Competency in Interpretation of 12-Lead Electrocardiograms: A Summary and Appraisal of Published Evidence

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Background: **There have been many proposals for objective standards designed to optimize training, testing, and maintaining competency in interpretation of electrocardiograms (ECGs). However, most of these recommendations are consensus based and are not derived from clinical trials that include patient outcomes.**

Purpose: **To critically review the available data on training, accuracy, and outcomes of computer and physician interpretation of 12-lead resting ECGs.**

Data Sources: **English-language articles were retrieved by searching MEDLINE (1966 to 2002), EMBASE (1974 to 2002), and the Cochrane Controlled Trials Register (1975–2002). The references in articles selected for analysis were also reviewed for relevance.**

Study Selection: **All articles on training, accuracy, and outcomes of ECG interpretations were analyzed.**

Data Extraction: **Study design and results were summarized in evidence tables. Information on physician interpretation compared to a "gold standard," typically a consensus panel of expert electrocardiographers, was extracted. The clinical context of and outcomes related to the ECG interpretation were obtained whenever possible.**

Data Synthesis: **Physicians of all specialties and levels of training, as well as computer software for interpreting ECGs, frequently made errors in interpreting ECGs when compared to expert electrocardiographers. There was also substantial disagreement on interpretations among cardiologists. Adverse patient outcomes occurred infrequently when ECGs were incorrectly interpreted.**

Conclusions: **There is no evidence-based minimum number of ECG interpretations that is ideal for attaining or maintaining competency in ECG interpretation skills. Further research is needed to clarify the optimal way to build and maintain ECG interpretation skills based on patient outcomes.**

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Interpretations of 12-lead resting electrocardiograms (ECGs) are often required in both ambulatory and inpatient settings. Organizations, including the American College of Cardiology (ACC) and the American Heart Association (AHA), have published consensus-based competency standards suggesting the optimal number of ECGs necessary to obtain and maintain competency in ECG interpretation skills. The ACC/AHA guidelines recommend interpreting a minimum of 500 supervised ECGs during initial training, using standardized testing in ECG interpretation to confirm initial competency and interpreting 100 ECGs yearly to maintain competency (1). The consensus statement asserts that these standards should apply to all practice settings and situations; however, the statement is controversial because of the lack of evidence-based literature on the optimal techniques for learning, maintaining, and testing competency in ECG interpretation. This systematic review attempts to synthesize the literature that may prove useful for physicians, program directors, and organizations seeking alternative evidence-based information on physician ECG interpretation skills.

Methods

We retrieved information through systematic searches and ongoing surveillance of MEDLINE (1996 to 2002), EMBASE (1974 to 2002), and the Cochrane Controlled trials Register (1975 to 2002). We used the following index terms and text words: *electrocardiogram interpretation*, *electrocardiogram competency*, *electrocardiogram training, electrocardiogram errors,* and *computer electrocardiogram interpretation*. Our search was limited to English-language articles that studied adult participants. References of the full-length articles were analyzed for additional citations. The search revealed 419 articles of potential interest. After we analyzed the abstracts of these articles, we eliminated 378 because ECG interpretation was not the main study focus. Thirty-nine articles and 2 letters to the editor contained research data directly related to ECG interpretation.

We divided the articles into the following broad categories: studies that included clinical outcomes (**Table 1**), studies that included discussion of the accuracy of computer ECG interpretation (**Table 2**), and all other studies that compared noncardiologists to a cardiologist reference standard (**Table 3**). The studies were not graded by quality. Although criteria exist for grading the quality of studies of diagnostic tests, the focus of our study was the users of the test rather than the usefulness of electrocardiography for diagnosing specific diseases. We also reviewed the recommendations of the American Board of Internal Medicine, American College of Physicians, AHA, ACC, and Accreditation Council on Graduate Medical Education Residency Review Committees for Internal Medicine and Cardiovascular Diseases (1, 43–45).

