Exploration of Cardiology

Open Exploration

Open Access Review

Theranostic advances in cardio-oncology: integrating precision diagnostics and targeted therapies for cardiovascular protection in cancer patients

Patrick Ashinze[1*], Nwoke Obinna Chidubem[2], Osagie Noze-Otote[1], Wuraola Salawu[3], Stephen Olowookere[4], Yusuf Tijani[1], Hussein Bello[1], Frederick Moody[1]

[1]Faculty of Clinical Sciences, University of Ilorin, Ilorin 240003, Nigeria

[2]Department of Pharmacology and Therapeutics, Faculty of Basic Clinical Sciences, College of Medicine, University of Nigeria, Nsukka 410001, Nigeria

[3]St John's Hospital, Livingston EH54 6PP (NHS Lothian), Scotland

[4]Obafemi Awolowo University Teaching Hospital Complex, Ile-Ife 220005, Nigeria

***Correspondence:** Patrick Ashinze, Faculty of Clinical Sciences, University of Ilorin, Ilorin 240003, Kwara State, Nigeria. patrickashinze@yahoo.com

Academic Editor: Eugenio Picano, Italian National Research Council, Italy

Received: May 6, 2026 **Accepted:** June 10, 2026 **Published:** November 4, 2026

Cite this article: Ashinze P, Chidubem NO, Noze-Otote O, Salawu W, Olowookere S, Tijani Y, et al. Theranostic advances in cardio-oncology: integrating precision diagnostics and targeted therapies for cardiovascular protection in cancer patients. Explor Cardiol. 2026;4:1012128. https://doi.org/10.37349/ec.2026.1012128

Abstract

Cardio-oncology has emerged as a critical interdisciplinary field addressing the growing burden of cardiovascular complications arising from modern cancer therapies. While advances in chemotherapy, targeted agents, and immunotherapies have substantially improved cancer survival, they have concurrently led to a significant rise in cancer therapy-related cardiac dysfunction (CTRCD), contributing to increased long-term morbidity and mortality among cancer survivors. Conventional surveillance strategies often detect cardiotoxicity only after irreversible myocardial injury has occurred, accentuating the need for more precise, proactive, and personalized approaches. Theranostics, integrating diagnostic imaging, molecular biomarkers, and targeted therapeutics, offers a promising paradigm to enable early detection, risk stratification, and tailored cardioprotective interventions in cardio-oncology. This review synthesizes recent advances in theranostic strategies relevant to cardio-oncology, spanning imaging-based, biomarker-driven, and nanotechnology-enabled approaches. Advanced imaging modalities such as hybrid PET/MRI, AI-enhanced echocardiography, and novel molecular radiotracers [e.g., ^{68}Ga-FAPI, ^{18}F-DHMT, [^{68}Ga]pentixafor] enable early identification of subclinical myocardial injury, inflammation, fibrosis, and metabolic dysfunction before overt declines in left ventricular ejection fraction occur. Complementing imaging, biomarker-driven theranostics including high-sensitivity cardiac troponins, natriuretic peptides, circulating and exosomal microRNAs, and cardiomyocyte-specific cell-free DNA, provide minimally invasive, real-time insights into myocardial stress, injury, and immune-mediated cardiotoxicity. Nanotheranostic platforms, such as liposomal doxorubicin and immunomodulatory nanoparticles, further enhance therapeutic precision by reducing off-target cardiac exposure while preserving antitumor efficacy.

© The Author(s) 2026. This is an Open Access article licensed under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, sharing, adaptation, distribution and reproduction in any medium or format, for any purpose, even commercially, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Despite these advances, clinical translation remains hindered by interdisciplinary fragmentation, limited access to advanced infrastructure, high development costs, regulatory heterogeneity between agencies, and reliance on surrogate endpoints rather than long-term cardiovascular outcomes. Theranostics represents a transformative approach in cardio-oncology. Integration of advanced imaging, molecular biomarkers, artificial intelligence, and nanotechnology holds significant promise for preserving cardiac health without compromising oncologic success. Embedding theranostic strategies into routine cardio-oncology practice is essential to advancing precision medicine and improving cardiovascular outcomes for cancer patients worldwide.

Keywords

cardio-oncology, theranostics, clinical translation, personalized medicine

Introduction

Cardio-oncology has emerged as a critical subspecialty focused on the intricate relationship between cancer therapies and their associated cardiovascular complications [1]. The field encompasses the prevention, diagnosis, and treatment of cardiac problems arising from chemotherapy and radiation, the protection of cardiac health before, during, and after cancer therapy, and the collaborative management of pre-existing heart conditions alongside oncological care [1, 2]. The rapid evolution of oncological treatments has significantly amplified the interplay between cardiology and oncology, with novel cancer therapies substantially improving survival rates, in some cases conferring additional years of life. This progress has been accompanied by an unintended consequence: an approximately two-to-six-fold increase in cardiovascular mortality among cancer survivors compared to the general population, a burden particularly evident following anthracycline-based chemotherapy, trastuzumab, and thoracic radiotherapy, which collectively represent the highest-risk treatment exposures [2, 3]. Early detection and treatment have demonstrated the capacity to reverse adverse cardiac effects in many oncological contexts; patients at high risk of cardiotoxicity are therefore prioritised for screening and monitoring to enhance early detection and minimise irreversible toxicity [4].

Theranostics, an evolving paradigm rooted in precision oncology, combines diagnostic imaging with targeted therapies to optimise cancer management. By leveraging nuclear medicine diagnostic techniques, clinicians can accurately diagnose, manage, and treat cancer patients through personalised approaches [5]. The field has facilitated the identification of cancer biomarkers using positron emission tomography (PET) and single-photon emission computed tomography (SPECT)-based molecular imaging. These tools enable the design of individualised treatment plans that precisely diagnose and treat cancer patients while minimising adverse effects and improving quality of life and survival rates [6, 7]. The growing complexity of cancer subtypes has driven innovation in precision medicine, tailoring treatments to an individual's unique genetic, molecular, and environmental profile. Breakthroughs in artificial intelligence (AI)-driven radiomics and nanotheranostics are advancing cancer care by enabling accurate diagnoses and targeted therapies [8].

