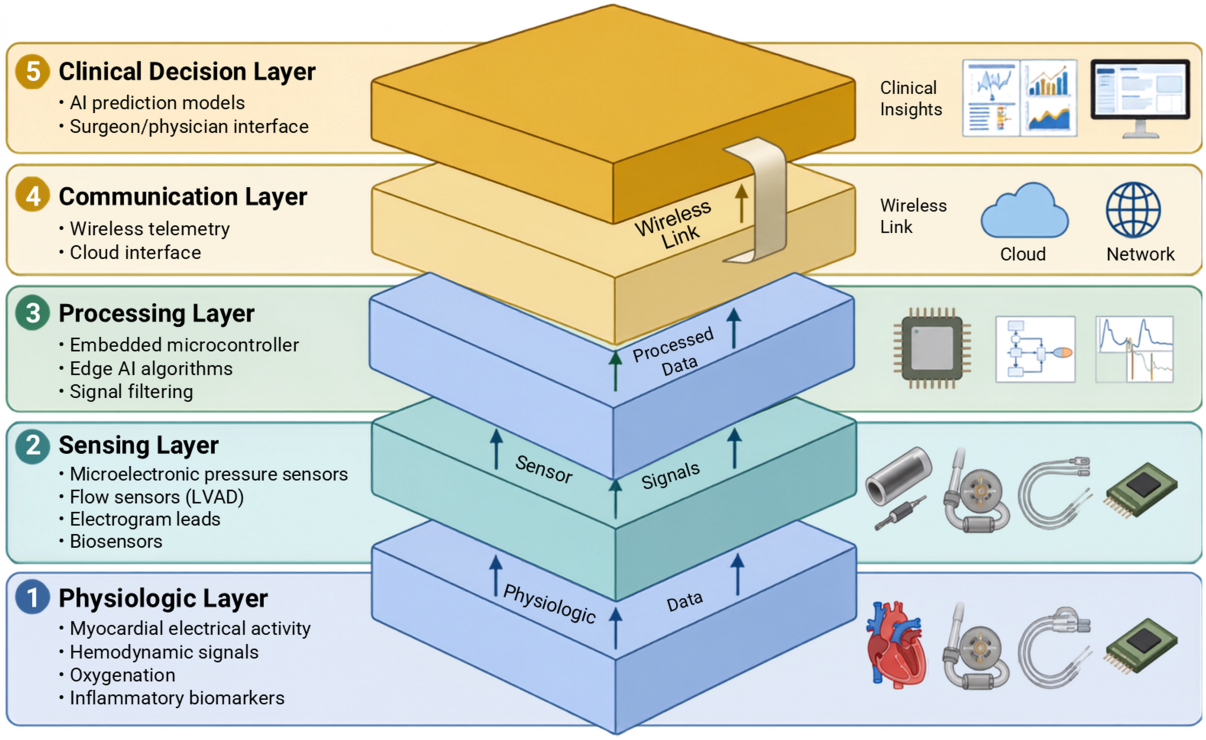

Figure 2. Architecture of an intelligent cardiothoracic implant ecosystem. AI: Artificial intelligence; LVAD: left ventricular assist device.

solution that has not yet been adapted to the bronchial anastomosis, where early perfusion data could flag impending ischemia before endoscopic or radiographic signs appear[66,67].

Second, esophagogastric anastomotic leak remains one of the most feared complications of esophagectomy, with delayed clinical recognition contributing substantially to morbidity and mortality. Peri-anastomotic microdialysis probes, placed on both the esophageal and gastric sides of the anastomosis to sample local tissue lactate in real time, have already been used in esophagectomy patients and can flag the metabolic signature of impaired perfusion before a leak becomes clinically or radiographically apparent[51].

Beyond implantable sensing, AI is also beginning to influence postoperative therapeutic management in lung transplantation. Although current AI applications predominantly focus on predictive analytics rather than implantable systems, recent LSTM-based models have demonstrated accurate forecasting of individualized tacrolimus dosing requirements in lung transplant recipients, illustrating how AI-guided therapeutic decision-making could ultimately be integrated with continuous implantable biosensing to enable closed-loop immunosuppressive management following lung transplantation[68].