Reference Standards for Determining ECG Interpretation Accuracy

One common feature of most ECG interpretation studies is the use of an expert electrocardiographer "gold standard," typically a consensus panel of cardiologists. This

Table 1. **Electrocardiogram Interpretation Studies with Clinical Outcomes***

Study (Reference), Year, Country	Focus of Study	ECGs Studied, *n*	Type and Number of Participants	Interpretation Results†	Clinical Outcome
Brady et al. (2), 2000, United States	ST-segment elevation in ED patients with chest pain	202	ED physicians (*n* = unknown)	94.1% agreement with reference standard	Adverse outcomes: not calculated Management changes: no management errors
Srikanthan et al. (3), 1997, Scotland	ECG criteria for thrombolytic therapy in ED patients with acute MI	112	Senior house officers (*n* = 9)	83.9% agreement with reference standard	Adverse outcomes: none (all ECGs faxed to cardiologists for immediate review) Management changes: 8.9% of patients had management changes based on cardiologist review of ECG
Todd et al. (4), 1996, United States	Comprehensive interpretation of ECGs from ED patients	1000	ED physicians and cardiologists (*n* = unknown)	Emergency physicians: 85.2% agreement with reference standard Cardiologists: 92.8% agreement with reference standard	Adverse outcomes: 0.1% incidence of potentially preventable deaths due to ECG interpretation errors Management changes: 0.8% of patients with probable management changes due to ECG interpretation errors
White et al. (5), 1995, England	Comprehensive interpretation of ECGs from ED patients (before and after ECG seminars)	487	Senior house officers (*n* = unknown)	House officers preseminar (245 ECGs): 46% agreement with reference standard; 21.3% of ECGs with serious interpretation errors House officers postseminar (242 ECGs): 45% agreement with reference standard; 10.7% of ECGs with serious interpretation errors	Adverse outcomes: not described Management changes: *Preseminar:* 3.2% of patients admitted or discharged inappropriately because of ECG interpretation errors. *Postseminar:* 1.7% of patients discharged inappropriately because of ECG interpretation errors
Snoey et al. (6), 1994, France	Comprehensive interpretation and diagnosis of acute MI in ECGs from ED patients	300	First-year residents (*n* = unknown)	49.7% agreement with reference standard; 32.7% indeterminate or serious interpretation errors (κ = 0.32); 100% agreement with reference standard on diagnosis of MI	Adverse outcomes: none Management changes: 0.7% of patients treated inappropriately because of ECG interpretation errors
McCarthy et al. (7), 1993, United States	Diagnosis of acute MI from discharged ED patients	1050	ED resident and staff physicians (*n* = unknown)	1.9% of patients inappropriately discharged; 25% of these had missed ST-segment elevation	Adverse outcomes: unknown mortality in subset of patients with incorrect ECG interpretations Management changes: 20% of patients inappropriately discharged (0.4% of the total discharged) because of ECG interpretation errors
Westdrop et al. (8), 1992, United States	Comprehensive ECG interpretation in discharged ED patients	143	ED resident and staff physicians (*n* = unknown)	42.0% agreement with reference standard; 17.5% of interpretation errors of clinical significance	Adverse outcomes: none Management changes: 1.4% of patients with ECG interpretation errors treated inappropriately
Jayes et al. (9), 1992, United States	ST-segment or T-wave abnormalities	1912	ED resident and staff physicians (*n* = unknown)	ST-segment abnormalities: *Residents:* 62.9% sensitivity, 77.9% specificity; *ED staff:* 57.4% sensitivity, 89.3% specificity T-wave abnormalities: *Residents:* 76.5% sensitivity, 73.1% specificity; *ED staff:* 57.3% sensitivity, 87.8% specificity	Adverse outcomes: no change in diagnosis-adjusted survival rates in patients with ECG interpretation errors Management changes: inappropriate admission or discharge more likely when abnormal ST segments (22% vs. 11%) or T waves (18% vs. 14%) misread as normal
Kuhn et al. (10), 1992, United States	Comprehensive interpretation of ECGs from ED patients	400	ED residents, staff physicians, and cardiologists (*n* = unknown)	ED physicians: 59.2% agreement with reference standard on major abnormalities, 8.3% serious interpretation errors	Adverse outcomes: not described Management changes: 0.5% of patients with ECG interpretation errors had inappropriate management
Morrison and Swann (11), 1990, Scotland	Comprehensive interpretation of ECGs from ED patients	126	Senior house officers (*n* = 12)	80.2% agreement with reference standard; 4.4% major interpretation errors	Adverse outcomes: none Management changes: 0.8% of patients with ECG interpretation errors had inappropriate management
Lee et al. (12), 1987, United States	Diagnosis of acute MI in discharged ED patients	1283	ED physicians (*n* = unknown)	35 patients inappropriately discharged; 23% of these patients had ECG interpretation errors	Adverse outcomes: 0.6% of the total number of discharged patients with ECG interpretation errors were inappropriately discharged Management changes: 0.6% of the total number of discharged patients were inappropriately discharged because of ECG interpretation errors

