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Review

Magnetic Field-Based Intervention in Cardiovascular Diseases: Biological Basis, Therapeutic Strategies, and Translational Challenges

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Abstract: Cardiovascular diseases remain the leading cause of death worldwide, and their burden continues to rise. As a noninvasive physical intervention, magnetic fields offer deep tissue penetration, remote programmability, and favorable spatiotemporal controllability, making them uniquely valuable for modulating cardiovascular function. This review systematically summarizes the biological basis of magnetic field actions on the cardiovascular system, including multi-scale effects on cardiac electrophysiology and ion channels, vascular endothelial function and microcirculatory perfusion, and cardiac autonomic regulation. On this basis, we synthesize therapeutic advances in three areas: electrophysiological intervention in arrhythmias, cardiac autonomic neuromodulation, and cardiac repair and regeneration. Preclinical evidence indicates that magnetic fields can mediate nonpharmacological intervention in arrhythmias, myocardial infarction, and heart failure, although clinical validation to date is limited to a single small randomized trial. Finally, we analyze translational bottlenecks (standardization of stimulation parameters, long-term in vivo safety assessment, and intelligent closed-loop control) and outline future directions integrating magnetic fields with regenerative medicine and artificial intelligence, aiming to provide new strategies for precision cardiovascular care.

Keywords: magnetic field; cardiovascular disease; autonomic neuromodulation; cardiac electrophysiology; cardiac repair

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1. Introduction

Cardiovascular diseases remain the leading cause of death and disability globally, and their burden continues to grow with population aging and the rising prevalence of metabolic risk factors. Conventional pharmacotherapy is limited by systemic toxicity and drug resistance, while surgery and interventional procedures cannot fully avoid postoperative complications and irreversible tissue injury. There is therefore an urgent need for noninvasive, tunable interventions. The cardiac autonomic nervous system maintains electrophysiological homeostasis through the dynamic balance between sympathetic and parasympathetic activity; under pathological conditions such as myocardial infarction (MI) and heart failure (HF), excessive sympathetic activation together with reduced vagal function constitutes the core substrate for malignant arrhythmias and sudden cardiac death [1,2]. Although device-based neuromodulation has entered clinical practice, it has long been constrained by unstable electrode–tissue interfaces, poor target specificity, and highly variable stimulation parameters [3].

As a noninvasive physical field, magnetic fields combine deep penetration, wireless remote delivery, and programmable spatiotemporal parameters. In recent years, integrated with magnetic-responsive nanomaterials and magnetoelectric transducing

structures, they have enabled a cross-scale "magnetic field–magnetic-responsive material–biological tissue" control paradigm [4]. Compared with highly mature electric-field strategies such as pulsed field ablation (PFA), magnetic intervention emphasizes reversible, remote modulation of function rather than structural destruction of tissue, and thus occupies a distinctive niche in autonomic rebalancing and cardiac repair. Earlier reviews of electromagnetic-field cardiovascular therapy have emphasized device patents and direct field effects [5]; building on this work, the present review centers on the materials-mediated, multi-scale pathway that has emerged over the past five years. Along two lines, namely the biological basis of magnetic field action on the cardiovascular system and its therapeutic applications, this review synthesizes recent progress and discusses the key issues in translating these findings from bench to bedside.

2. Biological Basis of Magnetic Field Actions on the Cardiovascular System

The cardiovascular effects of magnetic fields are not mediated by a single pathway but arise through multiple layers, including ion channel gating, vascular endothelial protection, and autonomic regulation. Understanding these mechanisms is a prerequisite for rational design of magnetic interventions. Throughout, it is useful to distinguish direct fields applied without magnetic-responsive materials, whose cardiovascular effects are generally weak, dose-dependent, and poorly reproducible, from fields acting through magnetic-responsive transducers (magnetic nanoparticles, magnetoelectric and magnetostrictive structures), which underpin most of the strong and specific effects discussed below.