This review summarises the most current theranostic approaches in cardio-oncology, including advanced imaging-based theranostics, biomarker-guided strategies, targeted drug delivery, and nanotheranostics. Clinical implications and future directions of these approaches are also discussed, with the objective of establishing a foundation for preventive, diagnostic, and therapeutic modalities. In the expanding cardio-oncology literature, numerous narrative reviews have addressed advances in imaging, biomarkers, and nanotechnology in isolation. This review distinguishes itself by synthesising these discrete technological strands into an integrative clinical workflow model centred on theranostics. A unifying framework is articulated that progresses from multi-modal risk assessment to targeted intervention, emphasising the synergistic clinical application of these tools. A consensus-style analysis of immediate translational opportunities and the specific cross-cutting barriers, regulatory, economic, and interdisciplinary, that must be overcome to implement this paradigm is also provided. The objective is to

move beyond cataloguing innovations and instead offer a clinically actionable perspective on how integrated theranostic strategies can be embedded into routine cardio-oncology pathways to improve patient outcomes.

Theranostic modalities

Theranostic modalities in cardio-oncology are best understood within a conceptual framework that integrates molecular mechanisms of cardiac injury, diagnostic detection, and targeted therapeutic response. At its core, theranostics operationalises a diagnostic-therapeutic loop: a molecular signal, whether a radiotracer binding to an upregulated receptor, an exosomal microRNA (miRNA) signature, or an elevated biomarker reflecting a specific injury pathway, simultaneously identifies the biological target and informs the selection of the therapeutic agent directed against it. The sections below address the three principal modality domains, imaging-based approaches, biomarker-driven strategies, and nanotheranostics, structured to move from the underlying biology to diagnostic application and then to therapeutic integration.

Advanced imaging technologies

Advanced imaging technologies are central to theranostics, offering non-invasive means to detect and characterise anatomic, biochemical, and functional pathology, thereby providing critical diagnostic information for precise treatment planning and real-time monitoring. The translation of advanced imaging theranostics faces heterogeneous validation. AI-echocardiography tools for global longitudinal strain (GLS) measurement are progressing through regulatory clearance processes, demonstrating improved reproducibility over manual methods, yet require rigorous external validation across diverse patient populations and ultrasound platforms [9]. Novel radiotracers such as ^{68}Ga-FAPI for fibrosis imaging remain in early-phase trials, with validation pathways longer and more resource-intensive owing to radiopharmaceutical regulatory requirements. A robust cost-effectiveness analysis is also lacking: although hybrid PET/MRI provides unparalleled multi-parametric data, it is surmisably higher in cost per scan compared to sequential standard tests, which must be justified by proven impact on treatment decisions and hard outcomes, evidence that is not yet mature [8–10].

Hybrid PET/MRI imaging

Cardiovascular magnetic resonance (CMR) is valuable for early cardiotoxicity detection by assessing cardiac anatomy, tissue composition, and function [9, 10]. CMR can detect subtle myocardial changes before a decline in left ventricular ejection fraction (LVEF) and accurately quantifies left ventricular mass changes that correlate with anthracycline dose and cardiac event risk [9]. Hybrid PET/MRI integrates PET's functional and metabolic capacity with MRI's enhanced anatomical detail and soft-tissue contrast [11]. This combination allows for enhanced lesion characterisation and precise image co-registration in a single session, providing incremental information beyond individual modalities. MRI additionally offers parameters such as dynamic contrast enhancement (DCE) for vascularisation assessment and diffusion-weighted imaging (DWI) for cellularity quantification, aiding in tumour characterisation [11, 12]. In cardio-oncology, ^{18}F-FDG PET/MRI can identify early anthracycline-induced myocardial damage by assessing glucose uptake, and shows promise for cardiac sarcoidosis by combining late gadolinium enhancement (LGE) MRI for myocardial injury with ^{18}F-FDG PET for active inflammation, offering stronger prognostic value than either modality alone [12, 13].

AI-driven echocardiography

AI, in particular machine learning (ML) and deep learning (DL), is transforming cardio-oncology by improving risk stratification, optimising treatment, and enabling individualised care. These techniques are also instrumental for early detection of cardiac dysfunction, enabling timely and personalised interventions to prevent irreversible damage [14]. AI models analyse electrocardiogram (ECG), echocardiographic, CT, and MRI data to identify patterns indicative of cardiotoxicity [15]. In echocardiography, AI addresses

limitations arising from user-dependency and measurement variability by automating complex assessments, enhancing diagnostic precision, and increasing accessibility [16]. Specific applications include improving the accuracy and efficiency of LVEF assessment and automating GLS measurement, a validated early marker for cardiotoxicity, thereby improving reproducibility and predictive accuracy [16, 17].

Novel radiotracers for molecular imaging

Novel radiotracers are designed with high specificity for molecular targets and optimal kinetics for signal detection, enabling paired diagnostic and therapeutic agents to target identical mechanisms, which is the core principle of theranostics [18]. Table 1 (see below) summarises key radiotracers with potential applications in cardio-oncology. Clinically, ^{68}Ga-DOTATATE and [^{68}Ga]pentixafor are most suited for imaging myocardial inflammation in the context of immune checkpoint inhibitor (ICI)-associated myocarditis, where CXCR4-positive immune cell infiltration can be quantified. The ^{18}F-DHMT tracer targets superoxide production and is most applicable to early anthracycline cardiotoxicity surveillance, while ^{68}Ga-FAPI provides direct imaging of fibroblast activation protein, facilitating the characterisation of myocardial fibrosis in post-therapy cardiomyopathy. The advantage of each tracer lies in its mechanistic specificity; the disadvantage is the limited availability of radiopharmaceutical infrastructure outside specialist centres.

Table 1. Summary of radiotracers and their applications in cardio-oncology [18, 19].