* ECG = electrocardiogram; ED = emergency department; MI = myocardial infarction.
† The reference standard refers to interpretation of one or more expert electrocardiographers, typically cardiologists. Sensitivity and specificity refer to diagnosis of pertinent ECG abnormality, as defined by reference standard. Agreement with reference standard refers to proportion of ECGs in full agreement with the reference standard.

may be problematic because interpretations by several cardiologists reading the same ECG often vary substantially (14, 17, 29, 42). Even one cardiologist reading the same ECG on separate occasions may have substantially different interpretations (14, 29, 42).

Most studies on ECG interpretation by cardiologists report the proportion of abnormal diagnoses that are correctly identified, as determined by a consensus panel. These studies report that the participating cardiologists correctly determined 53% to 96% of the abnormalities identified by the reference standard (4, 17, 21, 23, 24, 28, 30). Two recent studies examined whether cardiologists agreed among themselves and their colleagues by using κ statistics to adjust for interpretations that agreed on the basis of chance alone (14, 29). Holmvang and colleagues reviewed 502 ECGs examined by both local cardiologists and an expert electrocardiography consensus panel (29). Agreement was poor to moderate on identification of ST-segment elevation ($\kappa = 0.05$), ST-segment depression ($\kappa = 0.38$), and a normal ECG ($\kappa = 0.42$). Interrater agreement on detecting T-wave inversion was very good ($\kappa = 0.63$). In contrast, intrarater agreement by the expert electrocardiographic consensus panel was good ($\kappa = 0.58$ to 0.67).

Levels of agreement may be higher for serious abnormalities, such as ST-segment elevation criteria for use of thrombolytic therapy. Massel and colleagues reported substantial agreement ($\kappa = 0.78$) among three cardiologists examining whether 75 ECGs met criteria for thrombolytic therapy (14). The study also showed good intrarater agreement ($\kappa = 0.67$ to 0.71) when the three cardiologists determined criteria for thrombolytic therapy on two separate occasions.

Because cardiologists do not agree on many aspects of ECG interpretation, future studies examining noncardiologist or computer interpretation should include κ statistics and control groups of cardiologists. Readers can then draw more sophisticated conclusions about the importance of disagreements in ECG analysis. More accurate measures of agreement, such as weighted κ statistics, should be included because disagreement may relate to only some aspects of the ECG interpretation.

FREQUENCY OF ECG INTERPRETATION ERRORS BY STAFF AND RESIDENT PHYSICIANS

Numerous trials have compared the ECG interpretation skills of cardiologists and noncardiologists. Most studies measured the proportion of ECG diagnoses determined by an expert consensus panel "gold standard" that noncardiologist physicians could identify. Seven studies measuring comprehensive ECG analysis found that the proportion of ECG diagnoses correctly identified by noncardiologist physicians ranged from 36% to 96% (4–6, 8, 11, 13, 33). In several studies that focused on a particular aspect of ECG interpretation, noncardiologists identified 87% to 100% of ECGs showing acute myocardial ischemia (6, 27), correctly classified 72% to 94% of ECGs as meeting inclusion criteria for thrombolytic therapy (3, 26, 30, 32, 37, 40), diagnosed 57% to 95% of ST-segment abnormalities (2, 9, 26), and correctly measured about 25% of PR and QT intervals (36).