2.1. Cardiac Electrophysiology and Ion Channel Modulation

Cardiac electrophysiology relies on the coordinated opening and closing of sodium, potassium, and calcium channels. Electromagnetic fields can modulate these channels in a frequency- and amplitude-dependent manner, thereby altering action-potential morphology and calcium-transient characteristics. Extremely low-frequency electromagnetic fields (15 Hz, 2 mT) have been reported to enhance sarcolemmal Na+/Ca2+ exchange and upregulate the sarcoplasmic/endoplasmic reticulum calcium ATPase, increasing calcium-transient frequency by approximately 57% and baseline calcium by approximately 9%, while decreasing transient amplitude by approximately 40%, producing a complex biphasic effect on excitation–contraction coupling [6]. At the molecular-simulation level, terahertz fields of specific frequencies alter ion permeation through sodium channels and differentially modulate the conductance of the potassium channel Kv1.2 and the sodium channel Nav1.5, suggesting selectivity among channel subtypes [7]. Complementing field-based modulation, vesicle-fusion-engineered artificial potassium channels can be inserted into cardiomyocytes to replace dysfunctional native K+ channels and restore abnormal action potentials, offering a non-field engineering route to repair electrical activity [8]. Mixed-frequency magnetic radiation can shift the discharge mode of cardiomyocytes from spiking to bursting and even to a resting state, offering a physical means of resetting electrical homeostasis [9].

Magneto-mechanical signal transduction represents a major mechanistic advance. Under an applied alternating magnetic field, highly anisotropic magnetic nanostructures generate nanonewton-scale mechanical forces at the local membrane, triggering Ca2+ influx through mechanosensitive ion channels [10]. Within a weak-field window of 12–56 mT and 5–125 Hz, magnetite nanodiscs can trigger transmembrane calcium entry, intracellular calcium-store release, and store-operated calcium entry simultaneously, without requiring exogenous mechanosensory genes, and evoke characteristic calcium transients in cell types as mechanistically diverse as cardiomyocytes and hippocampal astrocytes [10]. Pharmacological dissection indicates that the response depends on an intact actin cytoskeleton and that the relative contribution of each calcium source differs across cell types, implying that magneto-mechanical forces act through a ubiquitous mechanotransduction chain; the specific contribution of channels such as Piezo1 remains to be confirmed in overexpression or knockdown models [10]. Remote magnetic activation

of spinal TRPV1 by magnetic nanocubes confers protection against myocardial ischemia–reperfusion (I/R) injury [11], while parallel mechanical forces generated by intracellular nanomagnets can durably shift the synchronized state of neuronal networks, suggesting plasticity that extends beyond immediate effects [12].

The intrinsic cardiac nervous system (ICNS) is not a homogeneous responder. Immunohistochemistry and patch-clamp studies have revealed neuronal subpopulations, including calbindin-D28k-positive neurons, that fall into several electrophysiological classes with distinct firing patterns, ion-channel dependence, and response thresholds to magnetically induced calcium influx [13]. The precision of magnetic regulation therefore depends not only on field strength and frequency but also on matching stimulation parameters to the intrinsic firing rhythm of target neurons, exploiting stochastic resonance or phase locking to enhance coupling efficiency and achieve stable functional modulation at lower energy. In addition, repeated intermittent magnetothermal priming can desensitize spinal TRPV1, reducing dorsal-root release of substance P and calcitonin gene-related peptide and suppressing cardiac sympathetic outflow, thereby attenuating I/R injury [11]. Together, these findings show that magnetic fields act not only directly on ion channels but also, through magnetic-responsive materials, by converting energy into membrane forces that indirectly reshape cardiac electrophysiology at the cellular-subtype level.