Radiotracer	Target	Diagnostic advantage	Potential application in cardio-oncology
^{68}Ga-DOTATATE	Somatostatin receptors (SSTR) on activated inflammatory cells	High sensitivity for inflammatory infiltration	Imaging myocardial inflammation in ICI myocarditis
[^{68}Ga]pentixafor	Chemokine Receptor CXCR4 on pro-inflammatory immune cells	Quantification of CXCR4+ immune cell burden	Imaging coronary inflammation and remodelling
^{18}F-DHMT	Superoxide production (reactive oxygen species)	Direct oxidative stress detection	Early detection of anthracycline-induced cardiotoxicity
^{68}Ga-FAPI	Fibroblast activation protein (FAP)	Direct imaging of active fibrosis	Imaging myocardial fibrosis in post-therapy cardiomyopathy

Biomarker-driven strategies

Biomarker-driven strategies offer sensitive, cost-effective, and minimally invasive approaches for cardiotoxicity surveillance, often providing insights before overt functional impairment is detectable by imaging. Critically, these biomarkers are not mere indicators of injury; each reflects a distinct mechanistic pathway, enabling their clinical utility to extend beyond detection to the guidance of targeted interventions.

Established cardiac biomarkers: troponins and natriuretic peptides

Anthracyclines exert their cardiotoxic effect primarily through topoisomerase IIβ inhibition, triggering mitochondrial reactive oxygen species (ROS) generation, double-strand DNA breaks within cardiomyocytes, and subsequent apoptosis. Trastuzumab, by contrast, impairs cardiomyocyte survival through ErbB2 receptor blockade, disrupting downstream survival signalling pathways including neuregulin-1/ErbB2 and PI3K/Akt. Cardiac troponins (cTnI and cTnT) are specific proteins released upon cardiomyocyte necrosis, providing a sensitive indicator of myocardial damage from these mechanisms [19]. High-sensitivity troponin (hs-Tn) assays enable earlier detection of subtle injury and predict subsequent irreversible CTRCD when elevated [20]. Natriuretic peptides (NPs), specifically B-type natriuretic peptide (BNP) and NT-proBNP, are released in response to myocardial stress and wall stretch from increased intracardiac pressures associated with ventricular dysfunction. Both troponins and NPs are recommended at baseline for patients receiving potentially cardiotoxic agents [20]. Limitations include their non-specificity to the underlying cause of damage and a lack of robust comparative analyses between different hs-Tn assays, hindering standardisation [20].

Circulating miRNAs (cmiRNAs) show promise as early biomarkers for anthracycline-induced cardiotoxicity. Specific cmiRNAs (e.g., miR-34a, miR-1, miR-423, miR-126, miR-130a) may predict

cardiotoxicity development [20]. Myeloperoxidase (MPO), implicated in inflammation and oxidative stress, is a promising early biomarker for CTRCD in breast cancer patients receiving anthracyclines and trastuzumab [20, 21]. Combining multiple biomarkers, such as MPO and troponin, may improve predictive accuracy.

Emerging liquid biopsy biomarkers

Liquid biopsy, a minimally invasive approach that analyses circulating tumour cells (CTCs), circulating tumour DNA (ctDNA), and other blood components, is primarily used in oncology for monitoring cancer progression [21, 22]. It carries additional potential for monitoring cardiotoxicity [22]. Changes in cardiomyocyte-specific cell-free methylated DNA (cfDNA) may indicate cardiomyocyte death from cardiotoxic therapies including radiation [22–24]. Importantly, cfDNA elevation following anthracycline exposure does not correlate closely with high-sensitivity cardiac troponin I (hs-cTnI), suggesting that these markers reflect distinct pathological processes and provide complementary mechanistic information. When cardiomyocyte cfDNA rises in the context of active cancer therapy, this signal may serve as a trigger for escalating cardioprotective measures, including the initiation of nanoparticle-based cardioprotective strategies, thereby operationalising the theranostic loop. Liquid biopsy enables dynamic tracking of both cancer progression and therapeutic cardiac responses, facilitating timely adjustments to therapy [23, 25].

Exosomal miRNAs

Exosomes are extracellular vesicles that mediate intercellular communication by carrying heterogeneous cargo, including miRNAs [26]. Exosomal miRNAs (ex-miRs) are stable in circulation and carry potential as non-invasive biomarkers for heart failure and cardiotoxicity [24]. Specific ex-miRs, including miR-107, miR-146a, and miR-502, are potential markers of doxorubicin-induced cardiotoxicity (DIC) [24, 26]. Exosomal miR-34a-5p, derived from PD-1 inhibitor-treated macrophages, is mechanistically linked to ICI-related cardiac dysfunction through induction of cardiac senescence. Beyond diagnostic potential, ex-miRs signatures are emerging as functional guides for therapeutic decisions: elevated miR-34a-5p may indicate a patient phenotype more likely to respond to senolytic or mitochondria-targeted interventions, while miR-107 upregulation may support selection of liposomal doxorubicin formulations with optimised cardiac protection profiles. This diagnostic-to-therapeutic translation exemplifies the operational theranostic loop in biomarker-guided cardio-oncology [24, 26].

cfDNA

cfDNA originates from dead cells releasing genomic DNA into the bloodstream. Its tissue specificity allows identification of cardiomyocyte-derived cfDNA. Elevated cardiomyocyte cfDNA levels following anthracycline chemotherapy are significantly associated with an increased risk of subsequent CTRCD [26]. While hs-cTnI also rises in this context, its poor correlation with cardiomyocyte cfDNA indicates distinct underlying pathological processes, and the two biomarkers therefore provide complementary clinical information.

Nanocarriers for reduced cardiotoxicity and enhanced efficacy

Nanotechnology offers transformative opportunities in cardio-oncology by enabling precise drug delivery, reducing systemic toxicity, and enhancing therapeutic efficacy [27]. Nanoparticles enhance bioavailability and stability, facilitating precise delivery to cancer cells, minimising cardiotoxicity, and improving efficacy. Their modular construction allows them to carry various components, enabling high local drug concentrations at the disease site while protecting healthy tissues [25, 27].