4. AI AS AN ENABLING LAYER

AI represents a critical technological layer transforming implantable microelectronic systems from passive therapeutic devices into adaptive physiologic interfaces. Figure 2 illustrates how AI enhances signal interpretation and therapeutic decision-making within implantable cardiac devices. Implantable cardiovascular devices generate large volumes of high-frequency physiologic data, including intracardiac electrograms, hemodynamic pressure signals, device performance metrics, and patient activity patterns. Traditional rule-based algorithms embedded in early implantable devices relied on predetermined thresholds to detect arrhythmias or trigger therapy[53].

In contrast, contemporary ML approaches enable more sophisticated pattern recognition, predictive modeling, and dynamic therapeutic modulation based on continuously evolving physiologic signals[55]. In cardiac rhythm management, AI has been applied to improve arrhythmia discrimination algorithms within ICDs and pacemakers[52]. ML models trained on large datasets of intracardiac electrograms can distinguish ventricular tachyarrhythmias from supraventricular rhythms or electrical noise with greater accuracy than earlier rule-based systems[54]. Improved arrhythmia classification has the potential to reduce inappropriate shocks and optimize device-mediated therapy delivery, a critical consideration given the psychological and physiologic consequences of unnecessary defibrillation therapy[69].

AI also enables predictive modeling in heart failure management using data streams derived from implantable hemodynamic sensors. Continuous pulmonary artery pressure monitoring systems provide granular hemodynamic measurements that can be integrated into predictive algorithms capable of identifying early physiologic deterioration before the onset of symptomatic decompensation[70]. Clinical trials evaluating pulmonary artery pressure-guided management strategies have demonstrated reductions in heart failure hospitalization when therapy is adjusted according to implant-derived hemodynamic data[16,71].

Mechanical circulatory support systems represent another domain in which AI may enable adaptive device control. Modern LVADs incorporate multiple sensors that monitor pump speed, motor current, pressure gradients, and flow characteristics[58]. Integration of ML algorithms into device controllers may allow automated detection of pump thrombosis, suction events, or hemodynamic instability, enabling real-time adjustments in pump performance[19]. Such adaptive control systems may represent an early example of closed-loop cardiovascular bioelectronics in which physiologic sensing directly modulates device therapy.

The computational architecture supporting AI-enabled implants may be distributed across multiple layers. Edge computing strategies incorporate lightweight algorithms directly within implantable hardware to enable real-time decision making without external data transmission[72]. Alternatively, cloud-based analytic platforms can process larger datasets derived from multiple implantable devices across patient populations, allowing development of predictive models that can be updated over time and deployed across device networks[73].

Human-AI interaction remains a central consideration in the deployment of intelligent implants. While automated algorithms can process physiologic data at a scale and speed beyond human capacity, clinical oversight remains essential for interpreting algorithmic outputs and integrating them within the broader context of patient care. As implantable devices increasingly incorporate autonomous or semi-autonomous decision-making capabilities, the relationship between algorithmic control and physician supervision will become a defining feature of future bioelectronic medicine[20].

5. ENGINEERING AND BIOLOGICAL BARRIERS

Despite rapid technological progress, the development of long-term implantable microchip systems remains constrained by multiple engineering and biological challenges, which are summarized together with their underlying mechanisms and clinical consequences in Table 3. Biocompatibility represents one of the most fundamental limitations[74]. Implantable devices inevitably trigger a foreign body response characterized by inflammatory cell recruitment, fibrotic encapsulation, and tissue remodeling around the device interface. Fibrotic capsule formation can interfere with sensor performance by altering analyte diffusion or attenuating physiologic signals, thereby reducing the accuracy of implantable biosensors[75].

