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REVIEW TOPIC OF THE WEEK

Computer-Interpreted Electrocardiograms

Benefits and Limitations

Jürg Schläpfer, MD,[a] Hein J. Wellens, MD[b]

ABSTRACT

Computerized interpretation of the electrocardiogram (CIE) was introduced to improve the correct interpretation of the electrocardiogram (ECG), facilitating health care decision making and reducing costs. Worldwide, millions of ECGs are recorded annually, with the majority automatically analyzed, followed by an immediate interpretation. Limitations in the diagnostic accuracy of CIE were soon recognized and still persist, despite ongoing improvement in ECG algorithms. Unfortunately, inexperienced physicians ordering the ECG may fail to recognize interpretation mistakes and accept the automated diagnosis without criticism. Clinical mismanagement may result, with the risk of exposing patients to useless investigations or potentially dangerous treatment. Consequently, CIE over-reading and confirmation by an experienced ECG reader are essential and are repeatedly recommended in published reports. Implementation of new ECG knowledge is also important. The current status of automated ECG interpretation is reviewed, with suggestions for improvement. (J Am Coll Cardiol 2017;70:1183–92) © 2017 by the American College of Cardiology Foundation.

The first attempts to automate electrocardiogram (ECG) analysis go back to the late 1950s (1,2), and it was soon expected that digital computers would have an important role in ECG processing and interpretation (3). Despite technical developments, the clinical use of the computerized ECG remained initially limited because of the lack of agreement on definitions of waves and common measurements, standardized criteria for classification, and terminology for reporting (4). To address these difficulties, efforts to propose standards and recommendations were developed, both in Europe and in the United States, to establish an international standard for computerized interpretation of the ECG (CIE) (5). The goals were to reduce the wide variation in wave measurements obtained by ECG computer programs and to assess and improve the diagnostic classification of ECG interpretation (6) so that similar measurements and diagnostic results could be obtained independent of the computer program used (4). However, despite all these efforts and advances in the field, an international accepted standard is still missing (5).

GENERAL COMMENTS ABOUT TECHNICAL ASPECTS

For digital ECG programs providing diagnostic interpretation, several technical aspects have to be considered:

1. Signal processing, including acquisition, conversion from analog to digital signals, and filtering to eliminate noise (e.g., myopotentials, movement artifacts, baseline wandering linked to respiration). Correct filtering is a fundamental step, as it can dramatically alter the final processed signal (5,6).
2. In the majority of automated systems, all ECG leads are now recorded simultaneously. Construction of representative template complexes (dominant complexes) excluding premature beats allows formation of an average complex for each lead (6).

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From the [a]Department of Cardiology, Lausanne University Hospital, Lausanne, Switzerland; and the [b]Cardiovascular Research Institute, Maastricht, the Netherlands. The authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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ABBREVIATIONS AND ACRONYMS

AF = atrial fibrillation

CIE = computerized interpretation of the electrocardiogram

ECG = electrocardiogram

LVH = left ventricular hypertrophy

STEMI = ST-segment elevation myocardial infarction

3. Waveform recognition, with precise determination of onset and offset of the different waves (P-wave, QRS complex, T-wave). The temporal alignment and superimposition of the representative complex for each lead offers more accurate labeling of wave onset and offset (6).
4. Measurements of intervals (PR, QRS, QT) and amplitude parameters. When performed, global interval measurements are associated with higher values than single lead measurements because they remove isoelectric intervals present in each of the single leads (7–9). This process is simple and straightforward when the ECG signal is registered in normal sinus rhythm, but it may become very complex in the presence of atrial arrhythmias (5), requiring time-domain or spectral analysis for recognition and discrimination of rapid electrical atrial activity. Manufacturers' algorithms for determining onset and offset of waves vary, and are the cause of recurrent differences in QRS duration and of differences in QT interval measurements (10–12).
5. In a recent study, 4 different current digital electrocardiographs were studied as to their automated measurement of RR, PR, QRS, and QT interval duration in 600 ECGs. It included 200 ECGs during QT interval studies in normal subjects, 200 ECGs in normal subjects during the peak of moxifloxacin administration (known to modestly prolong the QT interval), and 200 patients with genotyped variants of long QT syndrome (8). Measured intervals and durations show small, but statistically significant group differences between manufacturers (8). Mean absolute differences between algorithms were similar for QRS duration and QT interval in normal subjects, but were significantly larger in patients with long QT syndrome (8).

