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Teaching Electrocardiogram Interpretation to Medical Students: Current Evidence, Challenges, and Future Directions

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Abstract **Original Research Article**

Background: Electrocardiogram (ECG) interpretation is a fundamental clinical competency expected from graduating medical students. Despite its importance in diagnosing arrhythmias, acute coronary syndromes, and conduction abnormalities, ECG interpretation remains a major challenge in undergraduate medical education. Traditional lecture-based instruction often fails to ensure long-term competency and confidence among medical students. ***Objective:*** This narrative review aims to summarize current evidence regarding ECG teaching strategies for medical students, identify major educational barriers, and discuss future directions in undergraduate ECG education. ***Materials and Methods:*** A narrative review of the literature was conducted using PubMed, Scopus, Google Scholar, and Web of Science databases. Articles published in English between 2000 and 2025 were screened using combinations of the keywords "electrocardiogram," "ECG," "medical students," "medical education," "simulation," "e-learning," "artificial intelligence," and "cardiology education." Original studies, systematic reviews, educational interventions, and expert recommendations related to undergraduate ECG education were included. ***Results:*** Contemporary evidence suggests that active learning approaches outperform traditional didactic teaching alone. Educational methods associated with improved ECG competency include case-based learning, flipped classrooms, simulation-based training, peer-assisted teaching, spaced repetition, and digital learning platforms [1-12]. E-learning and mobile applications provide flexible opportunities for repetitive practice and self-directed learning [5-7]. Simulation-based education improves clinical reasoning, confidence, and emergency preparedness [8,9]. Artificial intelligence-assisted educational tools may further personalize ECG learning and provide adaptive feedback [24-27]. However, several barriers persist, including curriculum fragmentation, cognitive overload, inadequate clinical exposure, and limited educational resources in low- and middle-income countries [15-19]. ***Conclusion:*** Modern ECG education should move beyond passive lecture-based teaching toward competency-based, interactive, and technology-enhanced learning models. Longitudinal curricula integrating simulation, digital education, and repeated clinical exposure may improve ECG interpretation competency and better prepare medical students for clinical practice.

Keywords: electrocardiogram, ECG, undergraduate medical education, cardiology education, simulation, artificial intelligence, e-learning, medical students.

Introduction

The electrocardiogram (ECG) remains one of the most widely used diagnostic tools in modern medicine [1,2]. Since its introduction into clinical practice, the ECG has become indispensable for the diagnosis and management of cardiac arrhythmias, acute coronary syndromes, electrolyte disturbances, and conduction abnormalities [3]. Physicians working in emergency medicine, cardiology, internal medicine, critical care, anesthesiology, and primary care are all expected to interpret ECGs accurately and rapidly [4].

Because of its major clinical importance, ECG interpretation is considered a core competency in undergraduate medical education [5]. Medical students are expected to recognize common and life-threatening abnormalities such as atrial fibrillation, ventricular tachycardia, ST-segment elevation myocardial infarction (STEMI), complete atrioventricular block, and hyperkalemia-related ECG changes [6]. However, despite the central role of electrocardiography in daily clinical practice, multiple studies have demonstrated inadequate ECG interpretation skills among medical students and junior physicians [7,8].

ECG interpretation is often perceived by students as difficult and intimidating [9]. Unlike disciplines based mainly on memorization, ECG analysis requires simultaneous integration of anatomy, physiology, electrophysiology, pattern recognition, and clinical reasoning [10]. Students must evaluate heart rhythm, intervals, electrical axis, wave morphology, conduction abnormalities, and ischemic changes while correlating findings with patient presentation [11].

Traditional ECG teaching has historically relied on lecture-based learning and textbook instruction [12]. Although these methods allow delivery of standardized information to large groups, they frequently fail to ensure long-term retention and practical competency [13]. Consequently, medical educators have explored alternative educational approaches including case-based learning, simulation-based education, peer-assisted teaching, e-learning, flipped classrooms, spaced repetition, and artificial intelligence-assisted instruction [14-18].

The rapid expansion of educational technologies has profoundly transformed medical pedagogy during the past two decades [19]. Online ECG modules, virtual simulations, mobile learning applications, and adaptive learning systems now provide students with greater opportunities for repetitive practice and self-directed learning [20]. Simultaneously, competency-based medical education has shifted focus from passive knowledge acquisition toward measurable clinical performance [21,22].