Mitigation strategies are an active area of investigation: antifibrotic-coated devices, such as the tranilast-eluting microchannel systems described earlier[44], and zwitterionic hydrogel coatings that resist protein

Table 3. Engineering and biological constraints in cardiothoracic intelligent implants

Challenge	Mechanism	Clinical consequence
Fibrotic encapsulation[74,75]	Foreign body response	Reduced sensor accuracy
Power limitation[76,77]	Battery constraints	Limited longevity
Mechanical stress[78,79]	Cardiac motion	Device fatigue/failure
Cybersecurity[80-82]	Wireless vulnerability	Malicious interference risk
Data overload[83,84]	High-frequency streams	Interpretability challenges

adsorption and cellular attachment have demonstrated promising reductions in fibrotic capsule formation in preclinical studies, with one recent study reporting over a 60% reduction in capsule thickness compared with an uncoated surface[85].

The dynamic mechanical environment of the thoracic cavity introduces additional challenges for device durability. The heart undergoes continuous cyclic motion, generating mechanical stress on implanted hardware and electrical leads. Repetitive mechanical forces can contribute to device fatigue, lead fracture, insulation degradation, and sensor drift over time[78]. Advances in flexible electronics and polymeric encapsulation materials aim to improve device resilience in high-motion biologic environments[79].

Power supply and energy transfer remain central engineering constraints in implantable microelectronics. Traditional implantable cardiac devices rely on lithium-based batteries with limited operational lifespan, necessitating periodic device replacement procedures[76]. Alternative strategies including wireless power transfer, inductive coupling, and energy harvesting from physiologic motion are under investigation as potential methods for extending device longevity[77]. Fully implantable systems, such as total artificial hearts, have demonstrated the feasibility of transcutaneous energy transfer systems capable of recharging internal batteries without transcutaneous wires, thereby reducing infection risk[86].

Cybersecurity represents an increasingly important consideration as implantable devices become connected to external monitoring networks. Modern implantable cardiac devices incorporate wireless communication systems that allow remote monitoring and device reprogramming. Although these features enhance clinical management, they also introduce potential vulnerabilities to unauthorized access or malicious interference. Theoretical studies have demonstrated that ICDs could potentially be subjected to remote reprogramming attacks capable of altering therapy parameters or inducing inappropriate shocks if adequate security protections are not implemented[80]. More recent countermeasures have moved beyond encryption alone: body-coupled communication techniques confine wireless signals to conduction through the tissue itself rather than open-air radiofrequency transmission, reducing the effective interception range from several meters to roughly a centimeter from the skin[81]. Lightweight authentication protocols tailored to the power and processing constraints of implantable hardware are being developed to secure device-reprogramming commands without exceeding a device's limited energy budget[82].

Another critical challenge lies in interpreting the large volumes of physiologic data generated by implantable systems. Continuous monitoring devices can produce vast datasets that may overwhelm conventional clinical workflows if not appropriately filtered and interpreted[83]. AI may help address this challenge by identifying clinically meaningful patterns within large physiologic datasets, but the development of robust algorithms capable of operating reliably across diverse patient populations remains an active area of research[84].

Table 4. Ethical and regulatory considerations in AI-integrated implantable devices

Domain	Key issue	Implication
Data ownership[87,88]	Continuous physiologic surveillance	Privacy concerns
Autonomy[89]	AI-driven therapeutic decisions	Reduced human oversight
Transparency[90]	Algorithm interpretability	Trust and accountability
Regulation[90]	Adaptive AI approval pathways	Evolving oversight models
Enhancement[91]	Beyond-therapeutic applications	Ethical boundary ambiguity

AI: Artificial intelligence.

6. ETHICAL AND REGULATORY CONSIDERATIONS

The integration of intelligent implantable microchips into human physiology raises complex ethical and regulatory considerations, including issues related to data governance, patient autonomy, algorithmic transparency, and regulatory oversight, as summarized in Table 4. Continuous physiologic monitoring generates detailed personal health data that may include information about cardiac rhythm, hemodynamic status, physical activity patterns, and other physiologic parameters. Determining ownership and governance of these data represents a major ethical challenge. Patients, healthcare providers, device manufacturers, and digital health platforms may all have potential interests in accessing and analyzing implant-derived data[87].

