International Journal of Sustainable Progress
Volume 4, Issue 1, June 2025
https://ijsp.globalpublisher.org/
https://globalpublisher.org/journals-1001/

Electrocardiograph devices: a comprehensive review of technology, clinical utility, economic impact, and environmental sustainability

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ABSTRACT
The electrocardiograph (ECG) remains one of the most widely used diagnostic tools in cardiovascular medicine, offering rapid, non-invasive assessment of cardiac electrical activity. This review provides a structured overview of ECG technology, encompassing its operational principles, device categories, and evolving form factors from conventional lead systems to wearable and implantable recorders. The advantages of ECG device including real-time monitoring, high sensitivity for arrhythmias, cost-effectiveness, and suitability for telemedicine are contrasted with limitations such as motion artifacts, interpretive dependency on clinician expertise, and electrode-related skin reactions. Clinical applications span acute coronary syndrome detection, arrhythmia diagnosis, pre-operative screening, and remote patient surveillance, increasingly augmented by artificial intelligence. Economic analysis reveals a global ECG market driven by aging populations and value-based care, with favorable cost-utility ratios when compared to advanced imaging modalities, although reimbursement disparities and upfront device
costs remain barriers in low-resource settings. The environmental footprint of ECG technology is critically examined, highlighting the burden of single-use electrodes, lead-set waste, and electronic hardware disposal. Emerging strategies such as reusable electrode systems, biodegradable substrates, and energy efficient device design are discussed as pathways toward sustainability. By synthesizing clinical, economic, and ecological perspectives, this article identifies trade-offs and opportunities for innovation, providing a holistic reference for clinicians, health system planners, and biomedical engineers.
Keywords: Electrocardiograph; ECG; advantages and disadvantages; clinical applications; economic analysis; environmental sustainability

1. INTRODUCTION

Since Willem Einthoven's first clinical recording in 1903, the electrocardiograph has evolved from a cumbersome string galvanometer into an indispensable, miniaturized diagnostic platform [1]. Modern ECG devices acquire, amplify, and display the heart's electrical potentials through surface electrodes, yielding waveforms that reflect atrial and ventricular depolarization and repolarization. The fundamental 12‑lead ECG, Holter monitors, event recorders, and smartphone‑enabled wearables collectively constitute a global market projected to exceed USD 7 billion by 2030 [2]. While clinical benefits are extensively documented, a comprehensive evaluation must also address economic and environmental dimensions that influence technology adoption and sustainability. The present review therefore aims to (i) describe contemporary ECG device architectures and their operational characteristics, (ii) systematically categorize
advantages and disadvantages, (iii) map clinical applications, (iv) quantify economic considerations including cost‑effectiveness and market dynamics, (v) assess the environmental life‑cycle impacts of ECG consumables and hardware, and (vi) highlight emerging solutions that reconcile performance with ecological responsibility.

2. FUNDAMENTALS OF ECG TECHNOLOGY

The surface ECG records the summation of cardiac myocyte action potentials via electrodes placed on the skin. A standard 12‑lead system uses ten electrodes (four limb, six precordial) to derive twelve voltage‑versus‑time traces, providing spatial information about the heart's electrical axis and regional ischemia [3]. Signal acquisition hardware includes instrumentation amplifiers with high common‑mode rejection, analog‑to‑digital converters, and microprocessor‑based processing for filtering (0.05–150 Hz) and rhythm analysis.
Contemporary ECG devices span several categories:

• Resting 12‑lead ECG: Gold‑standard for morphological diagnosis, typically used in hospitals and outpatient clinics.

• Holter monitors: Continuous 24–48‑hour ambulatory recording, enabling capture of intermittent arrhythmias.

• Event recorders and patch monitors: Patient‑activated or auto‑triggered devices worn for up to 30 days, improving diagnostic yield for infrequent symptoms.

• Wearable and smart‑textile ECG: Integrated into watches, chest straps, and garments, facilitating consumer‑oriented wellness tracking and medical‑grade monitoring when coupled with cloud analytics

• Implantable loop recorders: Subcutaneously inserted devices for long‑term (up to 3 years) rhythm surveillance in cryptogenic stroke or unexplained syncope.
Signal processing algorithms, increasingly powered by machine learning, extract heart rate variability, detect atrial fibrillation, and quantify QT intervals, reducing manual interpretation time.