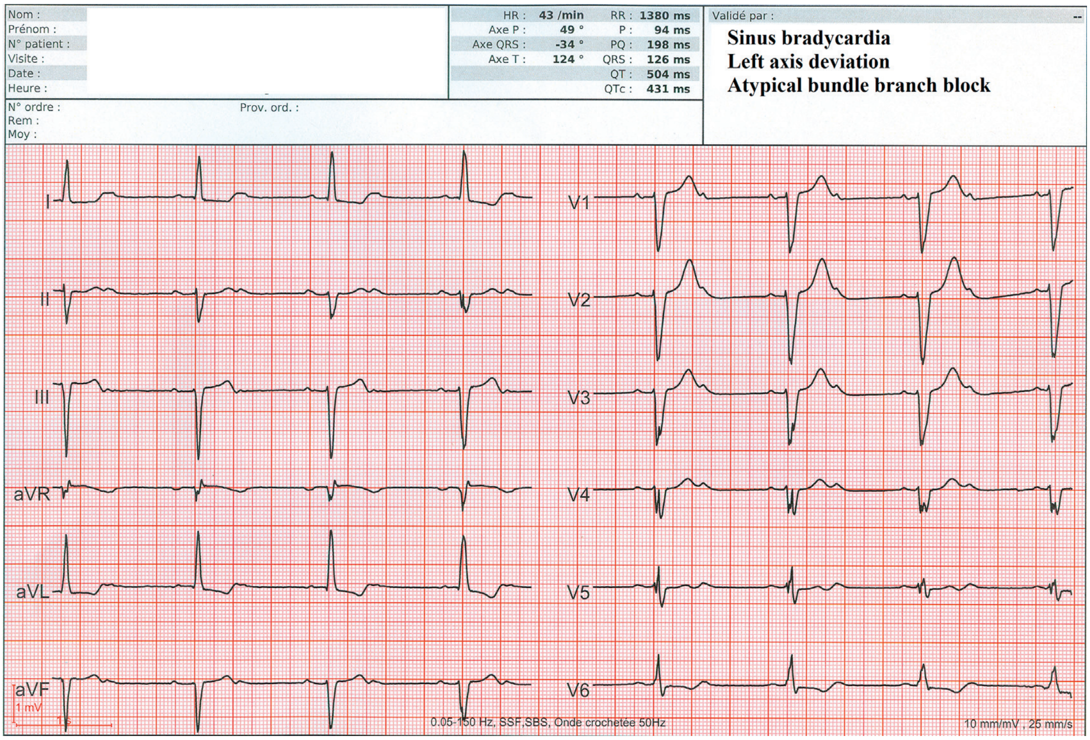
   Amplitude measurement discrepancies were less frequently reported, but day-to-day variability in amplitude measurements have been described, leading to significant differences in voltage measurements and, consequently, in computer diagnoses (5–10). Despite progress in the development of the various algorithms, differences in measurements results persist, and the call for standardization and recommendations for definitions of waves and references, already initiated in the 1970s, still remains incompletely answered (10,13). Statements using precise measurement of ECG amplitudes and durations can approach experienced readers in sensitivity, specificity, and reproducibility (14). However, statements that depend on waveform configuration (e.g., repolarization) and relationship between waveforms (e.g., irregular P waves, atrioventricular conduction disturbances) (**Figure 1**) may be less accurate, as the computer reading the ECG does not have the visual pattern recognition skills of a human being (14,15).
6. Interpretation using diagnostic algorithms to the processed ECG. These algorithms are proprietary, and may perform differently when applied to ECG signals processed by different methods (6). Measurement differences among various standard ECG systems may be sufficiently large to alter diagnostic conclusions (4). This may have clinical consequences and, for example, interfere with the selection of candidates for cardiac resynchronization therapy, as QRS duration is the main determinant for device implantation in these patients (11,12).
7. Finally, data compression, transmission, and archiving are also important aspects of digital processing (5).