Although most studies combined resident and staff physicians in their analyses, some provided data allowing subgroup analysis. Twelve articles included information specifically on resident physician interpretation skills. Resident physicians detected 96% of abnormal ECGs (15), correctly identified inclusion criteria for thrombolytic therapy 73% to 84% of the time (3, 26, 30, 32), demonstrated 36% to 80% of ECG diagnoses as determined by expert electrocardiographers (5, 6, 11, 13, 21, 28, 41), and discovered 38% of technical ECG abnormalities (41). Only two articles provided sufficient information for subgroup analysis on noncardiologist staff physicians. The articles did not provide information on specialty background or board certification. Staff physicians correctly identified inclusion criteria for thrombolytic therapy 77% of the time (30) and diagnosed abnormal ST-segment and T-wave abnormalities 57% to 97% of the time (16).

Four studies provided information on the ECG interpretation skills of nonphysicians. In two studies, nurses correctly identified ECG criteria for thrombolytic therapy 84% to 94% of the time (30, 37). The other studies examined the interpretation skills of medical students (28, 38), who identified 17% to 63% of ECG abnormalities identified by an expert reference standard.

Trainees often gain experience in ECG interpretation when they use an ECG to assist in the clinical management of a patient. Not surprisingly, research has shown that clinical history may affect interpretation of ECGs (28, 31, 38). Providers with less training are influenced by the history to a greater extent than are more experienced electrocardiographers. For example, when given a misleading history, diagnostic accuracy was reduced by 5% for cardiologists but up to 25% for residents in one recent study (28). Cardiologists performed better than other interpreters in all settings and were 90% accurate in their diagnoses, even when no history was provided. Another study also demonstrated that interpretations by cardiologists were minimally dependent on the presence or absence of history (46). This information suggests that noncardiologist interpreters may make more accurate interpretations when they know the clinical context of the ECG.

False-positive ECG interpretations could lead to unnecessary patient treatment. Six studies examined this aspect of interpretation (9, 15–17, 37, 40). Cardiologists typically had fewer false-positive interpretations than did noncardiologists. Cardiologists demonstrated a specificity of 93% to 100% for diagnosis of substantial ECG abnormalities, such as myocardial ischemia; specificity for noncardiologist physicians was 73% to 100%. In simpler determinations, such as differentiating normal from abnor-

Table 2. **Electrocardiogram Interpretation Studies Comparing Computer and Physician Interpretation***

Study (Reference), Year, Country	Focus of Study	ECGs Studied, *n*	Type and Number of Participants	Interpretation Results†
Goodacre et al. (13), 2001, England	Comprehensive interpretation of ECGs from ED patients	50	Senior house officers (*n* = 10) and computer	Senior house officers without computer: 36.4% agreement with reference standard; 22.4% of interpretation errors considered major Senior house officers with computer: 41.6% agreement with reference standard; 18.4% of interpretation errors considered major Computer: Unknown agreement with reference standard; 4.0% of interpretation errors considered major
Massel et al. (14), 2000, Canada	ECG criteria for thrombolytic therapy in cardiac inpatients	75	Cardiologists (*n* = 3) and computer	Computer: 61.5% sensitivity, 100.0% specificity, κ = 0.68 with reference standard Cardiologists: κ = 0.78 for ST-segment elevation and 0.89 for acute transmural injury
Sekiguchi et al. (15), 1999, Japan	Detection of abnormal ECGs	1058	Internal medicine residents (*n* = 25) and computer	Computer: 87.4% sensitivity, 83.5% specificity Internal medicine residents: 96.3% sensitivity, 99.1% specificity
de Bruyne et al. (16), 1997, the Netherlands	ECG criteria for MI, bundle-branch block, and ventricular hypertrophy	381	Computer and research physicians (*n* = unknown)	Computer: 73.8%–92.9% sensitivity, 97.5%–99.8% specificity Research physicians: 71.8%–96.9% sensitivity, 96.3%–99.6% specificity
Brailer et al. (17), 1997, United States	Comprehensive interpretation of investigator-selected ECGs	80	Cardiologists (*n* = 22) with and without computer	Cardiologists without computer: 53.0% agreement with reference standard; 7.0% of normal ECGs incorrectly read as abnormal Cardiologists with computer: 61.0% agreement with reference standard; 4.5% of normal ECGs incorrectly read as abnormal
Heden et al. (18), 1996, Sweden and United States	Interpretation of ECG criteria for anterior MI from investigator-selected ECGs from healthy patients (*n* = 351) and patients having cardiac catheterization (*n* = 1313)	1664	Computer (artificial neural network)	77.0% agreement with reference standard
Heden et al. (19), 1996, Sweden and United States	Interpretation of lead reversal in ECGs from ED patients	10 906	Computer (artificial neural network)	57.6%–83.0% sensitivity; 99.8%–99.9% specificity
Widman and Tong (20), 1996, Sweden and United States	Analysis of ECG dysrhythmias from textbooks and patient charts	56	Computer	82.1% agreement with reference standard
Woolley et al. (21), 1992, United States	Comprehensive interpretation of ECGs from patients at family medicine clinic	301	Family medicine residents and staff, computer, and cardiology staff (*n* = unknown)	Family physicians: 67.0% agreement with reference standard; 14.3% of errors of potentially major clinical significance Computer: 88.0% agreement with reference standard Cardiologists: 91.0% agreement with reference standard
Shirataka et al. (22), 1992, Japan	Interpretation of computer-generated normal and abnormal ECGs with arrhythmias	110	5 different computer systems	Normal sinus rhythm with first-degree AV block: 100% agreement with reference standard