2.2. Vascular Endothelial Function and Microcirculatory Protection

The endothelial barrier and microcirculatory perfusion are central to myocardial blood supply and represent another important target of magnetic protection. Low-frequency magnetic fields attenuate myocardial I/R injury by scavenging reactive oxygen species (ROS) and modulating the nitric oxide (NO) pathway: in I/R models, magnetic exposure reduced cardiac-enzyme release and infarct size, accompanied by elevated NO bioavailability and suppressed formation of peroxynitrite ($ONOO^-$), indicating that protection is tied to the NO/$ONOO^-$ oxidative–nitrosative balance rather than to a purely thermal effect [14]. This dual antioxidant–vasodilator mechanism overlaps partly with the pathways of clinical ischemic preconditioning. Importantly, magnetic biological effects do not arise only from "actively applied" fields: under zero-field (magnetically shielded) conditions, measurable changes in blood-flow velocity and vascular tone occur, indicating that the geomagnetic background itself participates in circulatory homeostasis, explaining why findings across studies are difficult to compare given differing geomagnetic backgrounds [15]. In another comparative setting, static magnetic fields and calcium-channel blockers both modulate microcirculatory tone but act at different sites and with different kinetics: the former tends to affect endothelium-derived factor release, and the latter directly blocks smooth-muscle calcium entry. This "comparable yet distinct" comparison further demonstrates that microcirculatory regulation by magnetic fields is multi-pathway and non-single-target [16].

Magneto-mechanical forces can also alter endothelial permeability, a relatively underappreciated route by which magnetic fields affect vascular function. Reciprocating forces generated by magnetic-responsive microstructures under field exposure can reversibly pull at inter-endothelial junctions and alter tight-junction distribution and barrier integrity, with permeability changes partially recovering upon field removal, contrasting with the irreversible injury caused by electric-field ablation [17]. Methodologically, microfluidic chips allow the electrical resistance, molecular leakage, and morphology of endothelial monolayers to be assessed under precisely controlled RF/magnetic exposure doses, quantitatively linking field parameters (strength, frequency, duration) to functional changes and mitigating the prior practice of "reporting effects without reporting doses" [18]. Overall, magnetic protection and modulation of the endothelium and microcirculation proceed through three parallel routes: antioxidant effects and NO/$ONOO^-$ balance, regulation of vasoactive factors, and magneto-mechanical control of barrier permeability. These provide a cellular basis for nonpharmacological adjunctive treatment of ischemic heart disease, although current

evidence derives mostly from cultured cells and animal models, with a dearth of direct in vivo microcirculatory observations.

2.3. Cardiac Autonomic Regulation

Autonomic imbalance is a key pathophysiological feature of cardiovascular disease and the most distinctive direction of magnetic intervention. The autonomic nervous system regulates heart rate, conduction, and contractility through the dynamic balance of sympathetic and parasympathetic tone, and heart rate variability (HRV) is a commonly used index of this balance. Large population-based cohort studies indicate that phenotypically measured HRV is associated with all-cause mortality, whereas genetically predicted HRV is not, indicating that the modifiable state of autonomic balance itself carries clinical significance and providing an epidemiological rationale for interventions using HRV as a readout [19]. As described in Section 2.1, the cellular and electrophysiological heterogeneity of the ICNS provides a basis for precise, subpopulation-specific magnetic control.

Mechanistically, magnetic autonomic modulation can act through the cholinergic anti-inflammatory pathway. By enhancing acetylcholine signaling, magnetic-responsive activation engages the peripheral cholinergic anti-inflammatory axis, reducing oxidative stress and inhibiting inflammasome-mediated cell injury via pathways such as M2AChR/OGDHL/ROS [20]. Importantly, autonomic regulation occurs not only at the level of neuronal excitability but also at the synaptic microenvironment. Under myocardial ischemia or structural remodeling, local mechanical disturbance and interstitial edema can distort the synaptic cleft, causing marked dissipation of acetylcholine during diffusion and weakening vagal efficacy. Anisotropic magnetic-responsive materials undergo controlled deformation under an alternating field, exerting spatial compression on the local synaptic microenvironment, shortening the cleft and raising the local effective transmitter concentration without increasing neurotransmitter synthesis, and thereby enhancing cholinergic transmission. Repetitive magnetic stimulation can additionally induce long-term potentiation of synapses, indicating that magnetic fields produce not only immediate effects but also lasting synaptic plasticity [21]. Combined transcranial and peripheral electromagnetic stimulation can modulate autonomic function within a defined range, providing experimental support for remote modulation of the brain–heart axis [22]. Together, these findings establish that magnetic fields intervene in cardiovascular disease by rebalancing sympathovagal tone and reshaping the synaptic microenvironment.

