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The role of electrocardiography in monitoring cardiac function in patients undergoing tumor radiotherapy: A systematic literature review

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► ***Review article***

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ABSTRACT

Background: Radiotherapy, an essential treatment for numerous malignancies, can lead to radiation-induced heart disease (RIHD), including pericarditis, coronary artery disease, cardiomyopathy, valvular dysfunction, or arrhythmias. Early cardiac monitoring is crucial for timely interventions. Electrocardiography (ECG), a widely available, non-invasive diagnostic tool, provides real-time insights into cardiac electrical activity. However, its utility in detecting and managing RIHD remains underexplored. ***Materials and Methods:*** A systematic literature search was performed using PubMed, Embase, and Web of Science, focusing on studies published in English up to 2025 in order to evaluate the role of ECG in monitoring cardiac function in patients undergoing radiotherapy, its diagnostic potential, limitations, and emerging advancements. ***Results:*** ECG can detect early signs of RIHD, including ST-segment changes, QT interval prolongation, T-wave abnormalities, and conduction disturbances. While ECG is useful for baseline assessment and ongoing surveillance, its specificity for RIHD-related structural and functional changes is limited. Clinical guidelines recommend ECG as part of routine cardio-oncology care, particularly for high-risk patients. Advancements in wearable devices, such as smartwatches that can measure ECG and artificial intelligence-driven ECG interpretation, may improve early detection, enabling real-time monitoring and improving patient outcomes. ***Conclusions:*** ECG allows for early detection and monitoring of RIHD in patients undergoing radiotherapy. Integrating ECG with multimodal imaging and biomarkers can enhance diagnostic accuracy. Future research should focus on refining ECG-based risk stratification models, improving detection algorithms, and optimizing clinical guidelines for cardio-oncology surveillance. Emerging technologies, including AI and remote monitoring, can advance the utility of ECG.

INTRODUCTION

Radiotherapy is a crucial treatment modality for a number of cancers, including thoracic cancers, in which the heart is typically in close proximity to the tumor that is being irradiated. While radiotherapy has significantly improved cancer survival rates, it can also lead to long-term adverse effects, including RIHD [1]. RIHD encompasses a range of cardiac pathologies, such as pericardial inflammation, cardiomyopathy, coronary artery narrowing, heart valve damage, electrical conduction disturbances, and arrhythmias. These conditions can diminish the quality of life for cancer survivors and substantially contribute to non-cancer-related mortality [2]. As the number of cancer survivors continues to rise, there is a growing need for a deeper understanding and proactive management of these later-onset effects of treatments. This underscores the importance of effective cardiac monitoring strategies [3]. The heart is now recognized as a critical "organ at risk" in radiotherapy planning, emphasizing the necessity of minimizing cardiac exposure [4]. Early detection of cardiac dysfunction in patients undergoing or following radiotherapy is essential for enabling timely interventions that may help mitigate the progression of RIHD and improve long-term outcomes [5]. Systematic cardiac monitoring can identify subclinical cardiac effects, allowing for proactive management strategies [6]. ECG, a widely available, non-invasive, and cost-effective diagnostic tool, plays a fundamental role in evaluating the heart's electrical activity. It provides essential information on heart rate, rhythm regularity, and the timing and strength of electrical impulses [7]. ECG can detect various cardiac abnormalities, including arrhythmias, myocardial ischemia, and conduction disorders. Due to its ease of use and broad diagnostic utility, ECG serves as a cornerstone for the initial cardiac assessment and may have value in the ongoing surveillance of patients undergoing radiotherapy who are at risk for RIHD [8, 9].

The development and severity of RIHD are linked to several variables, including total radiation dose,

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dose per fraction, amount of heart irradiated, and specific anatomical substructures within the radiation field. For example, higher cumulative doses (>30 Gy) and fractionation schedules (>2 Gy/ fraction) significantly increase the risk, and left-sided thoracic radiation is a very important risk factor due to increased exposure of crucial cardiac regions like the left anterior descending artery [10-12]. This can result in a spectrum of pathologies ranging from acute pericarditis and accelerated coronary artery disease to late-onset cardiomyopathy, valvular stenosis or regurgitation, and complex arrhythmias [1-3, 13]. ECG may be an insightful and non-invasive tool in this context as its use extends beyond the detection of general arrhythmias to that of subtle but significant electrophysiological alterations, such as ST -segment deviation, T-wave abnormalities, QT interval lengthening, and conduction disturbance, which may reflect early myocardial, pericardial, or conduction system injury secondary to radiation therapy [14-16]. It is important to interpret these ECG results in the context of patient-specific radiation exposures and risk profiles for the purposes of early intervention and improved long-term cardiovascular outcomes in cancer survivors.