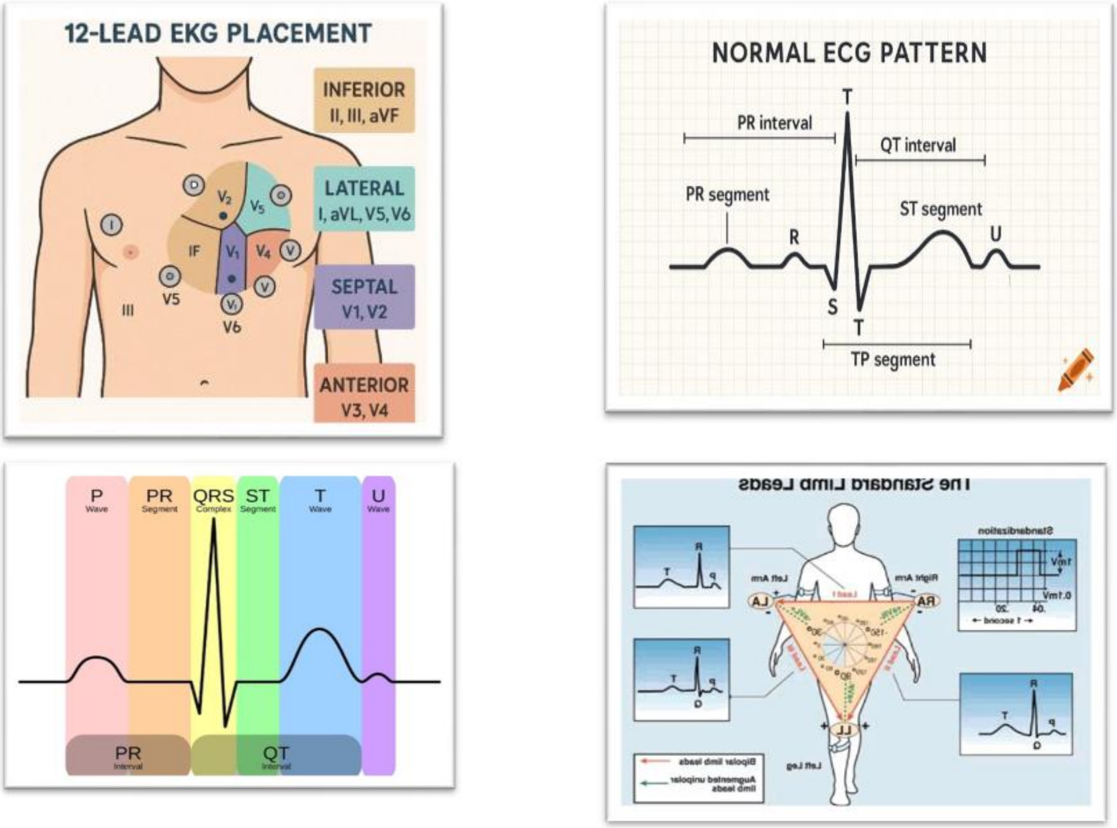

Figure1: standard ECG lead placement and normal electrocardiographic waveform components.

3. ADVANTAGES AND DISADVANTAGES

3.1 Advantages

ECG devices offer a unique combination of attributes that sustain their clinical primacy:
Non‑invasiveness and speed: A 10‑second recording suffices for rhythm and ischemia screening, with minimal patient discomfort.

• High sensitivity for arrhythmias: Paroxysmal atrial fibrillation detection rates exceed 90% with extended monitoring, enabling timely anticoagulation [6.]

• Portability and connectivity: Pocket‑sized recorders and smartphone‑based systems permit point‑of‑care use in remote or resource‑limited settings, with seamless data transmission to specialists.

• Cost‑effectiveness: Compared to echocardiography, cardiac MRI, or nuclear imaging, ECG is
inexpensive and widely available, supporting population‑level screening programs [7.]

• Patient empowerment: Consumer wearables promote health awareness and early arrhythmia detection, potentially reducing emergency department visits.

• Low energy requirements: Battery‑powered designs allow prolonged ambulatory recording without frequent recharging. 3.2 Disadvantages and Limitations Despite its utility, the ECG possesses inherent constraints:

• Artifact susceptibility: Movement, muscle tremor, and poor electrode contact generate noise that can obscure subtle ST‑segment changes or P‑waves, leading to erroneous computer interpretations

• Interpreter dependency: Accurate diagnosis requires significant training; automated algorithms
exhibit variable specificity, risking false‑positive alarms that trigger unnecessary downstream testing.

• Limited structural information: The ECG reflects electrical activity only; it cannot directly visualize chamber size, valve function, or pericardial effusion.

• Electrode‑related adverse effects: Prolonged wear can cause skin irritation, allergic contact dermatitis (often due to gel or adhesive components), and pressure ulcers in frail patients.

• Data overload: Extended monitoring generates vast datasets that may overwhelm clinicians and
health information systems without robust triage tools.

• Disposable waste: Single‑use electrodes and lead‑wire sets contribute substantially to medical
plastic waste (discussed in Section 6)

Figure 2: environmental impact of ECG technology and sustainable solutions including biodegradable electrodes and reusable materials, medical waste and recycling practices.