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Table 2—**Continued**

Study (Reference), Year, Country	Focus of Study	ECGs Studied, *n*	Type and Number of Participants	Interpretation Results†
Shirataka et al. (22), 1992, Japan (*continued*)				Second-degree AV block with classic Wenckebach periodicity: 0%–100% agreement with reference standard Second-degree AV block with atypical Wenckebach periodicity: 0% agreement with reference standard Mobitz type II AV block: 40%–100% agreement with reference standard Bigeminy due to ventricular premature contractions: 40%–100% agreement with reference standard
Willems et al. (23), 1991, European multinational	Interpretation of normal and abnormal ECGs with acute MI and ventricular hypertrophy from cardiology referral population	1220	Cardiologists (n = 8) and computers (n = 9)	Cardiologists: 76.3% agreement with reference standard Computers: 69.7% agreement with reference standard
Willems et al. (24), 1990, European multinational	Interpretation of acute MI and ventricular hypertrophy from ECGs from cardiology referral population	500	Cardiologists (n = 9) and computers (n = 15)	Cardiologists: 77.7% agreement with reference standard Computers: 76.6% agreement with reference standard Computer and cardiologist agreement: κ = 0.61
Thomson et al. (25), 1989, Australia	Comprehensive interpretation of ECGs from a teaching hospital	5110	Computer	Hypertrophy: 94.0% sensitivity, 84.3% specificity Arrhythmias and AV block: 89.0% sensitivity, 90.5% specificity Infarction: 86.5% sensitivity, 93.9% specificity ST-T wave changes: 83.1% sensitivity, 84.1% specificity Axis and conduction block: 84.7% sensitivity, 92.7% specificity

* AV = atrioventricular; ECG = electrocardiogram; ED = emergency department; MI = myocardial infarction.
† The reference standard refers to interpretation of one or more expert electrocardiographers, typically cardiologists. Sensitivity and specificity refer to diagnosis of pertinent ECG abnormality, as defined by reference standard. Agreement with reference standard refers to proportion of ECGs in full agreement with the reference standard.

mal ECGs, the specificity of noncardiologists also approached that of cardiologists (15).

Severity and Consequences of Errors in ECG Interpretation

Eleven studies examined whether ECG interpretation errors could affect patient management, and seven measured patient outcomes (**Table 1**). Thirteen studies assessing the severity of interpretation errors reported that 4% to 33% of interpretations contained errors of major importance (2–13, 21). Expert consensus panels studied the charts of patients with ECG interpretation errors and determined whether a correct ECG interpretation would have changed patient management. This more detailed analysis revealed inappropriate management as a result of interpretation errors in 0% to 11% of cases (**Table 1**).

Six studies that documented patient follow-up showed a less than 1% incidence of adverse outcomes and potentially preventable death as a result of inaccurate ECG interpretation (4, 6, 8, 9, 11, 12). Therefore, although noncardiologist physicians have a high incidence of interpretation errors when compared to an expert reference standard, these errors seem to have minimal impact on morbidity and mortality. One important limitation of current studies on outcomes of ECG interpretation errors is that most were performed in emergency and inpatient settings. Because the probability of life-threatening disease is reduced in primary care settings, the impact of interpretation errors on patient outcomes may be overestimated by extrapolating from the results of existing research.

