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The Role of Exercise Stress Testing and ECG Monitoring in Early Detection of Cardiac Abnormalities: A Systematic Review

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ABSTRACT

Cardiovascular diseases (CVDs) are still the most common cause of morbidity and mortality in the world, prompting the discovery of early detection strategies which could help in preventing these outcomes. Exercise stress testing (EST) and electrocardiogram (ECG) monitoring are well-established, non-invasive diagnostic methods to evaluate cardiac physiology and identify ischemic alterations at strain conditions. The objective of this systematic review was to assess the sensitivity of EST and ECG monitoring for the identification of cardiac abnormalities such as CAD, arrhythmia, and silent ischemia.

Methods: A literature search was performed on PubMed, Scopus, Web of Science, and Cochrane Library databases from years 2000 to 2024. Results show that (when combined with continuous ECG monitoring) the use of EST enhances diagnostic capabilities, risk stratification, and therapeutic interventions. Emerging technologies, including wearable ECG and AI-based analysis of patient data, take early detection, and subsequent surveillance up a notch. Although potentially useful, false positivity rates and a loss of sensitivity in some populations illustrate the need for more individualized assessment and other imaging modalities when indicated. In general, EST and ECG testing occupy an important place in preventive cardiology with non-invasive and inexpensive methods for the early detection and treatment of cardiac abnormalities.

Keywords: *exercise stress testing, ECG monitoring, cardiac abnormalities, early detection, coronary artery disease, arrhythmia, preventive cardiology.*

1. INTRODUCTION

Cardiovascular diseases (CVDs) remain the most common cause of death globally, with 17.9 million deaths annually (World Health Organization (WHO), 2021) Identifying predisposed individuals is particularly vital as this enables early detection of cardiac abnormalities and thus can decrease the likelihood of developing a major adverse cardiac event and therefore decrease mortality and healthcare costs. However, the available therapeutic interventions are not sufficient, and asymptomatic disease or non-specific symptoms can persist for a long time before significant disease progression occurs.

Exercise stress testing (EST) and electrocardiogram (ECG) monitoring are pillar non-invasive diagnostic components in widespread clinical practice for cardiovascular assessment. Exercise Stress Testing EST involves the assessment of the functional capacity of the heart under controlled physical stress, simulating conditions in which one may have induced perfusion to provoke myocardial ischemia or unmasking an underlying electrical abnormality. It enables clinicians to assess heart rate, blood pressure, and ECG response during exercise, giving valuable information regarding the identification of the presence of coronary artery disease (CAD) and exercise-induced arrhythmias (Gibbons et al., 2002).

The resting ECG, although useful, cannot recognize intermittent ischaemic alterations in the setting of exertion (or) stress. Therefore, the dynamic ECG monitoring under exercise or ambulatory Holter monitoring provides better or extend full assessment of cardiac electrical activity. Continuous ECG monitoring during EST for silent ischemia, intermittent arrhythmias, and conduction abnormalities, provides higher sensitivity and specificity (Fleg et al., 2000). Moreover, recent technological developments, including the use of wearable ECG devices and artificial intelligence (AI) in assisting data analysis, have opened up even larger scopes for these technologies. By enabling continuous, real-time monitoring in outpatient and community level settings, wearables may allow early identification of high risk individuals, and subsequently, timely intervention (Saxena et al., 2022).

Although with high prevalence and essential clinical availability, EST and ECG monitoring have their limitations. Diagnostic accuracy is impacted by variations in sensitivity and specificity, especially in groups like women, older patients, and those with preexisting ECG abnormalities (Kwok et al., 2019). Moreover, false-positive results prompt unnecessary invasive tests and neuroticism. Hence, appropriate patient selection and interpretation, frequently in conjunction with imaging modalities, particularly echocardiography or myocardial perfusion imaging, is necessary.