ALGORITHM ACCURACY

Algorithm accuracy may vary according to both the manufacturer's automated program and the level of the participating ECGs' over-readers. Indeed, these algorithms are usually tested in comparison with the diagnosis of expert physicians, cardiologists, electrophysiologists, or using a consensus of experts (6), considered to be the "gold standard." Furthermore, ECG interpretation is a mixture of both subjective and objective aspects, where even experienced cardiologists or experts can disagree, resulting in significant interobserver variability (16). Additionally, ECG databases used in testing computer programs may insufficiently represent the overall population; in fact, they should be sufficiently large and diverse to contain all possible clinical diagnoses to mirror daily medical practice (5). Direct comparative evaluation of the performance of commercially available CIE programs has never been performed, mainly due to the reluctance of the manufacturers who own the various algorithms. From this perspective, more collaboration among the various manufacturers would be desirable (**Central Illustration**).

CURRENT STATUS OF CIE. In 1991, the first systematic assessment of computer programs compared the performance of 9 electrocardiographic computer programs with that of 8 cardiologists in interpreting ECGs in 1,220 clinically validated cases of various disorders (17). All together, the median total accuracy

FIGURE 1 Atrioventricular Block



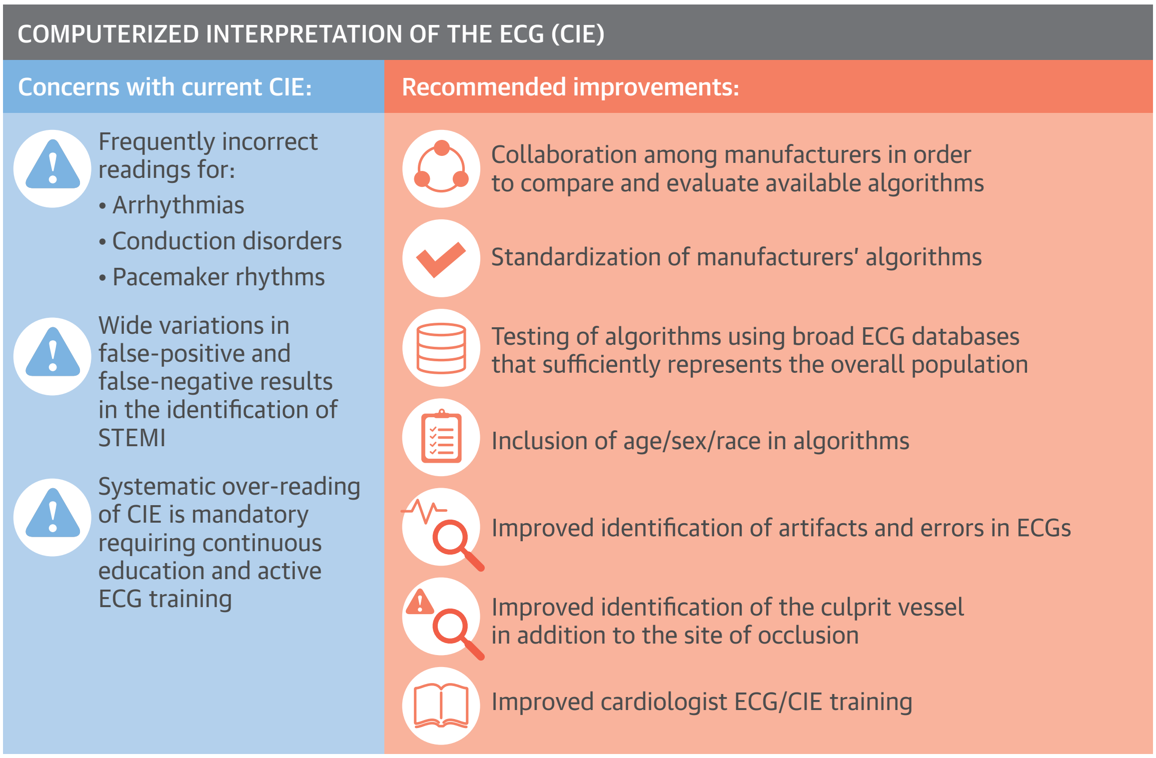
Unrecognized 2:1 atrioventricular block. The blocked sinus P-wave is partially hidden in the preceding T-wave.