This challenge is compounded by the fact that existing governance frameworks may not yet be adequate to the task: a 2025 survey of healthcare, IT, and blockchain professionals evaluating ISO, GDPR, and HIPAA compliance mechanisms found persistent dissatisfaction with their effectiveness across data encryption, access control, audit trails, and consent management, suggesting that regulatory frameworks designed for conventional electronic health records may require substantial adaptation for continuously streaming, implant-derived physiologic data[88]. Unlike a single clinical encounter, an implantable device generates a persistent data stream whose ownership, secondary use, and commercial value remain unresolved questions that current health-data law addresses only partially.

Autonomy represents another important ethical dimension in the context of closed-loop implantable systems. Devices capable of automatically adjusting therapy based on physiologic inputs introduce a degree of algorithmic control over patient physiology. While such automation may improve therapeutic precision, it also raises questions about the appropriate balance between automated device function and human decision-making authority. For example, ICDs deliver potentially life-saving but painful shocks in response to detected arrhythmias, and the criteria used by device algorithms to trigger therapy must be carefully validated and clinically justified[89].

Transparency of AI algorithms is particularly important for life-sustaining devices such as pacemakers, ventricular assist devices, and defibrillators. Clinicians must be able to understand the operational logic of algorithms that influence therapeutic decisions, particularly when these systems operate autonomously within the body. Regulatory frameworks for medical devices have historically been designed around static hardware and software configurations[90]. Adaptive ML algorithms that evolve over time pose new regulatory challenges because their behavior may change as additional data are incorporated into training models.

The distinction between therapeutic and enhancement applications also warrants ethical consideration. Implantable microelectronic technologies developed for medical treatment may potentially be adapted for human enhancement applications, including augmentation of cognitive performance, physical endurance, or sensory perception[91]. The ethical boundaries governing such applications remain the subject of ongoing debate within bioethics and regulatory policy.

7. TOWARD BIOHYBRID AND INTELLIGENT CARDIOTHORACIC SYSTEMS

Emerging developments in tissue engineering, bioelectronics, and AI are beginning to converge toward the concept of biohybrid cardiothoracic systems[92]. These platforms combine living biological tissues with embedded electronic sensing and control systems capable of monitoring physiologic function in real time. One example involves engineered myocardial patches designed to repair damaged cardiac tissue following myocardial infarction[93]. Integration of microelectronic sensors within such constructs could enable continuous monitoring of electrical activity, contractile function, and metabolic status within engineered tissues.

Similarly, tissue-engineered vascular grafts and prosthetic conduits may eventually incorporate embedded sensors capable of detecting flow dynamics, pressure gradients, or early structural degeneration[94]. Such "smart grafts" could provide early warning signals indicating graft failure, thrombosis, or infection before clinical symptoms emerge.

Neuromorphic implants represent another emerging frontier. These devices are designed to mimic neural architectures and may enable advanced forms of autonomic neuromodulation for cardiovascular disease. Modulation of vagal or sympathetic neural pathways has been explored as a therapeutic strategy for heart failure and arrhythmias, and implantable neuromorphic systems could potentially enable more precise control of autonomic cardiac regulation[95,96].

Another transformative concept involves the development of digital twins of the cardiovascular system. Digital twins are computational models that simulate the physiologic behavior of individual patients using real-time physiologic data streams. Implantable sensors could continuously feed physiologic data into patient-specific digital models, allowing predictive simulation of disease progression and therapeutic responses[97]. Such integrated systems could eventually allow clinicians to test therapeutic strategies within computational simulations before implementing them *in vivo*.

Distributed implant ecosystems may ultimately represent the next stage of bioelectronics medicine. Instead of relying on single implantable devices, future systems may consist of networks of interconnected micro-sensors distributed throughout the myocardium, vasculature, and thoracic organs[98]. These sensor networks could collectively monitor physiologic parameters and coordinate therapeutic responses through integrated computational platforms.