The objective of this narrative review is to examine current evidence regarding ECG teaching methods for medical students, explore the major educational barriers affecting ECG learning, and discuss future perspectives in undergraduate cardiology education.

Materials and Methods

A narrative review of the literature was conducted using PubMed, Scopus, Google Scholar, and Web of Science databases. The search strategy combined the following keywords and Medical Subject Headings (MeSH): “electrocardiogram,” “ECG,” “electrocardiography,” “medical students,” “undergraduate medical education,” “cardiology education,” “simulation,” “e-learning,” “flipped classroom,” “artificial intelligence,” “gamification,” and “medical pedagogy.”

Articles published in English between January 2000 and March 2025 were considered eligible for inclusion. Additional relevant references were identified through manual screening of bibliographies from selected articles.

Original studies, systematic reviews, meta-analyses, educational interventions, and expert recommendations related to ECG interpretation teaching for undergraduate medical students were included. Articles focusing exclusively on postgraduate trainees or practicing physicians without undergraduate educational relevance were excluded.

The retrieved literature was analyzed narratively. Major themes related to educational barriers, teaching strategies, digital education, competency assessment, simulation, and artificial intelligence were identified and synthesized qualitatively.

Results

Importance of ECG Interpretation in Undergraduate Medical Education

ECG interpretation is considered a fundamental competency for all graduating physicians regardless of specialty [5]. Newly graduated doctors are frequently required to interpret ECGs in emergency situations, particularly in resource-limited settings where specialist consultation may not be immediately available [6].

Failure to correctly identify ECG abnormalities may result in delayed diagnosis, inappropriate treatment, increased morbidity, and potentially fatal outcomes [7]. Misinterpretation of STEMI, ventricular tachycardia, or severe hyperkalemia may have catastrophic consequences [8].

Several studies have demonstrated insufficient ECG interpretation skills among medical students [15,16]. Jablonover *et al.,* reported that many graduating students were unable to recognize common arrhythmias and ischemic abnormalities [17]. Similarly, Nilsson *et al.,* observed low confidence levels among students regarding ECG interpretation despite completion of cardiology rotations [18].

Why ECG Interpretation Is Difficult for Medical Students

Cognitive Complexity

One of the major reasons ECG interpretations remains difficult is its high cognitive complexity [9,10]. Students must integrate multiple domains of knowledge simultaneously, including cardiac anatomy, electrophysiology, vector analysis, and clinical medicine [11].

Unlike purely theoretical disciplines, ECG interpretation requires advanced pattern recognition and rapid clinical reasoning [12]. Many students struggle to transform theoretical electrophysiological concepts into practical diagnostic skills [13].

Curriculum Fragmentation

In many institutions, ECG teaching occurs during isolated modules without sufficient longitudinal reinforcement [14]. Students may initially acquire ECG interpretation skills during cardiology courses but gradually lose competency because of limited continued exposure [15].

Limited Clinical Exposure

Repeated exposure to ECG tracings is essential for developing diagnostic proficiency [16]. However, many students encounter relatively few ECGs during clinical rotations outside cardiology departments [17].

Anxiety and Lack of Confidence

Students commonly perceive ECG interpretation as intimidating and stressful [18]. Fear of making diagnostic errors may contribute to reduced engagement and avoidance behaviors [19].

Core ECG Competencies for Medical Students

Most experts agree that undergraduate ECG curricula should prioritize clinically relevant competencies rather than highly specialized electrophysiological detail [20].

Students should be able to:

- Determine heart rate and rhythm
- Recognize sinus rhythm
- Identify atrial fibrillation and flutter
- Diagnose supraventricular and ventricular tachycardia
- Evaluate PR, QRS, and QT intervals
- Recognize bundle branch blocks
- Identify acute ischemic changes
- Detect atrioventricular conduction abnormalities
- Recognize electrolyte-related ECG changes
- Apply systematic interpretation methods

Table 1: Recommended Core ECG Competencies for Medical Students

Domain	Expected Competency
Rhythm analysis	Recognition of sinus rhythm and major arrhythmias
Conduction abnormalities	Identification of AV block and bundle branch block
Ischemia	Recognition of STEMI and ischemic changes
Intervals	Interpretation of PR, QRS, and QT intervals
Electrolyte disorders	Recognition of hyperkalemia-related changes
Clinical reasoning	Correlation of ECG findings with clinical context
Emergency medicine	Recognition of life-threatening ECG abnormalities

Traditional Teaching Methods

Didactic Lectures

Lecture-based teaching remains the most common educational strategy worldwide [12]. Lectures allow efficient delivery of standardized information to large groups of students [13].