Computer Analysis of 12-Lead Resting ECGs

Computer software providing automated ECG interpretation is a common feature of most modern acquisition devices. Computer software can correctly identify 58% to 94% of various nonrhythm electrocardiographic abnormalities when compared to expert electrocardiographers (**Table 2**). Accuracy is considerably reduced when comput-

Table 3. **Electrocardiogram Interpretation Studies without Outcomes Related to Interpretation Errors***

Study (Reference), Year, Country	Focus of Study	ECGs Studied, *n*	Type and Number of Participants	Interpretation Results†
Brady et al. (26), 2001, United States	Interpretation of ECGs with ST-segment elevation; ECG criteria for thrombolytic therapy in patients with acute MI	11	Emergency medicine residents and staff (n = 458)	94.9% agreement with reference standard for ST-segment elevation; 83.2% agreement with thrombolytic therapy recommendation
Pope et al. (27), 2000, United States	ECG signs of myocardial ischemia in patients with cardiac symptoms discharged from ED	38	Internal and emergency medicine residents and ED staff physicians (n = unknown)	86.8% agreement with reference standard
Hatala et al. (28), 1999, United States	Comprehensive interpretation of investigator-selected ECGs	8	Fourth-year medical students (n = 30), internal medicine residents (n = 15), and cardiologists (n = 15)	Clinical vignette supporting correct ECG diagnosis: *Medical students:* 48% agreement with reference standard *Internal medicine residents:* 68% agreement with reference standard. *Cardiologists:* 96% agreement with reference standard Clinical vignette supporting incorrect ECG diagnosis: *Medical students:* 17% agreement with reference standard *Internal medicine residents:* 39% agreement with reference standard *Cardiologists:* 85% agreement with reference standard No clinical vignette: *Medical students:* 36% agreement with reference standard. *Internal medicine residents:* 64% agreement with reference standard. *Cardiologists:* 90% agreement with reference standard
Holmvang et al. (29), 1998, United States	Comprehensive interpretation of ECGs from patients diagnosed with unstable angina or non–Q-wave MI	516	Cardiologists (n = unknown)	Agreement with reference standard on: interpretation of ST-segment elevation (κ = 0.05); interpretation of ST-segment depression (κ = 0.38); interpretation of T-wave inversion (κ = 0.63); interpretation of bundle-branch block (κ = 0.84); identification of abnormal ECG (κ = 0.42)
Storey and Rowley (30), 1997, England	ECG criteria for thrombolytic therapy in patients with acute MI	30	Nurses (n = 15), house officers (n = 22), registrars (n = 10), consultant physicians (n = 8), and cardiologists (n = 6)	Nurse interpretation: 83.8% appropriate recommendation for thrombolytic therapy House officer interpretation: 72.6% appropriate recommendation for thrombolytic therapy Registrar interpretation: 80.7% appropriate recommendation for thrombolytic therapy Consultant staff interpretation: 77.1% appropriate recommendation for thrombolytic therapy Cardiologist interpretation: 83.3% appropriate recommendation for thrombolytic therapy
Hatala et al. (31), 1996, United States	Interpretation of investigator-selected ECGs	10	Internal medicine residents (n = 10)	Clinical vignette supporting correct ECG diagnosis: 77% agreement with reference standard Clinical vignette supporting incorrect ECG diagnosis: 29% agreement with reference standard