Table 1. Categorized advantages and disadvantages of ECG devices. (Compiled from [3,6,8,9,11]).

Category	Advantages	Disadvantages
Diagnostic performance	High sensitivity for rhythm disorders, real-time ischemia detection	Limited by artifact, poor specificity in screening low-risk populations
Usability	Rapid acquisition, minimal patient preparation	Lead misplacement alters morphology; adhesive failures in sweaty skin
Economic	Low per-test cost, reusable hardware	High-volume consumable expenditure; false positives increase downstream costs
Portability	Compact, battery-powered, telemedicine-ready	Wearable device accuracy may not meet clinical standards
Environmental	Reusable cables reduce waste in some settings	Dominance of single-use electrodes, packaging, and electronic waste

4 .CLINICAL APPLICATIONS

The ECG's versatility underpins its use across the continuum of cardiovascular care:

• Acute coronary syndromes: ST-segment elevation myocardial infarction (STEMI) triage relies on the 12-lead ECG, reducing door-to-balloon time [10]. Serial ECGs improve sensitivity for non-STEMI.

• Arrhythmia diagnosis and management: Holter and event monitors identify atrial fibrillation, supraventricular tachycardias, ventricular ectopy, and bradyarrhythmias guiding antiarrhythmic therapy or device implantation [6.]

• Screening and risk stratification: Pre‑participation sports screening, pre‑operative assessment, and pharmacovigilance (e.g., QTc monitoring with antipsychotics or antibiotics) rely on baseline and follow‑up ECGs [11.]

• Electrolyte and drug‑effect recognition: Characteristic patterns of hyperkalemia, hypocalcemia,
and digitalis effect provide bedside diagnostic clues.

• Remote patient monitoring: Tele‑ECG programs reduce heart failure readmissions by detecting
early signs of decompensation through heart rate variability and arrhythmia burden [12.]

• Artificial intelligence integration: Deep learning models trained on millions of ECGs can now predict left ventricular dysfunction, silent atrial fibrillation, and even non‑cardiac conditions such
as anemia, expanding the ECG's diagnostic horizon [5,1

5 .ECONOMIC PERSPECTIVES

5.1 Market Dynamics and Cost‑Effectiveness The ECG devices market is growing at a compound annual rate of 5–7%, driven by the rising prevalence of cardiovascular disease, adoption of telemedicine, and consumer health trends [2]. High‑volume, low‑cost 12‑lead systems dominate hospital procurement, while the wearable patch segment exhibits the fastest expansion due to reimbursement for extended monitoring. Cost‑effectiveness analyses consistently demonstrate that ECG‑based screening for atrial fibrillation in older adults yields incremental cost‑effectiveness ratios well below common willingness‑to‑pay thresholds, particularly when stroke prevention is modeled [7]. Compared to advanced imaging such as coronary CT angiography for stable chest pain, the resting ECG is orders of magnitude cheaper, though less anatomically specific.

5.2 Reimbursement and Health System Impact In many high‑income countries, ambulatory ECG monitoring is reimbursed under diagnosis‑related group codes or fee‑for‑service schedules, incentivizing uptake. However, the economic evaluation of novel wearable devices is complicated by unclear billing pathways and concerns that over‑detection of subclinical findings may escalate healthcare utilization without proportional benefit [14]. Conversely, in low‑ and middle‑income countries, the capital cost of 12‑lead machines and the shortage of trained
interpreters limit access, prompting interest in ultra‑low‑cost smartphone ECG devices that offset initial expenditure through task‑shifting.

Table 2. Economic comparison of selected ECG modalities. (Adapted from [2,7,14]).

Modality	Approx. cost per test (USD)	Reimbursement landscape	Main economic advantage
12-lead resting ECG	25–50	Widely covered	Lowest cost, universal availability
24-hour Holter	150–300	Covered with prior auth	High diagnostic yield for daily symptoms
30-day patch monitor	350–600	Increasing coverage	Superior detection of infrequent arrhythmias
Smartphone single-lead	5–15 (device amortized)	Limited	Mass screening, telemedicine scalability

5.3 Indirect Economic Benefits

Remote ECG monitoring reduces travel costs, lost productivity, and emergency department visits. A systematic review estimated that telehealth ECG programs for heart failure save approximately USD 1,200 per patient‑year by averting hospitalizations [12]. From a societal perspective, return on investment improves when devices are integrated into chronic disease management ecosystems rather than used in isolation.