3. Therapeutic Applications of Magnetic Field Technology in Cardiovascular Disease

Building on the above biological basis, magnetic field technology has yielded several therapeutic strategies in arrhythmias, autonomic disorders, and cardiac repair. These are discussed below by disease and intervention route.

3.1. Electrophysiological Intervention in Arrhythmias

Arrhythmias, particularly atrial fibrillation (AF) and malignant ventricular arrhythmias, are the primary targets of magnetic electrophysiological intervention. On the electric-field side, PFA, owing to its myocardial selectivity and low tissue damage, has accumulated long-term safety and efficacy data in AF, with large-sample evidence such as the MANIFEST-PF registry [23,24]; this mature electric-field strategy serves as a comparator for magnetic intervention. In contrast to structural destruction by electric fields, magnetic intervention emphasizes reversible modulation of electrical activity. Among the limited clinical evidence, a single-center, double-blind, sham-controlled randomized trial (n=26) evaluated transcutaneous magnetic stimulation (TcMS) targeted to the left stellate ganglion in ventricular tachycardia (VT) storm: its prespecified primary endpoint (freedom from sustained VT at 24 h) did not reach statistical significance, although VT episodes within 72 h were significantly reduced in the active group and some patients showed signs of sympathetic blockade, suggesting a possible role in short-term stabilization of VT storm; given the small sample, single-center design, and limited

statistical power, larger multicenter trials are required [25]. For refractory ventricular arrhythmias, device neuromodulation targeting the stellate ganglion and spinal cord has become an important nonpharmacological option, although unstable electrode interfaces and poor target specificity remain unresolved [26]. It should be emphasized that PFA now enjoys registry data encompassing more than a thousand patients, whereas magnetic intervention currently rests only on this small randomized trial; this gap in evidence hierarchy is itself a reality that the field must confront.

The autonomic nervous system plays a key role in the initiation and maintenance of arrhythmias, and the relationship between autonomic modulation and arrhythmias has been systematically reviewed [27]. For inherited channelopathies such as long-QT syndrome, Brugada syndrome, and catecholaminergic polymorphic ventricular tachycardia, invasive interventions such as conventional stellate ganglion resection carry high risk, whereas targeted autonomic magnetic regulation, by suppressing excessive sympathetic activation and raising the ventricular fibrillation threshold without invasive surgery, offers a new route to prevention of sudden cardiac death [28]. This direction reflects a shift from "ablating lesions" to "modulating networks."

3.2. Cardiac Autonomic Neuromodulation

For the autonomic imbalance seen in AF, MI, and HF, magnetic fields have generated a family of strategies aimed at functional rebalancing. Direct proof-of-concept studies showed that extremely low-level (pico-Tesla) electromagnetic fields applied to the cervical vagal trunks or non-invasively across the chest suppress ganglionated-plexi firing and reverse AF inducibility in canine models [29]. In AF, abnormal firing of the intrinsic cardiac ganglionated plexi (ICGP) and sympathovagal imbalance are central to AF initiation and maintenance, and neuroscience-guided AF therapies are emerging [30,31]. It should be noted that radiofrequency or pulsed-field ablation, which relies on irreversible tissue injury, can reduce AF burden in the short term, but long-term follow-up suggests it may disrupt local neural architecture, inducing chronic neural fibrosis and compensatory ectopic reinnervation that contribute to late recurrence. Magnetic intervention emphasizes functional rather than structural change: driving magnetoelectric transducing structures around the ganglionated plexi to generate physiological-level electrical signals can modulate local parasympathetic tone, prolong atrial effective refractory period, and suppress electrical remodeling without destroying tissue. Oral magnetoelectric structures that achieve noninvasive AF neuroimmunomodulation via the "gut–brain–spleen–heart" axis have demonstrated a new paradigm of remote, contactless neuromodulation [32]: these oral microparticles embed magnetostrictive Fe_3O_4@$BaTiO_3$ nanogenerators within a conductive PEDOT:PSS matrix and a dopamine–alginate adhesive layer, and when adhered to the gastric wall under an alternating field they generate pulsed currents that activate vagal afferents, engage brainstem autonomic circuits and the splenic cholinergic anti-inflammatory pathway, and shorten AF duration in a rat model. Compared with conventional ablation, ganglionated-plexus-targeted intervention prioritizes functional modulation over structural destruction, and electrophysiological and histologic studies of pulsed-field targeting of the plexi continue to refine its therapeutic boundaries [33,34].