Liposomal doxorubicin

Encapsulation alters doxorubicin biodistribution, reducing accumulation in the myocardium while promoting tumour accumulation via the enhanced permeability and retention (EPR) effect [28]. This significantly lowers myocardial drug concentrations, reducing the topoisomerase IIβ-mediated oxidative injury that underlies anthracycline cardiotoxicity. Liposomal doxorubicin also induces interferon-stimulated genes (ISGs) in the heart, promoting cell survival and reducing apoptosis [28, 29].

pH-sensitive nanoparticles and thermally responsive biopolymers

pH-sensitive nanoparticles are engineered to respond to the acidic tumour microenvironment (TME), selectively releasing their payload at the disease site while maintaining stability in healthy tissues. Thermally responsive biopolymers respond to mild local hyperthermia (approximately 41°C) at the tumour site. These biopolymers promote preferential accumulation and drug release within the heated tumour, significantly reducing doxorubicin accumulation in the myocardium and preserving cardiac function [28, 29].

Immunomodulatory nanoparticles for cardiac protection

Immunomodulatory nanoparticles are designed to interact specifically with the immune system, enhancing or suppressing its activity for therapeutic outcomes [30]. They address challenges of conventional immunotherapy by delivering tumour antigens and adjuvants to antigen-presenting cells (APCs) and modulating the TME [30]. Nanotheranostics combine diagnostic and therapeutic capabilities, permitting direct delivery of agents to damaged cardiac tissues for targeted, localised treatment with minimal systemic adverse effects. This approach can improve the safety profile of ICIs, which can cause immune-related adverse events including myocarditis, by achieving specific and localised immune response modulation in tumour tissue while reducing systemic side effects [30]. Figure 1 provides an infographic summary of biomarkers of theranostic interest in cardio-oncology [19, 21, 24, 30].

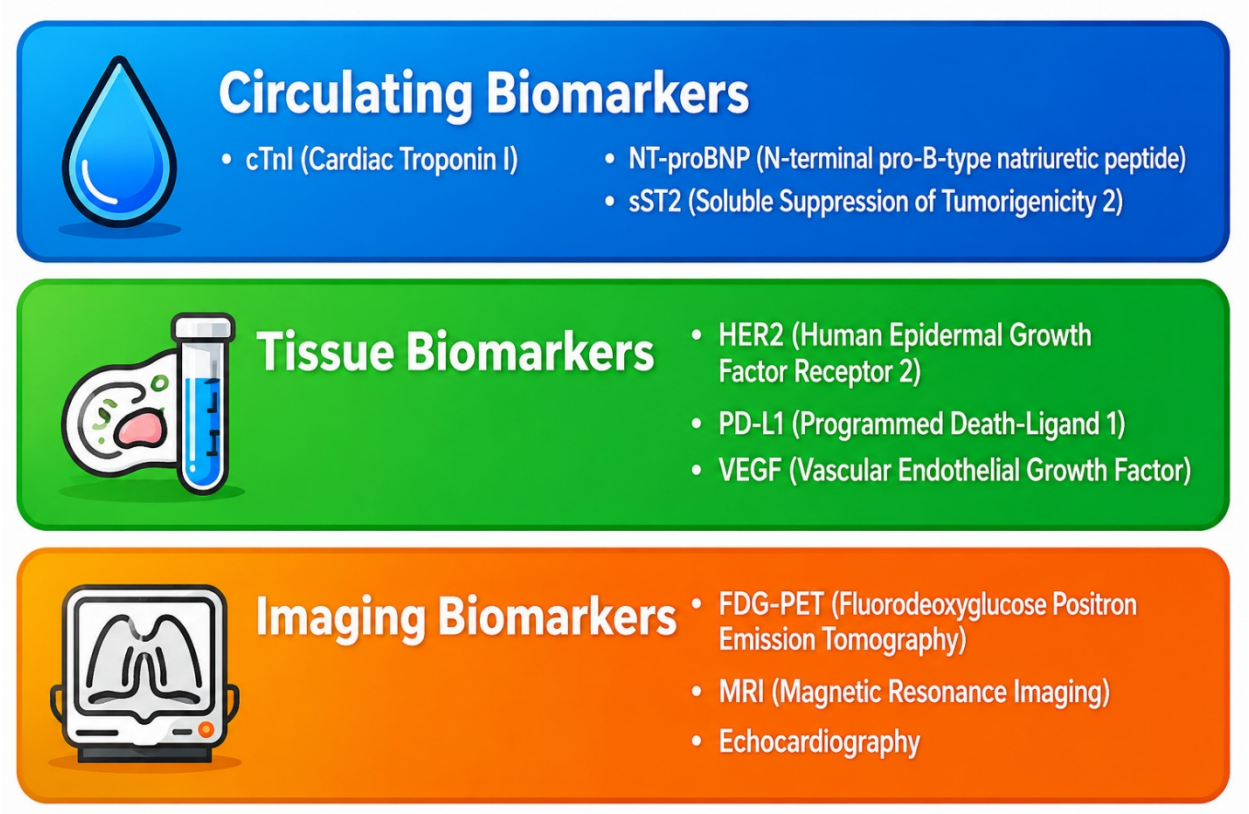


Figure 1. An infographic summary of biomarkers of theranostic interest in cardio-oncology [19, 21, 24, 30].

Clinical translation: opportunities and barriers

The integration of theranostics into cardio-oncology faces significant translational hurdles despite its transformative potential. This section examines key implementation barriers, illustrative clinical case studies, and critical regulatory and economic considerations shaping real-world adoption.

Challenges in implementation

Interdisciplinary fragmentation remains a fundamental barrier. Cardio-oncology trials such as STOP-CA highlight persistent gaps in collaborative trial design, where cardiologists and oncologists frequently operate independently [31]. Recruitment challenges arise from competing clinical priorities, with a sizable number of eligible patients declining participation owing to overwhelmed care schedules [31]. Exclusion of patients with comorbidities such as hypertension and diabetes creates selection bias, limiting generalisability to real-world populations [31].

Cost and accessibility present substantial hurdles. Advanced theranostic modalities including PET/MRI hybrid imaging and novel radiotracers (e.g., ^{68}Ga-FAPI, ^{18}F-DHMT) require specialised infrastructure unavailable outside tertiary centres [4, 11]. Radiopharmaceutical production faces complex logistical challenges, including radionuclide supply chains and regulatory requirements [4]. Development costs for a single agent may exceed one billion US dollars with timelines spanning 10 to 15 years [4], while patient-specific dosimetry calculations further increase resource demands [4].