8. FUTURE RESEARCH AGENDA

The barriers outlined above - fibrotic encapsulation, power limitation, mechanical stress, cybersecurity vulnerability, and data overload on the engineering side [Table 3], and data ownership, algorithmic transparency, and adaptive regulatory pathways on the ethical side [Table 4] - define the priorities for the research agenda that follows. Rather than representing an independent set of technological aspirations, the directions below are framed explicitly as responses to these constraints.

Future research in intelligent cardiothoracic implants will likely focus on developing integrated therapeutic systems capable of continuously sensing physiologic signals, interpreting these data through advanced computational methods, and delivering adaptive therapeutic responses. Achieving this will require concurrent progress on the power-limitation and mechanical-stress constraints identified in Table 3, since closed-loop responsiveness is only clinically useful if the underlying device can sustain years of reliable operation in a moving thoracic field. Such systems aim to move beyond passive monitoring toward closed-loop platforms in which physiologic information directly informs therapeutic adjustments, enabling more

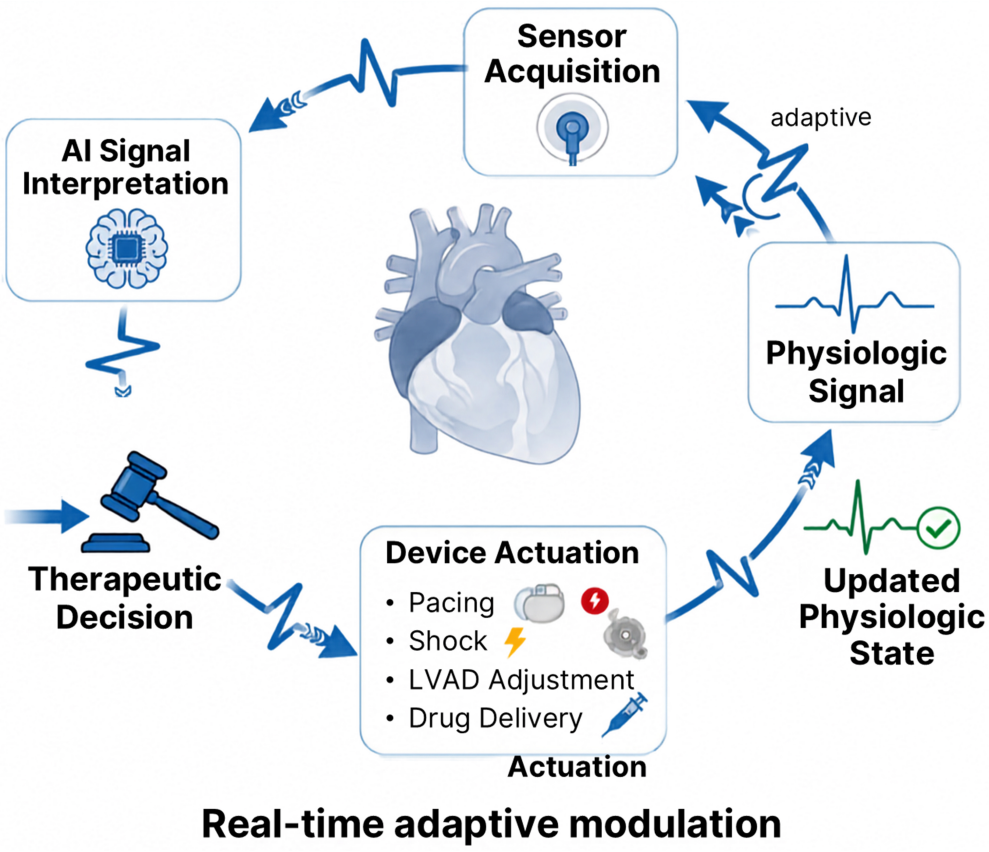

Figure 3. Closed-loop therapeutic control in AI-enhanced cardiac devices. AI: Artificial intelligence; LVAD: left ventricular assist device.

responsive and individualized disease management. Figure 3 depicts the closed-loop architecture linking physiologic sensing, AI-based data interpretation, and adaptive therapeutic intervention.