This review explores the role of ECG in monitoring cardiac function in patients receiving tumor radiotherapy. It covers the principles of ECG, examines the mechanisms of RIHD in cancer patients, outlines ECG findings associated with RIHD manifestations, evaluates the advantages and limitations of ECG, reviews current clinical guidelines, and highlights future directions in ECG technology for cardio-oncology. The novelty of this review is that, given the relative lack of comprehensive research in this area, we consolidate existing knowledge and emphasize the need for further investigation into ECG -based monitoring for RIHD.

Search criteria

The search used various combinations of terms, including “electrocardiograp*”, “radiotherap*”, “cardiotoxic*”, “radiation-induced heart disease”, “RIHD”, “arrhythmi*”, “myocard*”, “valv*” and “function*”, with appropriate boolean modifiers and operators. The search timeline was from database inception to April 2025. PubMed, EMBASE, and Web of Science were all searched. Inclusion criteria encompassed original research articles, reviews, and meta-analyses, as well as clinical guidelines related to ECG monitoring of heart function. Studies assessing ECG changes in any aspect of heart function, valvular function, RIHD, arrythmias, cardiomyocyte function, or cardiotoxicity specifically were screened based on the abstract, and if deemed relevant, the full-text was read and any relevant references were also obtained.

RIHD manifestations and risks

RIHD encompasses a spectrum of cardiac complications that vary in onset and clinical presentation. The mechanisms underlying radiation-induced cardiotoxicity involve a series of events triggered by the exposure of cardiac tissues to ionizing radiation during radiotherapy [3]. Radiation exposure can damage the DNA of cardiac cells, induce oxidative stress through the generation of reactive oxygen species, and stimulate the release of inflammatory and profibrotic cytokines [17, 18]. Whilst there are limited studies showing the specific molecular mechanisms by which radiotherapy induces damage to heart tissue, the study of other forms of radiation provides insights. Electromagnetic radiation from cell phones was shown to decrease superoxide dismutase, catalase, and glutathione peroxidase levels, and increase the concentration of malondialdehyde levels, suggesting increased oxidative stress [19]. These processes contribute to fibrosis in the vasculature, myocardium, heart valves, and pericardium [13, 20, 21]. Endothelial cell injury is a key factor in the pathogenesis of RIHD, leading to inflammation, altered coagulation, and increased platelet activity [22-26]. A major consequence is the acceleration of atherosclerosis in coronary arteries, particularly in the proximal segments, such as the left anterior descending and right coronary artery. Myocardial fibrosis can lead to ventricular remodeling, diastolic dysfunction, and conduction abnormalities [27-30]. Valvular heart disease may develop due to fibrosis and calcification, primarily affecting the aortic and mitral valves [13]. Additionally, the pericardium is vulnerable to radiation injury, which can result in pericarditis and pericardial effusion [31, 32].

Pericarditis may present in an acute form within days to months after radiotherapy or as chronic/ constrictive pericarditis developing months to years later. Coronary artery disease, characterized by accelerated atherosclerosis, primarily affects the proximal coronary arteries and can lead to myocardial ischemia and infarction. Cardiomyopathy, resulting from direct myocyte damage and fibrosis, may lead to heart failure with either reduced or preserved ejection fraction. Valvular heart disease develops due to fibrosis and calcification of the heart valves, predominantly affecting the aortic and mitral valves, leading to stenosis or regurgitation. Additionally, conduction disorders and arrhythmias, including bradycardia and tachycardia, can arise from radiation-induced damage to the heart’s electrical conduction system [33-37].

Risk factors for RIHD include higher cumulative radiation doses to the heart (typically >30 Gy) [38] and higher fractionated doses (>2 Gy) [10, 11]. Of note, in one study, it was shown that the risk of adverse side effects such as acute skin reactions and bone marrow suppression in patients undergoing radiotherapy for early breast cancer was low in patients receiving hypofractionated radiotherapy (2-5 Gy per day)