However, several studies suggest that lecture-based teaching alone is insufficient for ensuring long-term ECG competency [1,2]. Passive learning limits student engagement and may impair retention [3].

Small Group Teaching

Small group sessions allow greater interaction between instructors and students [4]. Students may analyze ECG tracings collectively and receive immediate feedback.

Compared with lectures, small-group teaching promotes active participation and improves confidence [5]. Nevertheless, these approaches require greater faculty resources and institutional organization.

Bedside Teaching

Clinical exposure during cardiology rotations allows students to correlate ECG findings with patient presentation [6]. Bedside teaching facilitates contextual understanding and clinical reasoning. However, bedside ECG teaching quality varies considerably depending on faculty involvement and patient availability [7].

Active Learning Strategies in ECG Education

Case-Based Learning

Case-based learning (CBL) has become increasingly popular in medical education [8]. Students analyze clinical scenarios accompanied by ECG tracings and discuss diagnostic and therapeutic implications.

CBL promotes clinical reasoning and improves knowledge retention [9]. By linking ECG findings to real patient cases, students develop stronger diagnostic frameworks [10].

Problem-Based Learning

Problem-based learning (PBL) encourages self-directed learning while solving clinical problems [11]. ECG interpretation may be integrated into cases involving chest pain, syncope, palpitations, or cardiac arrest.

PBL promotes critical thinking but requires experienced facilitators and substantial preparation [12].

Peer-Assisted Learning

Peer-assisted learning involves teaching sessions led by senior students or junior residents [20]. Students often feel more comfortable asking questions in peer-led educational environments.

Peer teaching may reduce anxiety and improve communication while increasing accessibility to educational support [20].

Flipped Classroom and Blended Learning

The flipped classroom model reverses the traditional educational structure [21]. Students review educational materials before classroom sessions, allowing classroom time to focus on interactive problem-solving and ECG interpretation exercises.

Several studies have demonstrated improved student engagement and examination performance with flipped classroom approaches [3,21,22].

Blended learning combines online educational resources with face-to-face instruction [22]. This hybrid model provides educational flexibility while preserving faculty mentorship.

Table 2: Comparison of Traditional and Modern ECG Teaching Approaches

Teaching Method	Advantages	Limitations
Lectures	Efficient for large groups	Passive learning
Small-group teaching	Interactive	Resource intensive
Case-based learning	Improves reasoning	Requires preparation
Flipped classroom	Active participation	Requires student preparation
E-learning	Flexible and accessible	Reduced face-to-face interaction
Simulation	Realistic clinical training	Expensive infrastructure

E-Learning and Digital Education

Digital learning technologies have transformed medical education during the last two decades [5-7]. ECG teaching is particularly suitable for digital instruction because ECG interpretation is highly visual and interactive [15].

Online Learning Platforms

Many institutions now provide online ECG learning modules incorporating:

- Interactive ECG tracings
- Self-assessment quizzes
- Automated feedback systems
- Video tutorials
- Adaptive learning pathways

Digital platforms allow repetitive ECG practice at individualized learning pace [30].

Mobile Applications

Smartphone applications have become increasingly popular among medical students [16]. Mobile ECG apps often include flashcards, rhythm recognition exercises, ECG libraries, and interactive quizzes.

Advantages of Digital ECG Education

- Flexible access
- Self-directed learning
- Immediate feedback
- Repeated practice opportunities
- Improved learner autonomy
- Standardized educational content

Limitations

Despite their advantages, digital educational tools cannot completely replace faculty mentorship and bedside teaching [7]. Excessive reliance on online resources may reduce interpersonal interaction and collaborative learning.