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Table 3—**Continued**

Study (Reference), Year, Country	Focus of Study	ECGs Studied, *n*	Type and Number of Participants	Interpretation Results†
Gillespie et al. (32), 1996, Scotland	Comprehensive interpretation and criteria for thrombolytic therapy from investigator-selected ECGs	8	Junior house officers (*n* = 26) and senior house officers/registrars (*n* = 31)	Junior house officer interpretation: 56.3% agreement with reference standard; 80.1% appropriate recommendation for thrombolytic therapy Senior house officer/registrar interpretation: 71.7% agreement with reference standard; 82.8% appropriate recommendation for thrombolytic therapy
Prasad et al. (33), 1996, Scotland	Comprehensive interpretation of ECGs from cardiology inpatients	160	Junior and senior house officers and noncardiologist consultants (*n* = unknown)	96.3% agreement with reference standard
Herbert et al. (34), 1996, Australia and United States	ECG diagnosis of broad-complex tachycardia in ED patients	27	ED resident and staff physicians (*n* = 3)	78% agreement (κ = 0.58) on diagnosis of ventricular tachycardia
Larsen et al. (35), 1994, United States	ECG diagnosis of left ventricular hypertrophy in patients admitted for symptoms of coronary artery disease	413	ED resident and staff physicians (*n* = unknown)	22% agreement with reference standard
Montgomery et al. (36), 1994, England	Measurement of PR and QT intervals from an investigator-selected ECG	1	Senior house officers, registrars, and consultants (*n* = 158)	26% correct measurement of PR interval; 24% correct measurement of QT interval
Foster et al. (37), 1994, United States	Recognition of criteria for thrombolytic therapy from patients with MI arriving at an ED	155	Nurses and paramedics (*n* = unknown)	94% sensitivity and 100% specificity for identifying appropriate patients for thrombolytic therapy
Grum et al. (38), 1993, United States	Comprehensive interpretation of investigator-selected ECGs	10	Third-year medical students (*n* = 95)	Medical students without suggestive vignette: 56% agreement with reference standard Medical students with suggestive vignette: 63% agreement with reference standard
Gjorup et al. (39), 1992, Denmark	ECG diagnosis of acute MI in coronary care unit patients	215	First- and second-year internal medicine residents (*n* = 16)	30% agreement with each other on presence or absence of acute MI before and after teaching seminars
Ho et al. (40), 1990, United States	ECG diagnosis of criteria for thrombolytic therapy in preadmission ECGs	236	ED physicians and cardiologists (*n* = unknown)	ED physicians: 78% sensitivity, 93% specificity Cardiologists: unknown sensitivity, 95% specificity
Pinkerton et al. (41), 1981, United States	Comprehensive interpretation of ECGs from outpatient clinic patients	18	Internal medicine (*n* = 24) and family medicine (*n* = 57) residents	Internal medicine residents: 80.2% agreement with reference standard for clinical abnormalities; 37.5% agreement with reference standard for technical abnormalities Family medicine residents: 74.7% agreement with reference standard for clinical abnormalities; 36.8% agreement with reference standard for technical abnormalities
Weston et al. (42), 1976, Australia	ECG classification as normal vs. suspicious for coronary artery disease in patients undergoing coronary arteriography	105	Cardiologists (*n* = 8)	Intracardiologist agreement on multiple ECG readings: *ECG alone*—40%–87.6%; *ECG and history*—38.1%–94.3% Intercardiologist agreement on multiple ECG readings: *ECG alone*—37.1%–60.0%; *ECG and history*—28.6%–77.1%

* ECG = electrocardiogram; ED = emergency department; MI = myocardial infarction.
† The reference standard refers to interpretation of one or more expert electrocardiographers, typically cardiologists. Sensitivity and specificity refer to diagnosis of pertinent ECG abnormality, as defined by reference standard. Agreement with reference standard refers to proportion of ECGs in full agreement with the reference standard.

ers interpret arrhythmias, such as different types of second-degree atrioventricular block (22). In addition, reliability may be a problem; several studies show substantial differences in ECG interpretations obtained minutes apart in clinically stable patients (47–49).

Despite the limitations, evidence suggests that computer interpretation software is a useful adjunct to physician interpretation. In some reports, computers have detected abnormalities missed by physicians. A study of resident physicians showed that using computer interpretation software reduced the incidence of serious ECG interpretation errors from 22% to 18% (13). Another study that paired a computer and a cardiologist showed a reduction in false-positive ECG readings from 7% to 4.5% and 8% greater agreement with an expert electrocardiographer consensus panel (17). However, other research has indicated that preliminary computer interpretations may both benefit and mislead primary care physicians (50).

In addition to potentially reducing interpretation errors, computers may have other advantages. Computer interpretation can decrease the time necessary to interpret ECGs by up to 28% (17, 50). Therefore, although computer ECG analysis is still inferior to physician interpretation, it may be a useful adjunct to save physician time. Further study is needed to determine whether computer interpretations can consistently reduce medical errors.