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when compared with conventional fractionated radiotherapy (<2 Gy) [39]. To the best of our knowledge, there are no studies assessing this in relation to heart function, but this may be a subject of a future study. The risk also increases with greater cardiac volume exposure to radiation. Younger patients at the time of radiotherapy may have a higher lifetime risk of developing late cardiac effects. The latency period between radiation exposure and the onset of RIHD can span years or even decades [12, 40-42]. For example, in a 33-year-old female patient treated with chemoradiotherapy, which included mantle field radiation therapy (total dose 3,930 cGy) for treatment of Hodkin's lymphoma, 11 years after successful treatment, she developed severe coronary vasculopathy that was attributed to the prior irradiation [40]. Additionally, concurrent treatment with cardiotoxic chemotherapeutic agents (including trastuzumab, anthracyclines, and fluorouracil) further elevates the risk, while pre-existing heart conditions and other cardiovascular risk factors increase susceptibility to RIHD [43, 44]. Another study showed that 3D conformal RT with 50.4 Gy and a simultaneous integrated boost dose of 14 or 16.8 Gy in the same 28 fractions in patients with a pre-existing atherosclerotic plaque increased the risk of developing a radiation-induced acute coronary event [41]. The radiation field and technique also play a role, with left-sided breast irradiation being particularly associated with increased cardiac exposure [9, 12, 17, 45, 46]. Studies suggest that even low mean cardiac doses may contribute to long-term cardiovascular complications. In younger patients who received a radiotherapy dose of ≥35 Gy, all the patients exhibited RIHD, with some presenting with multiple manifestations. These manifestations included increased interstitial myocardial fibrosis, a thickened pericardium, and fibrous thickening of the endocardium [41, 42]. Over a five-year follow-up, patients experienced major cardiac complications such as pericardial effusion, atrial fibrillation, and two instances of sudden death. The primary predictor of these cardiac events following chemoradiotherapy was the extent of radiation exposure to the heart, with increased exposure correlating with a higher incidence of adverse outcomes [47].

ECG findings in radiation-induced cardiac complications

Studies specifically examining ECG variations in patients undergoing radiotherapy are limited; therefore, in some instances, the following section extrapolates ECG findings from similar cardiac manifestations observed in non-radiation-induced settings. In radiation-induced pericarditis, the ECG may show diffuse ST-segment elevation and PR-segment depression, similar to other causes of pericarditis, often accompanied by sinus tachycardia [48]. ECG changes can evolve through distinct stages, with chronic pericarditis potentially presenting as left atrial enlargement, atrial arrhythmias, right axis deviation, and reduced QRS voltage [14, 49, 50]. While radiation-induced coronary artery diseases do not have specific ECG markers, they may exhibit signs of myocardial ischemia or infarction, including ST-segment depression or elevation, T-wave inversion, or the presence of Q waves. T-wave abnormalities and poor R-wave progression are also commonly observed. Radiation-induced cardiomyopathy in patients receiving a 1.5-3.0 Gy daily dose of intensity-modulated radiation therapy (cumulative dose of 40.0-70.0 Gy) was typically associated with non-specific ECG findings, such as low QRS voltage, conduction disturbances, ST-T wave changes, and arrhythmias [51]. In radiation-induced valvular heart disease, ECG findings are generally non-specific but may suggest hemodynamic consequences of valve dysfunction, such as left ventricular hypertrophy or atrial fibrillation [52]. Radiation-induced arrhythmias can manifest as bradyarrhythmias, tachyarrhythmias, and conduction abnormalities such as right bundle branch block. Additionally, QT interval prolongation may occur, increasing the risk of arrhythmias [47, 53-56].

Table 1. Summary of potential ECG findings associated with common cardiac complications in RIHD.

Cardiac complication	Potential ECG findings
Pericarditis (acute)	Diffuse ST-segment elevation, PR-segment depression, reciprocal changes in aVR, sinus tachycardia
Pericarditis (chronic)	Left atrial enlargement, atrial arrhythmias, right axis deviation, low QRS voltage
Coronary artery disease	ST-segment depression/elevation, T-wave inversion, Q waves, T-wave changes (early), poor R-wave progression
Cardiomyopathy	Low QRS voltage, conduction disturbances, ST-T wave changes, bradycardia, tachycardia
Valvular heart disease	Left ventricular hypertrophy (in aortic valve disease), atrial fibrillation (in mitral valve disease), ST-segment changes (with co-existing coronary artery disease), bradycardia (with left ventricular dysfunction)
Arrhythmias	Sinus bradycardia, sinus tachycardia, atrial fibrillation, atrial flutter, ventricular tachycardia, AV block, right bundle branch block, 'rSr'* pattern, QT interval prolongation

*A QRS morphology seen in V1-V2, showing a small R wave, a deep S wave, and a taller second R' wave.

A baseline ECG is recommended for all patients before initiating potentially cardiotoxic cancer treatments, including radiotherapy. This helps identify pre-existing cardiovascular conditions and establishes a reference point for future monitoring [1]. Abnormal findings may warrant a referral to a cardiologist. ECG monitoring should be considered during radiotherapy for high-risk patients, including those with implantable cardioverter-defibrillators (ICDs) or a history of ventricular arrhythmias [57]. The use of remote cardiac monitoring via smartwatches is

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currently being investigated [58]. Regular ECGs are recommended for long-term cardiac surveillance following chest radiotherapy, with the frequency determined by individual risk factors and symptoms. An annual cardiovascular risk assessment, including an ECG, is often advised [59, 60]. ECGs play a crucial role in detecting early signs of RIHD, such as arrhythmias, ischemic changes, or conduction abnormalities. For a comprehensive assessment, ECG findings can be integrated with echocardiography and cardiac biomarkers [6]. Any ECG abnormalities may prompt further investigation if necessary.