of the computer programs was 6.6% lower than that of the cardiologists. This comparative study was limited to a few common ECG diagnostics, such as ventricular hypertrophy, old myocardial infarctions of various locations, and selected combinations of these categories (3,17). The performance of some programs was almost as accurate as the best cardiologists, whereas others were clearly inferior. Furthermore, the degree of variability in diagnostic accuracy among computer programs was significantly greater than that among cardiologists (6,17). CIE was found to be most frequently incorrect in arrhythmias, conduction disorders, and pacemaker rhythms (18).

Arrhythmias. In a study by Shah and Rubin (19), using 2,112 randomly selected, standard 12-lead ECGs, CIE was accurate in interpreting sinus rhythm (positive predictive accuracy 95%), but the performance was significantly less in nonsinus rhythms (positive predictive accuracy 53.5%), with the computer unable to produce a rhythm interpretation in 2% of traces. The difficulty in making a correct diagnosis of the underlying rhythm was linked to recognizing P waves with a small amplitude (**Figure 2**), varying P-wave morphologies or P waves masked by underlying noise, QRS complexes, or T or U waves (**Figure 1**) (19). Atrial fibrillation (AF) is another diagnostic challenge. In a recent review Taggar et al. (20) found, when comparing the automated software diagnosis with the one by health care or primary care professionals, that CIE showed a borderline greater specificity for AF diagnosis. Overinterpretation of AF was documented in 9.3% to 19% of ECGs (21,22), the most prevalent underlying rhythm in these cases being sinus rhythm and sinus tachycardia with premature atrial beats or baseline artifacts (**Figure 3**) (22). Misdiagnosis of AF was present in 11.3% in the series of Hwan Bae et al. (22), and was more frequent in the elderly. These recognized limitations may result in initiation of unnecessary, potentially harmful medical treatment or the use of inappropriate diagnostic resources in up to 10% of patients (21,22). Additional failure of the ordering physician to correct the false CIE can be another factor leading to inadequate treatment.

Pacemaker rhythms. According to older publications, up to 75% of pacemaker rhythms were misinterpreted (14,18,19). Failure to recognize low-voltage pulses during pacemaker activity led to multiple errors, such as myocardial infarction in varying

CENTRAL ILLUSTRATION Current Status of Computerized ECG Interpretation and Required Improvements