In MI, excessive sympathetic activation and immune remodeling of the left superior cervical ganglion (LSCG) are closely linked to malignant ventricular arrhythmias. Animal studies have revealed lymph-node-like immune remodeling of the LSCG after infarction, accompanied by an increased number of TH-positive adrenergic neurons, smaller somata, and a time-dependent rise in inflammatory factors such as IL-1β and IL-6, providing the anatomical basis for a self-reinforcing sympathetic storm; interventional experiments show that resecting the LSCG or knocking down the NGF receptor trkA within it reverses sympathetic remodeling and improves arrhythmia susceptibility, providing causal evidence for reversing local sympathetic imbalance through neuromodulation [35]. Along these lines, injectable magnetic hydrogels that precisely stimulate the vagus nerve have been shown to accelerate cardiac repair after MI [36]; in that work, a chitosan/β-

glycerophosphate thermoresponsive hydrogel loaded with superparamagnetic iron oxide, driven at approximately 100 mT and 20 Hz, achieved selective stimulation of a single vagus nerve and, over four weeks, improved cardiac function, reduced infarct size, and suppressed inflammatory infiltration; magnetic-responsive vagal stimulation attenuates pyroptosis and I/R injury via the M2AChR/OGDHL/ROS axis [20]; wireless self-powered optogenetic systems for long-term cardiac neuromodulation likewise improve post-infarction remodeling [37]. In HF, sustained activation of the sympathetic nervous system and the renin–angiotensin–aldosterone system drives disease progression and death, producing abnormal cAMP/PKA signaling that leads to hyperphosphorylation of RyR2-associated phospholamban and disordered intracellular calcium homeostasis; the sympathetic nervous system has thus become an important therapeutic target [38]. The advantage of magnetic fields lies in rebuilding global autonomic balance through trans-system neural networks rather than acting only on local myocardium: carotid baroreceptor stimulation improves pulmonary vascular remodeling and right-ventricular dysfunction in pulmonary arterial hypertension, demonstrating noncontact control of deep autonomic structures [39]. Together, these studies show that magnetically mediated autonomic modulation acts at multiple levels: inflammation, electrophysiology, and neurohormonal regulation.

3.3. Cardiac Repair and Regeneration

After cardiac injury, intrinsic reparative capacity is limited, and magnetic field technology shows promise through magnetic-responsive materials and targeted delivery. At the cellular level, magnetic stimulation enhances the angiogenic potential of mesenchymal stromal cells in vascular tissue engineering [40], and magnetically labeled iPSC-derived extracellular vesicles enable MRI/MPI-guided targeted regenerative delivery for MI repair [41], providing a means for precise homing of cells and biologics.