Evidence generation barriers include an overreliance on surrogate endpoints such as LVEF changes rather than clinically meaningful outcomes, for example, heart failure hospitalisations [31]. Statistically significant LVEF differences (e.g., 1.3% in STOP-CA) may not translate to tangible patient benefits [31]. Short follow-up durations, typically 12 to 24 months, fail to capture late cardiovascular complications [31].

Evidence hierarchy and the case for pragmatic trials

A central barrier to the routine integration of advanced theranostics is the predominance of proof-of-concept and observational data over high-level clinical evidence. For most novel radiotracers, exosomal biomarker panels, and nanotheranostic platforms, robust validation from multicentre randomised controlled trials (RCTs) demonstrating an impact on hard cardiovascular outcomes, such as heart failure hospitalisation and cardiovascular mortality, is absent. Current clinical guidelines rightly remain anchored to established tools such as serial echocardiographic LVEF. Competing strategies, including the universal prophylactic use of cardioprotectants (e.g., dexrazoxane, ACE inhibitors) in high-risk cohorts, offer a simpler, evidence-supported alternative to complex biomarker-guided approaches. Adoption of precision theranostics must therefore be contingent on generating evidence that it outperforms conventional strategies in both efficacy and cost-effectiveness. Future trial designs must move beyond surrogate endpoints toward pragmatic studies in which theranostic-guided management is compared against standard care for primary endpoints of patient survival and morbidity.

Case studies in practice

ICI myocarditis management

ICIs trigger fulminant myocarditis via CD8+ T-cell-driven inflammation [30]. Emerging approaches combine [^{68}Ga]pentixafor PET, targeting CXCR4-positive inflammatory cells, with cardiac MRI to detect subclinical inflammation [13]. Biomarker-guided strategies using exosomal miR-34a-5p provide mechanistic insight into cardiac senescence, enabling risk stratification [24, 26].

CAR-T cardiovascular complications

Cytokine release syndrome (CRS) affects 50 to 90% of CAR-T recipients and causes haemodynamic compromise [32]. Theranostic monitoring combines liquid biopsy biomarkers, including endothelial-derived cfDNA and interleukin-6, with echocardiographic strain imaging to guide tiered interventions [25, 26]. Engineering advances incorporating on/off safety switches aim to minimise systemic toxicity [32].

Biomarker-guided statin intervention

The STOP-CA trial utilised baseline high-sensitivity troponin T (hs-TnT) and NT-proBNP to identify lymphoma patients likely to benefit from atorvastatin prophylaxis [31]. Statin recipients demonstrated reduced CTRCD rates (8% vs. 22% placebo), particularly those with elevated biomarkers [31]. Ongoing research is exploring polygenic risk scores to refine patient selection [20].

Regulatory and economic considerations

Divergent regulatory pathways between the FDA and EMA complicate development. FDA orphan designation requires conditions affecting fewer than 200,000 US patients, versus the EMA threshold of fewer than 5 per 10,000 EU prevalence [4]. Radiopharmaceuticals face additional complexity under FDA investigational new drug (IND) requirements, where diagnostic-therapeutic pairs may require separate approvals despite biological equivalence [4]. Collaborative mechanisms such as the FDA-EMA Parallel Scientific Advice programme show promise in harmonising requirements for rare toxicities [4].

Value-based frameworks must evolve to address theranostic economics. Traditional cost-effectiveness models are not well suited to combined diagnostic-therapeutic agents, where upfront imaging costs (e.g., ^{68}Ga-DOTATATE PET) are offset by optimised patient selection [4, 27]. Patient-specific dosimetry exemplifies this value, enabling personalised dosing to maximise efficacy while minimising toxicity [4].

Economic and equity considerations for global adoption

The economic model and accessibility of theranostics are pivotal to their real-world impact. Infrastructure for advanced modalities, including cyclotron-produced radiotracers and high-field MRI, is concentrated in high-income tertiary centres, creating the risk of a theranostic divide across health systems. A pragmatic, value-based implementation strategy is required, structured across three tiers. At the foundation tier, widespread deployment of validated, low-cost tools such as AI-enhanced point-of-care ultrasound and hs-Tn assays should be achievable across most clinical settings. An advanced tier would involve strategic referral networks for novel biomarker panels or SPECT/CT at regional hubs. The investigational tier would concentrate centralised expertise for PET/MRI and nanotherapeutic trials. Demonstrating that early theranostic intervention reduces downstream costs of heart failure management will be essential for justifying initial investments and achieving equitable access [9, 10, 27].

Future directions

Advancements in gene editing, AI, and targeted therapeutics are reshaping the landscape of cardio-oncology. Table 2 (see below) outlines the current validation status, key strengths, major limitations, and recommended clinical context for the principal theranostic modalities under evaluation, providing a practical framework for prioritising their integration into cardio-oncology pathways.

Table 2. Validation status, strengths, limitations, and recommended context for principal theranostic modalities in cardio-oncology.

Modality	Stage of validation	Key strength	Major limitations/cost	Recommended context
AI-GLS (Echocardiography)	Regulatory-cleared devices; multi-society guideline support	High reproducibility; low incremental cost; portable	Algorithm vendor variability; requires quality image acquisition	First-line serial monitoring for patients on anthracyclines or trastuzumab
Cardiomyocyte cfDNA	Early-phase clinical studies	High tissue specificity for injury; mechanistic insight	No standardised approved assay; high per-test cost (£300–£700)	Investigational risk stratification in high-dose therapy or clinical trials
^{68}Ga-FAPI PET	Preclinical and early phase I in cardio-oncology	Direct imaging of active fibrosis; quantifiable signal	Limited tracer availability; high scan cost; no outcome data	Research tool for characterising unexplained post-therapy cardiomyopathy

Emerging technologies

CRISPR and gene editing

Gene editing carries significant potential for cardio-oncology. In vivo CRISPR-Cas9 strategies have successfully corrected pathogenic sarcomere gene variants in animal models of hypertrophic cardiomyopathy, reducing cardiac hypertrophy and fibrosis [33]. High-throughput CRISPR screens in human iPSC-derived cardiomyocytes are also identifying genes, including SLCO1A2 and SLCO1B3, that influence doxorubicin sensitivity [32]. Future CRISPR-based strategies may also be applicable to the repair

of chemotherapy-induced DNA damage or patient-specific cardiomyopathy mutations, enabling truly personalised cardioprotection [33, 34].