Another important research direction involves expanding the use of implantable biosensing technologies for the early detection of pathophysiologic changes within cardiovascular and thoracic systems. Progress here is contingent on mitigating fibrotic encapsulation, the mechanism identified in Table 3 as the principal driver of declining sensor accuracy over time; without durable sensor-tissue interfaces, expanded biosensing coverage will not translate into reliable long-term data. Coupling these sensing capabilities with programmable therapeutic platforms may allow dynamic adjustment of treatment strategies based on real-time biologic feedback.

Advances in sensing technologies and computational analytics may also enhance the safety and performance of implantable therapeutic devices by enabling earlier identification of device-related complications and physiologic instability[53,99]. These same analytic pipelines must be designed against the cybersecurity vulnerabilities and data-overload/interpretability challenges flagged in Table 3, since a system that improves complication detection while introducing a wireless attack surface or an uninterpretable alert burden would trade one clinical risk for another. Improved integration of physiologic monitoring with device control systems could support more precise regulation of therapeutic function and reduce the incidence of adverse events associated with long-term implantable support technologies.

As the number and complexity of implantable devices increase, the development of standardized communication frameworks will become increasingly important. Interoperability at this scale directly raises the data-ownership and regulatory questions summarized in Table 4: cross-device data sharing multiplies the