Table 2. Summary of recommendations for cardiac monitoring with ECG before, during, and after radiotherapy.

Time Point	Recommendation	Risk stratification
Before radiotherapy	Baseline 12-lead ECG to identify pre-existing conditions	All patients receiving potentially cardiotoxic radiotherapy
During radiotherapy	Consider continuous ECG monitoring	Patients with ICDs and history of ventricular arrhythmias, high-risk patients
After radiotherapy - short-term	ECG monitoring at intervals based on risk and treatment regimen	Patients with higher mean heart dose, concurrent cardiotoxic therapies, pre-existing conditions
After radiotherapy - long-term	Annual cardiovascular risk assessment including ECG	All survivors treated with potentially cardiotoxic radiotherapy or radiation to the chest, particularly patients deemed to be at high-risk prior to radiotherapy

ECG offers several advantages for monitoring cardiac function in patients undergoing radiotherapy. It is a non-invasive, well-tolerated, readily available, and cost-effective diagnostic tool. ECG provides immediate data on heart rate and rhythm while detecting signs of myocardial ischemia, pericarditis, and conduction disturbances [7, 61]. It is useful for both baseline assessment and ongoing monitoring, with portable devices enabling its application in various settings, including remote monitoring [62].

Despite its advantages, ECG has certain limitations. Findings in RIHD can be non-specific and may overlap with other cardiac conditions. Its sensitivity and specificity in detecting early cardiomyopathy or valvular heart disease are limited [63-65]. ECG primarily assesses electrical activity and may not accurately reflect structural or functional changes. Additionally, artifacts can interfere with recordings, and observed changes may not always correlate with the severity of dysfunction [66, 67]. Long-term ECG monitoring may improve sensitivity for detecting infrequent arrhythmias, though algorithm-based detection may miss some arrhythmias compared to human review [68]. As a result, ECG alone is often insufficient for diagnosis and typically requires integration with other diagnostic modalities for a comprehensive assessment. These can include X-ray, CT, MRI, ultrasonography, and nuclear medicine imaging; an excellent review covers the use of multi-modal imaging technologies for the differential diagnosis of myocarditis [69].

Cardio-oncology guidelines from organizations such as the European Society of Cardiology (ESC) and the American Society of Clinical Oncology (ASCO) emphasize the importance of cardiovascular risk assessment and monitoring during and after cancer treatment, including radiotherapy [70-72]. ECG is recommended as part of both the initial evaluation and ongoing follow-up [73]. Cancer survivors who have undergone cardiotoxic therapies or chest radiation are advised to undergo an annual cardiovascular risk assessment, including an ECG [16, 72, 74, 75]. For patients receiving radiotherapy, recommendations include a baseline ECG, potential ECG monitoring during treatment for high-risk individuals, and regular post-radiotherapy surveillance ECGs based on individual risk factors and symptoms [72, 76]. Guidelines also suggest integrating ECG with other diagnostic modalities. Specific actions based on ECG findings may include discontinuing QT-prolonging therapies and referring patients with significant abnormalities to cardiology for further evaluation [70-73].

Future perspectives and conclusions

Recent advancements in ECG technology include the development of portable and wearable devices for continuous monitoring, integration with electronic health records (EHR), enhanced signal processing, and device miniaturization. Artificial intelligence (AI) is also being explored to assist in ECG interpretation, detect cardiotoxicity, and predict cardiovascular events. AI-enabled ECG technology has the potential to serve as a cost-effective screening tool for early cardiac risk detection [77]. Furthermore, remote ECG monitoring and telemedicine improve access to cardiac care and support the early detection of abnormalities. The National Health Service (NHS) in the United Kingdom is currently exploring the use of smartwatches for remote ECG monitoring following radiotherapy [58].

ECG is a vital tool for monitoring cardiac function in patients undergoing tumor radiotherapy, playing a key role in detecting various cardiac complications. While ECG is widely accessible and easy to use, its limitations highlight the need for integration with other diagnostic modalities to ensure a comprehensive assessment.

Clinical guidelines emphasize the importance of ECG in cardio-oncology management, and future advancements, particularly in artificial intelligence and remote monitoring, offer promising opportunities to enhance cardiac surveillance and improve outcomes for cancer survivors. However, further research is needed to fully harness these innovations in addressing RIHD.

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