Simulation-Based ECG Teaching

Simulation-based education has emerged as one of the most effective methods for teaching acute clinical skills [8,9].

Simulation sessions may involve:

- Acute coronary syndrome management
- Cardiac arrest scenarios
- Tachyarrhythmia recognition
- Bradycardia management
- ACLS algorithms
- Emergency rhythm interpretation

Simulation integrates ECG interpretation with real-time clinical decision-making [28].

High-Fidelity Simulation

High-fidelity simulators recreate realistic physiological responses and improve situational awareness [29].

Simulation-based ECG training improves confidence, teamwork, communication, and emergency preparedness [28,29].

Low-Fidelity Simulation

Even low-cost simulation approaches such as virtual scenarios or rhythm-monitor exercises may significantly improve learning outcomes [35].

Table 3: Educational Benefits of Simulation-Based ECG Training

Educational Outcome	Impact
Diagnostic confidence	Increased
Clinical reasoning	Improved
Emergency preparedness	Enhanced
Knowledge retention	Improved
Team communication	Strengthened
Student engagement	Increased

Spaced Repetition and Deliberate Practice

One major challenge in ECG education is poor long-term retention [10]. Educational psychology research demonstrates that repeated exposure distributed over time improves memory consolidation [11].

Spaced Repetition

Spaced repetition involves reviewing educational content at progressively increasing intervals [10]. Repeated ECG interpretation practice improves durable retention and diagnostic confidence.

Deliberate Practice

Deliberate practice refers to repetitive structured practice combined with targeted feedback [18,19]. Experts emphasize that ECG competency requires interpretation of hundreds of ECG tracings rather than isolated theoretical sessions [18].

Gamification in ECG Education

Gamification integrates game-design principles into educational activities [23].

Examples include:

- Competitive ECG quizzes
- Leaderboards
- Interactive team challenges
- ECG escape rooms
- Educational games

Gamification increases student motivation and reduces anxiety associated with difficult subjects [23].

Several studies have demonstrated improved student satisfaction and short-term learning outcomes with gamified ECG teaching [23].

Artificial Intelligence and the Future of ECG Education

Artificial intelligence (AI) is rapidly transforming both clinical cardiology and medical education [24-27].

AI-Assisted Learning Platforms

AI-powered educational systems may:

- Adapt question difficulty to learner performance
- Identify student weaknesses
- Provide personalized feedback
- Generate individualized learning pathways
- Analyze interpretation errors
- Create synthetic ECG cases

Chatbots and Virtual Tutors

Large language models and AI chatbots may function as virtual ECG tutors capable of explaining concepts, generating quizzes, and answering student questions [25,26].

Risks and Limitations

Despite their promise, AI-assisted educational systems raise important concerns:

- Risk of overreliance on automation
- Reduced development of independent reasoning
- Ethical concerns regarding data privacy
- Potential dissemination of misinformation

AI should complement rather than replace human clinical reasoning [27].

Table 4: Potential Applications of Artificial Intelligence in ECG Education

Application	Educational Benefit
Adaptive learning systems	Personalized education
Automated feedback	Rapid correction of errors
AI-generated quizzes	Increased practice opportunities
Virtual tutors	Accessible learning support
Synthetic ECG generation	Expanded case diversity
Performance analytics	Competency tracking

Educational Barriers and Student Perceptions

Several studies have investigated student perceptions regarding ECG education [15-18].

Students frequently describe ECG interpretation as intimidating and excessively complex [18]. Many report anxiety during examinations and clinical rotations because of fear of diagnostic errors [19].

Another major issue is curriculum fragmentation [14]. In many institutions, ECG teaching occurs during isolated modules without longitudinal reinforcement throughout medical school.

The quality of faculty supervision also strongly influences educational outcomes. Effective ECG teaching requires instructors capable of simplifying complex concepts, encouraging systematic interpretation, and providing constructive feedback.

Standardized Approaches to ECG Interpretation

Several authors emphasize the importance of teaching systematic ECG interpretation methods [19].

Most structured approaches encourage sequential analysis of:

1. Heart rate
2. Rhythm
3. Cardiac axis
4. PR interval
5. QRS duration
6. QT interval
7. Wave morphology
8. ST-segment abnormalities
9. T-wave abnormalities
10. Clinical correlation

Structured interpretation frameworks reduce cognitive overload and minimize diagnostic errors [33].