AI and ML

ML constitutes another transformative tool. Models integrating patient data, including demographics, cancer type, and treatment regimens, can identify patients at high risk for cardiotoxicity [35]. DL applied to routine ECGs can detect subclinical declines in ejection fraction following anthracyclines, with reported AUC values of approximately 0.93 [36]. AI algorithms applied to cardiac imaging, including echocardiography, MRI, and CT, improve quantification of cardiac volumes and function, highlighting subtle changes before symptoms emerge [37]. These tools facilitate earlier intervention by identifying at-risk patients and streamlining surveillance.

Mitochondria-targeted antioxidants

Mitochondria-targeted antioxidants are a promising pharmacological advance. Compounds such as Mito-TEMPO and MitoQ accumulate in cardiomyocyte mitochondria and scavenge ROS. Preclinical studies demonstrate that Mito-TEMPO administered during chemotherapy significantly reduces doxorubicin- and 5-fluorouracil-induced cardiac injury by preserving mitochondrial function [38]. Mitochondria-targeted coenzyme Q analogues (e.g., MitoQ, SKQ1) have similarly protected animal hearts from drug-induced oxidative damage [37]. Clinical trials are required to confirm the safety and efficacy of these agents as co-administered cardioprotectants.

Next-generation agents

CAR-T cell engineering

CAR-T therapy is expanding beyond haematological malignancies into solid tumours, with new designs improving cardiac safety. Recent engineering advances include affinity tuning and logic-gated receptors requiring two tumour signals to activate, thereby sparing healthy tissues. On/off safety switches and methods for local delivery of CAR-T cells aim to confine activity to tumour sites, retaining anti-tumour potency while minimising on-target, off-tumour cardiotoxicity of the type observed in early HER2-directed CAR trials [39].

Hybrid imaging-AI pipelines

Hybrid imaging modalities combined with AI analysis represent a further frontier. PET/CT or MRI/PET scans can measure myocardial metabolism and fibrosis in cancer patients, and AI-based analysis can detect early cardiotoxic changes. AI-enhanced hybrid imaging substantially improves the accuracy and efficiency of cardiotoxicity assessment. In practice, such pipelines could allow real-time monitoring of cardiac function during therapy, so that oncologists and cardiologists can adapt treatment, for example by pausing chemotherapy or initiating cardioprotective agents, at the earliest detectable signal [40].

Global priorities

As cardio-oncology continues to evolve, it is essential to address global priorities that ensure equitable access to care, foster collaborative research, and establish comprehensive registries. These initiatives are critical for bridging gaps in knowledge, improving patient outcomes, and promoting health equity across diverse populations. Figure 2 presents a summating theranostic workflow illustration from diagnostics to precision healthcare.

Conclusions

Theranostics is redefining cardio-oncology by enabling simultaneous diagnosis and treatment of cancer therapy-related cardiovascular disease, marking a transition toward precision care. Mechanistically grounded advances, including hybrid PET/MRI imaging that targets specific molecular pathways of injury, exosomal biomarker profiling that translates miRNA signatures into therapeutic selection criteria, and



Figure 2. A theranostic workflow illustration from diagnostics to precision healthcare delivery.

nanotheranostic platforms that reduce anthracycline-mediated topoisomerase IIβ injury at the cardiomyocyte level, are collectively establishing a theranostic framework in which diagnostic signal and therapeutic action are functionally linked rather than conceptually adjacent. Real-world integration remains limited by cost, regulatory complexity, and interdisciplinary fragmentation. Two specific recommendations emerge from this evidence synthesis. First, multicentre pragmatic RCTs comparing theranostic-guided cardio-oncology management against standard care should be designed with primary endpoints of heart failure hospitalisation and cardiovascular mortality, rather than surrogate imaging parameters. Second, a tiered implementation model should be formally adopted, committing to universal access to validated low-cost tools such as AI-GLS echocardiography and hs-Tn assays, while restricting novel radiotracers and nanotheranostic platforms to investigational contexts until outcome data mature. Collaborative efforts to establish global registries, develop robust AI-driven decision tools, and promote equitable access to emerging technologies are urgently required. Realising the full potential of theranostics in cardio-oncology demands unified action from the laboratory to the clinic.

Abbreviations

AI: artificial intelligence

BNP: B-type natriuretic peptide

cfDNA: cell-free DNA

cmiRNAs: circulating microRNAs

CMR: cardiovascular magnetic resonance

CTRCD: cancer therapy-related cardiac dysfunction

DL: deep learning

ECG: electrocardiogram

ex-miRs: exosomal microRNAs

GLS: global longitudinal strain

hs-cTnI: high-sensitivity cardiac troponin I

hs-Tn: high-sensitivity troponin

ICI: immune checkpoint inhibitor

LVEF: left ventricular ejection fraction

miRNA: microRNA

ML: machine learning

MPO: myeloperoxidase

NPs: natriuretic peptides

PET: positron emission tomography

RCTs: randomised controlled trials

ROS: reactive oxygen species

TME: tumour microenvironment

Declarations

Acknowledgments

The authors acknowledge The Lind League, Nigeria, for providing the institutional resources that supported this research project. Some of the subfigures in this manuscript were generated with the assistance of artificial intelligence image generation tools [Perplexity AI]. These images were reviewed and verified by the authors prior to inclusion.

Author contributions

PA: Conceptualization, Methodology, Writing—original draft, Writing—review & editing, Supervision, Validation, Project administration. NOC: Writing—original draft, Writing—review & editing, Data curation. ONO: Writing—original draft, Writing—review & editing, Data curation. WS: Writing—original draft, Writing—review & editing, Data curation. SO: Writing—review & editing, Supervision. YT: Writing—original draft, Writing—review & editing, Data curation. HB: Writing—original draft, Writing—review & editing, Data curation. FM: Writing—original draft, Writing—review & editing, Data curation. All authors read and approved the submitted version.

Conflicts of interest

The authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

No funding was received for this work.