6.ENVIRONMENTAL PERSPECTIVES

6.1 Material Footprint of ECG Consumables

The environmental burden of ECG diagnostics originates primarily from single‑use items: adhesive electrodes (Ag/AgCl sensor, hydrogel, foam backing, plastic release liner), disposable lead‑wire sets, paper tracings, and sterile packaging. A single 12‑lead recording typically generates 30–60 g of non‑biodegradable waste [15]. When multiplied by millions of daily tracings globally, the cumulative impact on landfill and incineration emissions is substantial. Electrode manufacturing involves silver, a precious metal with energy‑intensive mining and refining, while polyvinyl chloride and polyurethane components persist in the environment for centuries.

6.2 Electronic Waste and Energy Consumption

Hospital‑grade ECG carts and telemetry transmitters become electronic waste (e‑waste) at end‑of‑life, containing lead, brominated flame retardants, and lithium batteries. Although the useful lifespan of a central monitoring station may exceed eight years, rapid innovation cycles in wearables render consumer‑grade ECG watches obsolete within 2–3 years, exacerbating the e‑waste stream [16]. Energy consumption of networked monitoring systems is non‑negligible;

however, compared to imaging equipment (MRI, CT), ECG devices are relatively energy‑efficient per patient encounter.

6.3 Strategies for Sustainability

Emerging solutions aim to align ECG diagnostics with circular economy principles:

• Reusable electrodes: Stainless steel or conductive‑textile electrodes with medical‑grade cleaning protocols can substitute single‑use variants for non‑critical applications, reducing waste by up to 80% over a device's lifetime [17]. Concerns about cross‑contamination require validated sterilization procedures.

• Biodegradable substrates: Research into chitosan‑based gels and polylactic acid electrode backings offers compostable alternatives that maintain signal quality comparable to conventional Ag/AgCl electrodes [18.]

• Lead‑set redesign: Modular cables with replaceable lead‑wires decrease whole‑set disposal; some manufacturers now offer reprocessing services.

• Green procurement and recycling: Hospitals with sustainability mandates preferentially purchase ECG devices certified under electronic product environmental assessment criteria and partner with recyclers to recover silver and copper from used electrodes [19.]

• Life‑cycle assessment (LCA): Quantitative LCA studies comparing disposable versus reusable systems show that reusable electrodes, when reprocessed efficiently, lower carbon footprint and water usage, though the benefit margin depends on local energy mix and sterilization energy demands [20

7.RESULTS AND DISCUSSION

This review synthesizes multi‑dimensional evidence to produce a balanced perspective on ECG device utilization. Clinically, the technology's advantages—non‑invasiveness, immediacy, and expanding AI‑enhanced diagnostic power—continue to outweigh its limitations. However, false positives, interpretation errors, and over‑reliance on automated algorithms remain quality‑of‑care concerns that necessitate clinician oversight and ongoing training. Economically, resting ECG and short‑term monitors are highly cost‑effective for targeted indications, yet indiscriminate screening of asymptomatic low‑risk individuals may strain budgets without proportionate health gains. Wearable and smartphone‑based ECG devices represent a double‑edged sword: they democratize access and enable early detection, but also generate a "worried well" phenomenon and increased follow‑up testing that can erode cost advantages. Health technology assessment frameworks must therefore incorporate not only device accuracy but also downstream resource utilization.

On the environmental front, the disposable‑dominated model of ECG consumables is increasingly at odds with climate‑conscious healthcare policies. The data suggest that transitioning to reprocessable electrodes and biodegradable materials is technically feasible without compromising signal fidelity. The main barriers are institutional inertia, upfront investment in sterilization infrastructure, and regulatory uncertainty regarding re‑use of medical electrodes in different patient populations. Economic incentives such as landfill taxes and extended producer responsibility schemes could accelerate adoption of eco‑design. Additionally, tele‑ECG programs inherently reduce patient travel emissions, offering a modest but real environmental co‑benefit.

The interplay among clinical need, economic reality, and ecological sustainability is complex. A reusable electrode may be environmentally superior but might increase labor costs for cleaning or require capital expenditure for autoclaves, potentially offsetting savings if energy comes from fossil fuels. Therefore, life‑cycle thinking must be localized. Future research should prioritize head‑to‑head trials that measure not only diagnostic accuracy but also total cost of ownership and carbon footprint for each ECG strategy.

8 .CONCLUSION

The electrocardiograph is a cornerstone of cardiovascular diagnosis, continually adapting through miniaturization, connectivity, and artificial intelligence. While its clinical and economic value is undisputed, the prevailing "take‑make‑dispose" consumption model for electrodes and accessories imposes a hidden environmental toll that can no longer be ignored. By adopting a holistic framework that balances clinical efficacy, cost‑effectiveness, and ecological integrity, stakeholders—including manufacturers, clinicians, hospital administrators, and regulators—can drive innovation toward high‑performance, affordable, and sustainable ECG solutions. The path forward involves embracing reusable and biodegradable materials, enforcing green procurement standards, and integrating environmental metrics into health technology assessments.

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