At the scaffold level, smart materials such as magnetic-responsive polysaccharide hydrogels combine magnetic responsiveness with favorable biocompatibility and can serve as carriers for local delivery and coupled mechano-chemical signaling under an applied field [42]. Complementing this, a distinct class of "preneuralized" scaffolds that do not depend on magnets offers a structural-repair approach: scaffolds loaded with inorganic components such as strontium silicate sustainably release Si/Sr ions, inducing neural-stem-cell differentiation into mature neurons and forming a neuron-rich preneuralized network before implantation, thereby enhancing maturation and synchronous contraction of infarct-zone cardiomyocytes and modulating circadian-rhythm-related gene expression to improve cardiac function [43]. These bioactive-ceramic scaffolds and the magnetic-responsive materials discussed earlier represent two routes: the former relies on intrinsic ionic release to rebuild the microenvironment, and the latter on externally applied fields for remote, spatiotemporally controlled stimulation; their integration can be anticipated. The axon-guidance cue semaphorin 3A (Sema3A) offers a target for understanding and treating post-infarction innervation disorders: in the normal heart, Sema3A acts through Nrp1/Plexin receptors to establish a chemorepulsive gradient that directs sympathetic innervation from epicardium to endocardium; after MI, reduced Sema3A expression at the infarct border removes this repulsive constraint, causing abnormal sympathetic sprouting alongside reduced parasympathetic fibers, together with disordered NGF distribution, forming a proarrhythmic substrate. In congestive HF, by contrast, Sema3A rises compensatorily and reduces neural density, indicating a bidirectional rather than unidirectional change [44]. In organoid models, three-dimensional magnetic torque stimulation, which applies controlled mechanical torque to the cell membrane within a rotating magnetic field, promotes structural and vascular maturation in human cardiac organoids and upregulates genes related to gap junctions (GJA1/Cx43), sarcomeres (TNNT2, MYH7, KCNJ2), and mechanotransduction (Lamin A/C, integrin α5/β3), accelerating functional and structural maturation and providing a new tool for in vitro drug screening and developmental studies [45]. These advances indicate that magnetic field technology is moving from purely functional modulation

toward combined functional and structural repair. Taken together, Table 1 summarizes the magnetic intervention strategies discussed above, ordered from the most clinically mature to purely preclinical stages, to make the uneven evidence landscape explicit.

Table 1. Summary of Magnetic-Field-Based Therapeutic Strategies in Cardiovascular Disease, Ordered from Most to Least Mature Evidence.

Therapeutic route	Refs.	Field / transducer	Model	Key finding	Evidence level
Pulsed field ablation (electric-field comparator)	[23,24]	Pulsed electric field; irreversible electroporation	AF patients; MANIFEST-PF registry (>1000 patients)	Established one-year safety/efficacy; sets the evidence benchmark that magnetic strategies must catch up to.	Clinical (registry)
Transcutaneous magnetic stimulation of left stellate ganglion	[25]	Noninvasive magnetic coil; nondestructive neuromodulation	VT storm patients; single-center double-blind RCT, n=26	24-h primary endpoint (freedom from sustained VT) not significant (P=.20); 72-h VT burden reduced (IRR 0.42, P<.001); safety signal in device-implanted patients.	Clinical (RCT, n=26)
Pico-Tesla EMF on vagal trunks / across chest	[29]	~0.034 uT, 0.95 Hz; extremely low-level EMF	Dogs (n=17), paced AF model	Suppressed ganglionated-plexi firing and reversed AF inducibility without tissue injury.	Preclinical (large animal)
Magneto-mechanical nanodiscs / TRPV1 nanocubes	[10,11]	Magnetite nanodiscs 12-56 mT, 5-125 Hz; Fe-oxide nanocubes conjugated to TRPV1 antibody, magnetothermal	Cardiomyocytes/astrocytes; mouse myocardial I/R	Nanonewton membrane forces open mechanosensitive Ca2+ channels without exogenous genes; intraspinal nanocube/TRPV1 desensitization cuts substance P/CGRP release	Preclinical (cell/animal)

				and attenuates I/R injury.	
Injectable magnetic hydrogel stimulating the vagus nerve	[36]	Chitosan/beta-glycerophosphate thermogel + SPIO; ~100 mT (peak 108 mT), 20 Hz	Rat MI; 4-week stimulation	Selective single-vagus stimulation; improved cardiac function, smaller infarct, suppressed inflammatory infiltration.	Preclinical (animal)
Oral magnetoelectric gut-brain-spleen-heart device	[32]	Gastric-adhered Fe3O4@BaTiO3 nanogenerator in PEDOT:PSS / dopamine-alginate; alternating magnetic field	Rat AF model	Contactless vagal-afferent activation via brainstem NTS and splenic cholinergic anti-inflammatory pathway; shortened AF duration.	Preclinical (animal)
Magnetic cell / scaffold / organoid strategies	[40,41,45]	Rotating magnetic torque; surface-bound magnetic particles; magnetically labelled EVs	MSCs, iPSC-EVs, hESC-derived cardiac organoids	Enhanced angiogenesis, MRI/MPI-guided targeted delivery, accelerated organoid structural/vascular maturation (Cx43, sarcomere genes).	Preclinical (in vitro)