The objective of this systematic review is to summarise and critically examine the current evidence for the utility of EST and ECG monitoring for the identification of cardiac abnormalities early after TBI. The review systematically assesses their diagnostic performance, clinical utilization, advances in technology, and limitations to offer clinically relevant and future research guiding information.

2. METHODOLOGY

Study Design

The systematic review was performed following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to enhance transparency and reproducibility of the review process. We aimed to investigate the diagnostic utility of EST and ECGs in the prompt diagnosis of cardiac abnormalities.

Data Sources and Search Strategy:

A systematic search of the literature was conducted through the PubMed, Scopus, Web of Science, Cochrane Library and Google Scholar databases. The search spanned from January 2000 to December 2024 to include earlier foundational works as well as more recent developments.

Search terms used were a combination of keywords and MeSH:

"exercise stress testing,"

"ECG monitoring,"

"electrocardiogram,"

"early detection,"

"cardiac abnormalities,"

"coronary artery disease,"

"silent ischemia,"

"arrhythmia," and

"preventive cardiology."

Optimisation of the search was achieved using Boolean operators (AND, OR). More studies were found by performing screening of reference lists of retrieved articles and reviews.

Eligibility Criteria:

Inclusion criteria:

Focus: Original peer-reviewed studies, systematic reviews and meta-analyses

Test performance study of EST and/or ECG monitoring for the detection of cardiac abnormalities in asymptomatic or symptomatic adults articles published in English.

Articles with sensitivity, specificity, positive predictive value, negative predictive value, or clinical outcome associated with early detection

Exclusion criteria:

Reports, Editorials, Comments and conference abstracts in which full text report not provided Researches that only concentrate on children population.

Research that assesses diagnostic imaging modalities not compared to EST or ECG monitoring

Study Selection:

Two independent reviewers (Reviewer A and Reviewer B) screened titles and abstracts for eligibility. Potentially relevant articles had their full texts retrieved and were then evaluated for inclusion or exclusion. Disagreements were discussed or resolved by a third reviewer.

Data Extraction:

Included studies were screened in duplicate, and data were extracted using a standardised template. **Information collected included**:

Author(s), publication year, and country.

Study design and sample size.

Patient demographics and clinical characteristics.

Type of test(s) performed (eg, treadmill EST, pharmacologic stress testing, Holter monitoring, wearable ECG)Diagnostic performance (sensitivity, specificity, positive predictive value, negative predictive value; Clinical outcomes and follow-up data reported.

Limitations noted by study authors.

Quality Assessment:

Methodological quality of included studies was examined by using Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) tool. The criteria assessed included patient selection, index test execution and interpretation, reference standard, and flow and timing. Risk of bias of studies rated as low, moderate, or high The final synthesis only included studies rated as acceptable in methodological quality.

Data Synthesis:

A narrative synthesis approach was taken due to heterogeneity of study design, populations and outcomes reported, precluding quantitative meta-analysis. Summary of findings: Diagnostic accuracy,. Clinical utility related to: Clinical utility in the general population, Clinical utility in specific populations, Technological innovations, Implementation challenges.

3. RESULTS

This systematic review included 132 studies that met the inclusion criteria. Studies were conducted in various geographic regions (North America, Europe, Asia, and Australia) and in both high-risk and general populations. The results focus on four main themes: diagnostic accuracy; potential clinical utility in diverse populations; areas for technological development; and challenges for implementation.

Exercise Stress Testing and ECG Follow-up: Diagnostic Accuracy

Exercise stress testing combined with continuous ECG monitoring (EST) has been found to be a useful test for coronary artery disease and exercise-induced arrhythmias across much of the studies included with most studies consistently showing good diagnostic performance.

The pooled sensitivity of Exercise Stress Test (EST) for significant CAD detection was 68% to 85% and specificity 70% to 90% (Gibbons et al, 2002; Kwok et al, 2019).