Table 5: Common Educational Challenges in ECG Teaching

Challenge	**Educational Consequence**
Cognitive overload	Reduced comprehension
Limited repetition	Poor long-term retention
Anxiety and low confidence	Avoidance behaviors
Curriculum fragmentation	Inconsistent competency
Limited faculty supervision	Reduced feedback quality
Overreliance on lectures	Passive learning
Limited clinical exposure	Poor contextual understanding

Faculty Development and Teacher Training

Improving ECG education also requires faculty development programs [20]. Many clinicians possess strong ECG interpretation skills but limited formal training in educational methodology.

Faculty development initiatives focusing on adult learning principles, active learning methods, and feedback delivery may improve ECG teaching quality.

Near-peer educators and residents may also represent valuable educational resources because they better understand common student difficulties.

Self-Directed Learning and Student Autonomy

Modern medical education increasingly emphasizes self-directed learning [5,7].

ECG interpretation is particularly suitable for autonomous learning because students can independently analyze large numbers of ECG tracings using online platforms and mobile applications.

Benefits of self-directed ECG learning include:

- Independent problem solving
- Continuous practice
- Diagnostic reasoning
- Personalized learning pace
- Lifelong learning habits

However, autonomous learning requires periodic faculty supervision to prevent development of incorrect interpretation habits.

Impact of COVID-19 on ECG Education

The COVID-19 pandemic accelerated adoption of digital medical education worldwide [30].

Virtual ECG workshops, online tutorials, remote simulation sessions, and digital case discussions became increasingly common during periods of reduced clinical exposure.

Several studies demonstrated that appropriately designed online ECG education could achieve learning outcomes comparable to traditional classroom instruction [30].

The pandemic highlighted the importance of educational flexibility and digital preparedness in undergraduate medical curricula.

Research Gaps in ECG Education

- Despite growing literature regarding ECG teaching, several research gaps remain.
- First, many studies evaluate short-term examination performance rather than long-term competency retention.
- Second, substantial heterogeneity exists regarding educational interventions and assessment methods.

- Third, relatively few studies originate from low- and middle-income countries [34].
- Finally, the long-term impact of AI-assisted ECG education remains uncertain [24-27].

Recommendations for Medical Schools

Based on current evidence, several practical recommendations may improve undergraduate ECG education:

- Introduce ECG teaching early during medical school
- Reinforce ECG interpretation longitudinally
- Prioritize active learning methods
- Incorporate simulation-based education
- Use spaced repetition strategies
- Integrate digital learning resources
- Promote competency-based assessment
- Encourage faculty development programs

Table 6: Practical Recommendations for Improving Undergraduate ECG Education

Recommendation	Expected Benefit
Longitudinal ECG curriculum	Improved retention
Active learning strategies	Increased engagement
Simulation-based teaching	Enhanced clinical reasoning
Spaced repetition	Better long-term memory
Structured interpretation methods	Reduced diagnostic errors
Competency-based assessment	Better practical performance
Digital learning integration	Increased accessibility
Faculty development	Improved teaching quality

CONCLUSION

Electrocardiogram interpretation remains one of the most important yet challenging competencies in undergraduate medical education. Traditional lecture-based teaching alone appears insufficient for ensuring durable competency among medical students.

Contemporary evidence increasingly supports active learning strategies including case-based learning, flipped classrooms, simulation-based education, e-learning, spaced repetition, peer-assisted teaching, and digital educational tools [1-23]. These approaches improve student engagement, confidence, diagnostic reasoning, and long-term retention.

Artificial intelligence and adaptive digital learning systems may further transform ECG education by providing personalized learning pathways and automated feedback [24-27]. However, these technologies should complement rather than replace clinical reasoning and faculty mentorship.

Future ECG curricula should emphasize competency-based learning, repeated clinical exposure, structured interpretation frameworks, and integration of digital technologies [31-35]. Particular attention should also be directed toward improving ECG education in low- and middle-income countries where educational resources may be limited [34].

Ultimately, improving undergraduate ECG education may enhance physician preparedness, improve patient safety, and contribute to better cardiovascular care worldwide.

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