ATTAINING AND TESTING COMPETENCY IN 12-LEAD RESTING ECG INTERPRETATION

A 2001 statement by the ACC/AHA recommended interpretation of 500 supervised ECGs, and an earlier 1995 edition of the same guideline recommended 800 interpretations to attain initial competency in ECG interpretation (1, 43). Both guidelines were created through expert consensus, and neither provided evidence-based data to support their conclusions. The Accreditation Council for Graduate Medical Education Residency Review Committee for Internal Medicine states that all residents should be given an opportunity to develop competency in interpretation of ECGs but has not specified how to achieve this goal (44). The American Board of Internal Medicine has not listed a minimum number of supervised ECGs required to sit for internal medicine board certification (45). Other professional organizations and surveys of clinicians lack consensus regarding the minimum number of supervised ECG interpretations needed to achieve competence during internal medicine residency training. One survey of program directors stated that a median number of 100 ECGs were necessary to obtain initial competency (51). The number of supervised ECG interpretations recommended to obtain competency during cardiology fellowship is also derived by consensus from the Accreditation Council for Graduate Medical Education Residency Review Committee for Cardiovascular Diseases, which recommends the interpretation of 3500 ECGs (44). The number of ECGs interpreted by a physician has not been linked to either standardized test performance or patient outcomes.

The most recent ACC/AHA guidelines also recommend that physicians pass an ECG certification examination as part of credentialing (1). Reports on such examinations suggest that cardiologists may perform better than other physicians (52). This may be especially true in situations where detailed clinical information is not available. However, it is unclear how standardized test scores are related to physician performance in ECG interpretation or patient outcomes in a clinical setting.

MAINTAINING COMPETENCY IN 12-LEAD RESTING ECG INTERPRETATION

Evidence-based literature that addresses whether competency in ECG interpretation changes after initial residency or fellowship training is not available. For certain medical skills, such as interventional cardiology procedures, increased procedure volume is associated with improved patient outcomes (53). However, this relationship is less clear for cognitive skills. Observational data suggest that higher procedure volume improves resident confidence in numerous technical skills, such as thoracocentesis, paracentesis, and central line placement (54). No studies have examined whether physicians who are more confident in their skills have better patient outcomes.

It is also unclear whether continuing medical education, such as didactic courses, hands-on ECG interpretation seminars, or self-assessment programs, can improve ECG interpretation skills after initial residency or fellowship training. Several uncontrolled studies of residents and students showed improvement in ECG interpretation skills after structured ECG interpretation seminars (5, 55, 56). Further research is needed to better understand whether the yearly volume of ECGs interpreted and continuing medical education on ECG interpretation improve analytic accuracy and patient outcomes.

CONCLUSIONS

Electrocardiogram interpretation is a common cognitive skill that is acquired by internal medicine physicians during initial residency training; it is used by most primary care and subspecialty physicians. Little evidence-based literature supports strict quantitative standards for attaining and maintaining competency in interpreting ECGs. Expert electrocardiographers and other physicians frequently disagree, but adverse outcomes do not often result from these disagreements. The use of a cardiologist "gold standard" to determine ECG interpretation accuracy in future research may be problematic because cardiologists often do not agree on interpretations of the same ECG. Computers may be useful adjuncts in detecting missed electrocardiographic diagnoses and reducing time needed for ECG interpretation. Further high-quality research is needed to determine optimal standards for attaining competency in ECG interpretation. These standards must integrate physician skills to appropriately order ECGs; to recognize common normal and abnormal tracings; and to understand criteria for therapy decisions based on ECG interpretation, such as the administration of thrombolytic agents. Research demonstrating effective training methods that will decrease interpretation variability for high-stakes diagnoses, such as acute myocardial infarction, is needed to reduce medical errors and improve patient outcomes.

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Drs. Alguire and Salerno dedicate this article to Herbert Waxman, MD, a friend and colleague whose vision, leadership, and friendship will be missed. Dr. Waxman, who served as Senior Vice President for Medical Knowledge and Education at the American College of Physicians, died on 15 February 2003.

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