Using exercise testing, silent ischemia, commonly masked on resting ECG, was detected in 25–50% of asymptomatic high-risk patients (Fleg et al., 2000, Shabana Khan, Sharick Shamsi et. al 2013). Ambulatory (Holter) electrocardiogram (ECG) monitoring has high sensitivity (90% or more) for transient arrhythmias that may not be provoked with exercise (Camm et al., 2017).

While the overall diagnostic yield was robust, a significant limitation remained with false-positive results, especially among patients who had abnormal baseline ECGs, those that had baseline left ventricular hypertrophy, and women with atypical symptoms.

Clinical Utility Across Different Populations:

A variety of populations have supporting evidence of EST and ECG monitoring:

High-risk asymptomatic patients: Individuals with minimal or previously undiagnosed CVD who received EST to help stratify cardiovascular risk and guide appropriate preventive interventions (Myers et al., 2002).Diabetic patients: Happier for us, silent ischemia was recognized early, changing treatment and lowering cardiac events (Wackers et al., 2004)

Older age: although the sensitivity was still acceptable, many patients could not perform an adequate exercise because of exercise capacity limitation and thus are better assessed with pharmacologic stress testing or submaximal exercise testing (Arena et al., 2007).

Athletes and the Physically Active: occult arrhythmias and structural heart disease have been identified using EST and prolonged ECG monitoring, aiding in the prevention of sudden cardiac death (Pelliccia et al., 2017).

Technological Advancements Enhancing Detection

Advances in technology have enhanced the accuracy of early diagnosis of EST and ECG monitoring. Continuous rhythm monitoring for prolonged periods was made possible with wearable electrocardiogram (ECG) devices (such as smart patches and chest bands) causing an increase in the detection rate of intermittent arrhythmias (Saxena et al., 2022).

By reducing observer variability and detecting small ischemic changes invisible to the human eye, AI-assisted ECG analysis improved diagnostic accuracy (Attia et al., 2019).

Remote risk assessment was achieved through the integration of ECG monitoring within telehealth platforms, a particularly valuable utility during the COVID-19 pandemic, but also enabling a beneficial procedure in remote or resource-poor settings.

Implementation Challenges All studies reported some challenges, namely; False-positive results that trigger unnecessary downstream testing which escalates both the cost and the risk of healthcare. The variability of exercise capacity, especially in elderly or comorbid patients, which sometimes restricts the usefulness of the test.

True motion artifacts from the architecture of wearable devices, as well as battery life and patient compliance to continuous monitoring protocols.

This highlights the need for equitable implementation strategies for advanced ECG and EST technologies, given the disparities in access to these technologies in low-resource settings.

Overall Outcomes:

Overall among the studies included, the proportion of contribution of using both EST and ECG monitoring was as follows: Better early detection of CAD and arrhythmias to intervene at the right time.

Improved risk stratification, leading to targeted lifestyle changes, medical therapy, and/or invasive procedures. Active management to a population of high-risk groups to reduce cardiovascular morbidity and mortality.

4. DISCUSSION

This systematic review underscores the important value of exercise stress testing (EST) followed by ECG monitoring for the early detection and risk stratification of cardiac abnormalities, including coronary artery disease (CAD), silent ischemia and different arrhythmias. The synthesis of evidence shows that these non-invasive diagnostic tools serve as promising cornerstones in preventive cardiology and enable timely interventions which can reduce morbidity and mortality. Clinical Effectiveness and Diagnostic Value. The results of the study corroborate that EST, particularly when coupled with continuous ECG monitoring, provides moderate-to-high sensitivity and specificity for diagnosing CAD and for determining provocation of exercise-induced arrhythmias. Our results are consistent with guidelines that have been jointly developed by several major cardiology societies (Gibbons et al., 2002; Fleg et al., 2000). That EST can induce ischemic changes or arrhythmias not apparent at rest highlights its utility for identifying subclinical disease and directing further diagnostic and therapeutic interventions. But the diagnostic performance differs by patient populations. Such extension may identify lower sensitivity (for example, in women and elderly patients because of less exercise capacity, atypical presentation of symptoms and baseline ECG abnormalities [Kwok et al., 2019; Arena et al., 2007]). Across these groups, adjunctive imaging modalities (eg, myocardial perfusion imaging or stress echocardiography) may enhance the diagnostic yield. Nevertheless, EST is still an inexpensive and readily available first-line option.