Copyright

© The Author(s) 2026.

Publisher's note

Open Exploration maintains a neutral stance on jurisdictional claims in published institutional affiliations and maps. All opinions expressed in this article are the personal views of the author(s) and do not represent the stance of the editorial team or the publisher.

References

1. Spannbauer A, Bergler-Klein J. Cardio-Oncology: A New Discipline in Medicine and Its Relevance to Hematology. Hämostaseologie. 2024;44:255–67. [DOI] [PubMed]
2. Sturgeon KM, Deng L, Bluethmann SM, Zhou S, Trifiletti DM, Jiang C, et al. A population-based study of cardiovascular disease mortality risk in US cancer patients. Eur Heart J. 2019;40:3889–97. [DOI] [PubMed] [PMC]
3. Herrmann J. From trends to transformation: where cardio-oncology is to make a difference. Eur Heart J. 2019;40:3898–900. [DOI] [PubMed]
4. Emmett L, Willowson K, Violet J, Shin J, Blanksby A, Lee J. Lutetium ^{177} PSMA radionuclide therapy for men with prostate cancer: a review of the current literature and discussion of practical aspects of therapy. J Med Radiat Sci. 2017;64:52–60. [DOI] [PubMed] [PMC]
5. Shrivastava S, Jain S, Kumar D, Soni SL, Sharma M. A Review on Theranostics: An Approach to Targeted Diagnosis and Therapy. Asian J Pharm Res Dev. 2019;7:63–9. [DOI]
6. Hapuarachchige S, Artemov D. Theranostic Pretargeting Drug Delivery and Imaging Platforms in Cancer Precision Medicine. Front Oncol. 2020;10:1131. [DOI] [PubMed] [PMC]
7. Song Y, Zou J, Castellanos EA, Matsuura N, Ronald JA, Shuhendler A, et al. Theranostics - a sure cure for cancer after 100 years? Theranostics. 2024;14:2464–88. [DOI] [PubMed] [PMC]
8. Papathanasiou N, Spiliotopoulou M, Karagkouni E, Apostolopoulos D, Katsakiori P, Yfantopoulos J, et al. Cost-Effectiveness of Positron Emission Tomography/Computed Tomography (PET/CT) in the Initial N-Staging of Head-Neck Cancer and Comparison with CT and Magnetic Resonance Imaging (MRI). Curr Oncol. 2025;32:677. [DOI] [PubMed] [PMC]
9. Theofilis P, Vlachakis PK, Oikonomou E, Drakopoulou M, Karakasis P, Apostolos A, et al. Cancer Therapy-Related Cardiac Dysfunction: A Review of Current Trends in Epidemiology, Diagnosis, and Treatment. Biomedicines. 2024;12:2914. [DOI] [PubMed] [PMC]
10. Wei X, Lin L, Zhang G, Zhou X. Cardiovascular Magnetic Resonance Imaging in the Early Detection of Cardiotoxicity Induced by Cancer Therapies. Diagnostics. 2022;12:1846. [DOI] [PubMed] [PMC]
11. Lee IS, Song YS, Choi YJ, Kim JI, Choi KU, Kim K. Dynamic Contrast-Enhanced MRI in the Evaluation of Soft Tissue Tumors and Tumor-Like Lesions: Technical Principles and Clinical Applications. Korean J Radiol. 2025;26:1054–74. [DOI] [PubMed] [PMC]
12. Zamorano JL, Lancellotti P, Rodriguez Muñoz D, Aboyans V, Asteggiano R, Galderisi M, et al. 2016 ESC Position Paper on cancer treatments and cardiovascular toxicity developed under the auspices of the ESC Committee for Practice Guidelines. Eur Heart J. 2016;37:2768–801. [DOI] [PubMed]
13. Subramanian M, Narasimhan B, Korabathina R, Batchu S, Ravilla VV, Roop M, et al. Utility of ^{18}F-FDG PET/CT and Cardiac MRI in early Cardiac Sarcoidosis. Indian Heart J. 2025;77:253–7. [DOI] [PubMed] [PMC]
14. Chen H, Ouyang D, Baykaner T, Jamal F, Cheng P, Rhee JW. Artificial intelligence applications in cardio-oncology: Leveraging high dimensional cardiovascular data. Front Cardiovasc Med. 2022;9:941148. [DOI] [PubMed] [PMC]