4. Challenges and Perspectives

Although the therapeutic potential of magnetic fields in cardiovascular disease has been widely demonstrated, clinical translation still faces several bottlenecks. First, stimulation parameters (frequency, field strength, duration, and spatial encoding) lack unified standards, making cross-study comparison difficult; a framework of multi-physics coupling simulation and parameter standardization is urgently needed [3]. Second, long-term in vivo safety is not yet fully elucidated: under the conditions of rapid cardiac pulsation and blood-flow shear, material retention, degradation products, and interactions with endogenous iron metabolism require systematic evaluation, and autonomic function should be incorporated as a dynamic safety endpoint in long-term follow-up [19]. Open-loop or invasive neuromodulation has shown relatively high recurrence rates in mid- to long-term follow-up, suggesting that fixed-parameter intervention alone is insufficient for durable efficacy.

In terms of evidence strength, the field currently shows a marked polarization. On one hand, several conclusions are relatively established: the frequency- and amplitude-dependent biphasic modulation of cardiomyocyte calcium transients, the myocardial selectivity and one-year safety of PFA, and the phenotypic association between HRV and all-cause mortality have all been replicated in independent laboratories or large cohorts

[6,19,23]. On the other hand, a great deal of work remains at an early, developmental stage: the specific role of channels such as Piezo1 in magneto-mechanical transduction, long-term in vivo degradation and iron-metabolism interactions of magnetic materials, and algorithmic optimization of closed-loop stimulation, all resting on preliminary evidence. The core problems that must be addressed are parameter standardization and target specificity: current studies span field strengths from millitesla to hundreds of millitesla and frequencies from hertz to terahertz, preventing direct comparison, and pure fields without magnetic-responsive materials struggle to selectively stimulate individual nerves. Finally, a balanced view is needed of directions with limited prospects: pure static magnetic fields without magnetic-responsive materials exert weak, poorly reproducible cardiovascular effects and offer little future as a standalone therapy; some highly novel strategies with long engineering chains, while conceptually valuable, require cautious assessment of long-term stability and translation and should not be overstated in a review.

Looking forward, magnetic intervention will develop toward intelligent, closed-loop operation. Drawing on brain–computer-interface concepts, wearable or implantable devices that continuously acquire HRV and local electrophysiological signals, combined with algorithms that dynamically optimize field strength, frequency, and spatial focusing, could enable individualized, adaptive autonomic control [3]. Given the marked inter-individual differences in cardiac autonomic anatomy, synaptic density, and genetic background, conventional open-loop stimulation cannot meet precision demands. On this basis, deepening the integration of physical-field intervention with regenerative medicine, using magnetic-responsive scaffolds to co-deliver neurotrophic factors and cellular components under field control, may overcome the traditional limitation of "improving function but struggling to repair structure." Dissecting the abnormal cAMP/PKA and RyR2 calcium-handling axis that links autonomic imbalance to myocardial deterioration remains a mechanistic priority that would connect autonomic modulation to improved calcium homeostasis [46]. Multimodal imaging combined with digital-twin simulation to dynamically assess material metabolism, neural remodeling, and electrophysiological changes will provide systematic support for safe translation.

5. Conclusions

Leveraging noninvasiveness, remote programmability, and deep penetration, magnetic field technology is moving from exploratory physical-effect research toward precision treatment of cardiovascular disease. Biologically, magnetic fields modulate cardiac ion channels, protect the vascular endothelium and microcirculation, and rebalance cardiac autonomic tone via cholinergic anti-inflammatory and other pathways; therapeutically, reproducible preclinical evidence now exists for electrophysiological intervention in arrhythmias, autonomic modulation, and cardiac repair and regeneration. As stimulation parameters are standardized, long-term safety data accumulate, and AI-powered closed-loop platforms are established, magnetic field technology is poised to become an important bridge connecting physical fields, materials science, and cardiovascular medicine, offering a new engineering–medicine approach to the long-term management of arrhythmias, MI, and HF.

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