Importance in Various Populations and Contexts:

The review highlights the appropriate use of EST and ECG monitoring across multiple clinical settings, including asymptomatic high-risk patients, diabetes and athletes. For example, in asymptomatic diabetic patients, when silent ischemia is detected, studies like that of the DIAD trial found changes in management and less future significant cardiovascular events (Wackers et al., 2004). In athletes, pre-participation screening with exercise stress testing (EST) and extended electrocardiogram (ECG) monitoring/recording can identify clinically silent arrhythmogenic disorders, thus broadening the scope of initiatives aimed at sudden cardiac death prevention (Pelliccia et al.).

Changes Driven by Technology and Remote Monitoring: Advancements in technology have paved way for greater possibilities than ever before in ECG monitoring. The use of wearable ECG devices and accompanying AI-assisted algorithms enhances the detection rate of paroxysmal arrhythmias and minor ischemic changes that would have been missed during standard exercise testing (Attia et al., 2019; Saxena et al., 2022). Telehealth initiatives often have a strong need for remote and continuous monitoring solutions as they allow proactive risk assessment and follow-up (without an office visit), a concept greatly emphasized during the pandemic period. Though these tech developments are promising, they also raise new hurdles like the need for strong data privacy protections, the establishment of common validation protocols, signal artifact reduction and incentivization of patient compliance.

Challenges and Limitations:

However, both EST and ECG monitoring have their disadvantages. False-positive results can cause needless downstream testing, escalation of costs to healthcare systems, and distress to the patients. Further, maximal exercise protocols are less feasible in elderly and comorbid patients due to limited exercise capacity. While fundamental problems like implementation barriers with access to testing and advanced technologies are still the major problems affecting the implementation of CRISPR systems, but they are powerful in low-resource settings. These differences need to be remedied to achieve equity in the delivery of cardiovascular care.

Future Directions:

In the future, it will be important to refine models of risk stratification that include data from EST, ECG, and genetic, biomarker, and imaging to better personalize these approaches. Big data analytics with machine learning may enhance diagnostic accuracy and inform tailored management approaches.

Longitudinal studies addressing this question are also warranted, especially in asymptomatic and/or high-risk populations, in order to enhance the understanding of the long-term impact of early detection on final clinical outcomes. Widespread adoption of new diagnostic tools driven by AI will also require strategies to broaden access to advanced monitoring technologies and to improve clinician training in their interpretation.

5. CONCLUSION

This systematic review highlights the importance of exercise stress testing (EST) and electrocardiogram (ECG) monitoring as valuable, affordable, and non-invasively deployable diagnostic methods for early identification of cardiac dysfunction. All of these modalities allow clinicians to unmask silent coronary artery disease, silent ischemia, and arrhythmias prior to the development of overt symptoms thus affording timely therapeutic interventions and improved patient outcomes. Although limited by false-positive rates and somewhat reduced applicability in selected populations, EST and ECG monitoring continue to represent cornerstones in preventive cardiology. The extent of diagnostic accuracy has been significantly expanded beyond what we routinely perform/encounter in a clinical setting recently, characterized by the integration of wearable devices and artificial intelligence–assisted analysis. Moving forward, we believe there are three areas in which test performance can be optimized in diverse patient populations, we can increase access to continuous monitoring technologies, and we can integrate quantitative-based risk management strategies. These tools strengthen early detection measures and if applied appropriately, healthcare systems can potentially avert major adverse cardiac events, thus contributing to a significant reduction in the global burden of cardiovascular disease.

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