15. Morelli MB, Bongiovanni C, Da Pra S, Miano C, Sacchi F, Lauriola M, et al. Cardiotoxicity of Anticancer Drugs: Molecular Mechanisms and Strategies for Cardioprotection. Front Cardiovasc Med. 2022;9: 847012. [DOI] [PubMed] [PMC]
16. Scalia IG, Pathangey G, Abdelnabi M, Ibrahim OH, Abdelfattah FE, Pietri MP, et al. Applications of Artificial Intelligence for the Prediction and Diagnosis of Cancer Therapy-Related Cardiac Dysfunction in Oncology Patients. Cancers. 2025;17:605. [DOI] [PubMed] [PMC]
17. Nechita LC, Tutunaru D, Nechita A, Voipan AE, Voipan D, Tupu AE, et al. AI and Smart Devices in Cardio-Oncology: Advancements in Cardiotoxicity Prediction and Cardiovascular Monitoring. Diagnostics. 2025;15:787. [DOI] [PubMed] [PMC]
18. Rauscher I, Eiber M, Souvatzoglou M, Schwaiger M, Beer AJ. PET/MR in Oncology: Non–^{18}F-FDG Tracers for Routine Applications. J Nucl Med. 2014;55:25S–31S. [DOI] [PubMed]
19. Murtagh G, Januzzi JL, Scherrer-Crosbie M, Neilan TG, Dent S, Ho JE, et al. Circulating Cardiovascular Biomarkers in Cancer Therapeutics-Related Cardiotoxicity: Review of Critical Challenges, Solutions, and Future Directions. J Am Heart Assoc. 2023;12:e029574. [DOI] [PubMed] [PMC]
20. Xiao H, Wang X, Li S, Liu Y, Cui Y, Deng X. Advances in Biomarkers for Detecting Early Cancer Treatment-Related Cardiac Dysfunction. Front Cardiovasc Med. 2021;8:753313. [DOI] [PubMed] [PMC]
21. Meo L, Savarese M, Munno C, Mirabelli P, Ragno P, Leone O, et al. Circulating Biomarkers for Monitoring Chemotherapy-Induced Cardiotoxicity in Children. Pharmaceutics. 2023;15:2712. [DOI] [PubMed] [PMC]
22. Roth SM, Vietsch EE, Barefoot ME, et al. Cardiomyocyte-specific circulating cell-free methylated DNA in esophageal cancer patients treated with chemoradiation. Gastrointest Disord (Basel). 2021;3: 100–12. [DOI] [PubMed] [PMC]
23. Moore ZR, Yu AF, Liu J, Dang CT, Oeffinger KC, Steingart R, et al. Quantification of methylation-specific cardiomyocyte cell-free DNA as an early marker of cardiotoxicity in patients with breast cancer receiving anthracyclines and trastuzumab. J Clin Oncol. 2022;40:12090. [DOI]
24. Khuanjing T, Chattipakorn SC, Chattipakorn N. Emerging Targets and Treatments for Doxorubicin-Induced Cardiac Inflammation. J Inflamm Res. 2026;19:546243. [DOI] [PubMed] [PMC]
25. Wang H, Zhang Y, Zhang H, Cao H, Mao J, Chen X, et al. Liquid biopsy for human cancer: cancer screening, monitoring, and treatment. MedComm. 2024;5:e564. [DOI] [PubMed] [PMC]
26. Yu AF, Moore ZR, Moskowitz CS, Liu JE, Dang CT, Ramanathan L, et al. Association of Circulating Cardiomyocyte Cell-Free DNA With Cancer Therapy–Related Cardiac Dysfunction in Patients Undergoing Treatment for *ERBB2*-Positive Breast Cancer. JAMA Cardiol. 2023;8:697–702. [DOI] [PubMed] [PMC]
27. Setia A, Challa RR, Vallamkonda B, Satti P, Mehata AK, Priya V, et al. Nanomedicine And Nanotheranostics: Special Focus on Imaging of Anticancer Drugs Induced Cardiac Toxicity. Nanotheranostics. 2024;8:473–96. [DOI] [PubMed] [PMC]
28. Askambayeva N, Myrzabay Z, Harahsheh AJ, Ishak R, Biniyazova A, Aljofan M. Early Cardiac Biomarkers for the Detection of Cancer Therapy-Related Cardiac Dysfunction in Breast Cancer: A Systematic Review and Meta-Analysis. J Clin Med. 2026;15:7882. [DOI] [PubMed] [PMC]
29. Gyöngyösi M, Lukovic D, Zlabinger K, Spannbauer A, Gugerell A, Pavo N, et al. Liposomal doxorubicin attenuates cardiotoxicity via induction of interferon-related DNA damage resistance. Cardiovasc Res. 2020;116:970–82. [DOI] [PubMed]
30. Miao M, Liu X, Zhang H, Dai H. Immuno-inflammatory mechanisms in cardio-oncology: new hopes for immunotargeted therapies. Front Oncol. 2025;15:1516977. [DOI] [PubMed] [PMC]
31. STOP-CA Trial: Statin Therapy Associated With Reduced Heart Dysfunction From Anthracyclines [Internet]. American College of Cardiology Foundation; c2026 [cited 2026 May 3]. Available from: https://www.acc.org/latest-in-cardiology/articles/2023/03/01/22/45/sat-930am-stop-ca-acc-2023

32. Sapp V, Aguirre A, Mainkar G, Ding J, Adler E, Liao R, et al. Genome-wide CRISPR/Cas9 screening in human iPS derived cardiomyocytes uncovers novel mediators of doxorubicin cardiotoxicity. Sci Rep. 2021;11:13866. [DOI] [PubMed] [PMC]
33. Strong A. CRISPR gene-editing therapies for hypertrophic cardiomyopathy. Nat Med. 2023;29:305–6. [DOI] [PubMed] [PMC]
34. Mullen M, Wen Tan WL, Rhee JW, Wu JC. Modeling Susceptibility to Cardiotoxicity in Cancer Therapy Using Human iPSC-Derived Cardiac Cells and Systems Biology. Heart Fail Clin. 2022;18:335–47. [DOI] [PubMed] [PMC]
35. Tolu-Akinnawo OZ, Ezekwueme F, Omolayo O, Batheja S, Awoyemi T. Advancements in Artificial Intelligence in Noninvasive Cardiac Imaging: A Comprehensive Review. Clin Cardiol. 2025;48:e70087. [DOI] [PubMed] [PMC]
36. Jacobs JEJ, Greason G, Mangold KE, Wildiers H, Willems R, Janssens S, et al. Artificial intelligence electrocardiogram as a novel screening tool to detect a newly abnormal left ventricular ejection fraction after anthracycline-based cancer therapy. Eur J Prev Cardiol. 2023;31:560–6. [DOI] [PubMed] [PMC]
37. Pang M, Wang S, Shi T, Chen J. Overview of MitoQ on prevention and management of cardiometabolic diseases: a scoping review. Front Cardiovasc Med. 2025;12:1506460. [DOI] [PubMed] [PMC]
38. Garcia-Robledo JE, Cabrera-Salcedo S, Brandauer AM, Romano F, Rengifo-Martinez J, Toro-Pedroza A, et al. Engineering the next generation of CAR T- cells: precision modifications, logic gates and universal strategies to overcome exhaustion and tumor resistance. Front Oncol. 2026;15:1698442. [DOI] [PubMed] [PMC]
39. Teske AJ, Moudgil R, López-Fernández T, Barac A, Brown SA, Deswal A, et al. Global Cardio Oncology Registry (G-COR): Registry Design, Primary Objectives, and Future Perspectives of a Multicenter Global Initiative. Circ: Cardiovasc Qual Outcomes. 2023;16:e009905. [DOI] [PubMed] [PMC]
40. Zhou Z, Wang J. From data to decision: a clinical pipeline for wearable AI in early cardiotoxicity detection. Cardiooncology. 2026;12:89. [DOI] [PubMed] [PMC]