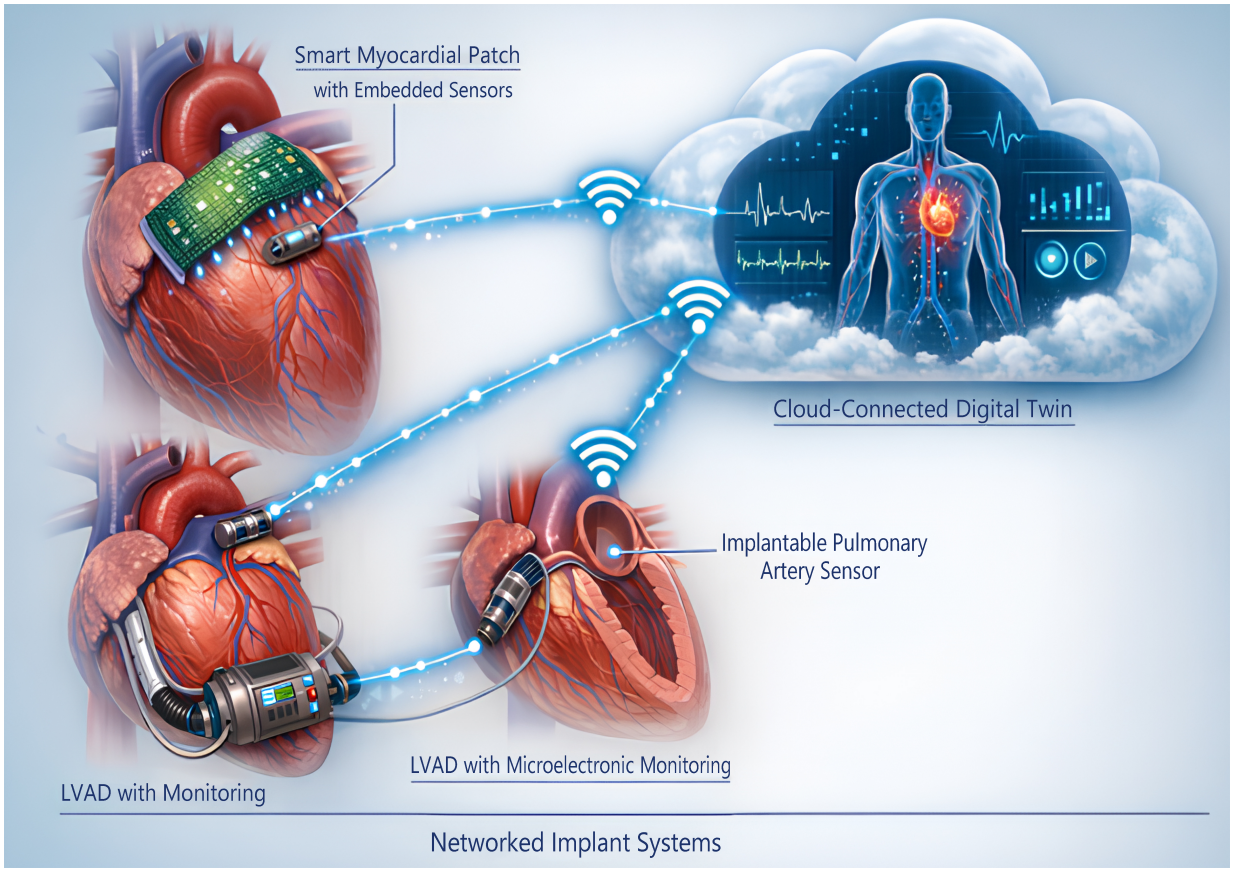

Figure 4. Future paradigm: biohybrid and distributed implant networks. LVAD: Left ventricular assist device.

number of parties with access to continuous physiologic surveillance, and current adaptive-AI approval pathways were not designed with multi-device ecosystems in mind. Interoperable systems capable of exchanging physiologic data across multiple devices and external monitoring platforms may enable coordinated networks of implantable technologies that collectively support patient monitoring and therapy, Figure 4 summarizes the future vision of biohybrid, interconnected implant networks supporting precision cardiothoracic care.

9. CONCLUSION

Redefining the human-technology boundary: The integration of intelligent microelectronic implants into human physiology is redefining the relationship between medicine, technology, and the human body. In cardiothoracic surgery, implantable electronic devices have substantially advanced the management of arrhythmias, heart failure, and advanced cardiac disease. Continued advances in microelectronics, biosensing technologies, wireless communication, and AI are expanding the capabilities of these systems far beyond traditional therapeutic paradigms.

The transition from episodic surgical intervention toward continuous physiologic interaction represents a fundamental shift in the practice of cardiovascular medicine. Implantable devices are evolving from isolated hardware components into integrated physiologic interfaces capable of sensing, interpreting, and modulating biologic function in real time. AI further accelerates this transformation by enabling adaptive therapeutic systems that can respond dynamically to complex physiologic signals.

As these technologies continue to mature, the role of the cardiothoracic surgeon will extend beyond device implantation toward participation in the multidisciplinary development of intelligent bioelectronic systems. Collaboration among surgeons, engineers, computer scientists, and bioethicists will be essential for ensuring that these technologies are deployed safely, ethically, and effectively.

Ultimately, intelligent implants may redefine the boundaries between human physiology and digital technology, enabling a future in which cardiovascular care is increasingly personalized, predictive, and continuously integrated with advanced bioelectronic systems.

DECLARATIONS

Authors' contributions

Conceptualization, methodology, validation, investigation, writing - original draft, writing - review and editing, project administration: Baudo, M.
Methodology, validation, investigation, writing - original draft, writing - review and editing, visualization: Rahouma, M.
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Investigation, literature review, writing - review and editing, assistance in preparing responses to reviewers, manuscript editing, approval of the final manuscript: Mansour, M. H.
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Conceptualization, methodology, validation, investigation, resources, writing - original draft, writing - review and editing, supervision, project administration: Rahouma, M.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, Google Gemini 2.5 Flash Image (Nano Banana), released August 26, 2025, was used to assist the authors in generating and refining visual elements of Figures 1-4. Figures 1-3 were composed and finalized by the authors, with selected individual visual elements generated with assistance from Google Gemini. Figure 4 was also prepared by the authors with assistance from Google Gemini. The Graphical Abstract was created entirely by the authors using Microsoft PowerPoint, including icons from PowerPoint's built-in icon library. No icons or graphical elements used in Figures 1-3 were obtained from third-party icon libraries or stock image platforms. The AI tool was used solely for visual/graphic assistance and did not influence the study design, data collection, analysis, interpretation, or scientific content of the work. All authors reviewed and approved the final figures and take full responsibility for their accuracy, integrity, and final content.

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Conflict of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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