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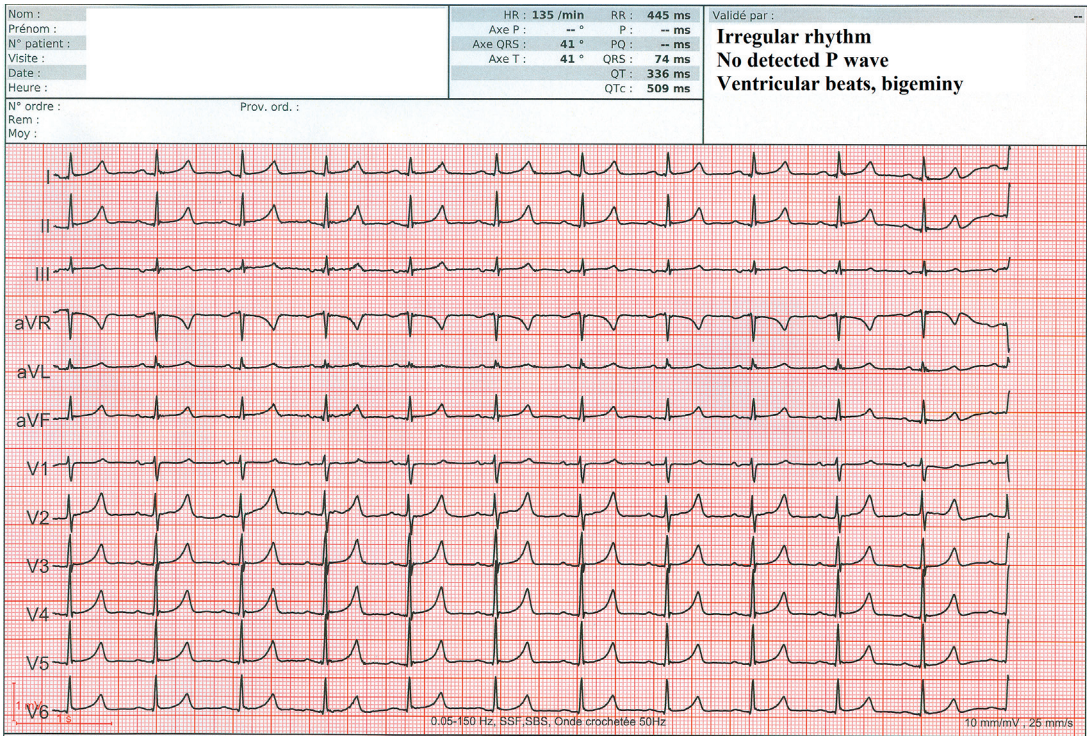
CIE = computerized interpretation of the electrocardiogram; ECG = electrocardiography; STEMI = ST-segment elevation myocardial infarction.

locations, left ventricular hypertrophy (LVH), left bundle branch block, or intraventricular conduction delay (**Figure 4**) (18). Substantial progress was recently made by many manufacturers now offering specific algorithms to allow detection of pacing artifacts, resulting in significant improvement in pacemaker rhythm diagnosis. However, these algorithms will need to be adapted to new developments in pacing, such as multisite pacing and resynchronization therapy.

Acute coronary syndromes. The ECG is the most important initial tool in diagnosing an acute ST-segment elevation myocardial infarction (STEMI) (23). ECG misinterpretation and misclassification may delay or prevent the diagnosis of acute myocardial infarction, unnecessarily prolonging the door-to-balloon time in the coronary laboratory (24). Automated systems have been developed to diagnose acute STEMI and tested in the emergency department or in the pre-hospital phase to speed up diagnosis and accelerate early reperfusion. These algorithms demonstrate wide variations in false positive (overdiagnosis in 0% to 42%) and false negative results (underdiagnosis in 22% to 42%) (25). Those discrepancies were illustrated by Garvey et al. (26), who recently showed the varying accuracy of 3 different available STEMI diagnostic algorithms to identify the location of the culprit coronary artery lesion. In these studies, different ECG machines with various algorithms were tested in patient groups with a different prevalence of STEMI. Also, CIE diagnoses were compared with interpretations from heterogeneous sources: cardiologists, emergency physicians, World Health Organization criteria, discharge diagnosis of STEMI, or catheterization laboratory findings (25). Because of its high false negative results in the identification of STEMI, it is not recommended that CIE be used as the sole means to activate the cardiac catheterization laboratory. It should always be used in conjunction with physicians, paramedics, or nurses

FIGURE 2 **Unrecognized Sinus Rhythm**



Unrecognized regular sinus rhythm with double counting of the heart rate (135 beats/min) due to T-wave oversensing. Consequently, the QTc interval is overestimated at 509 ms; note that no QT prolongation warning appears in the diagnosis report.

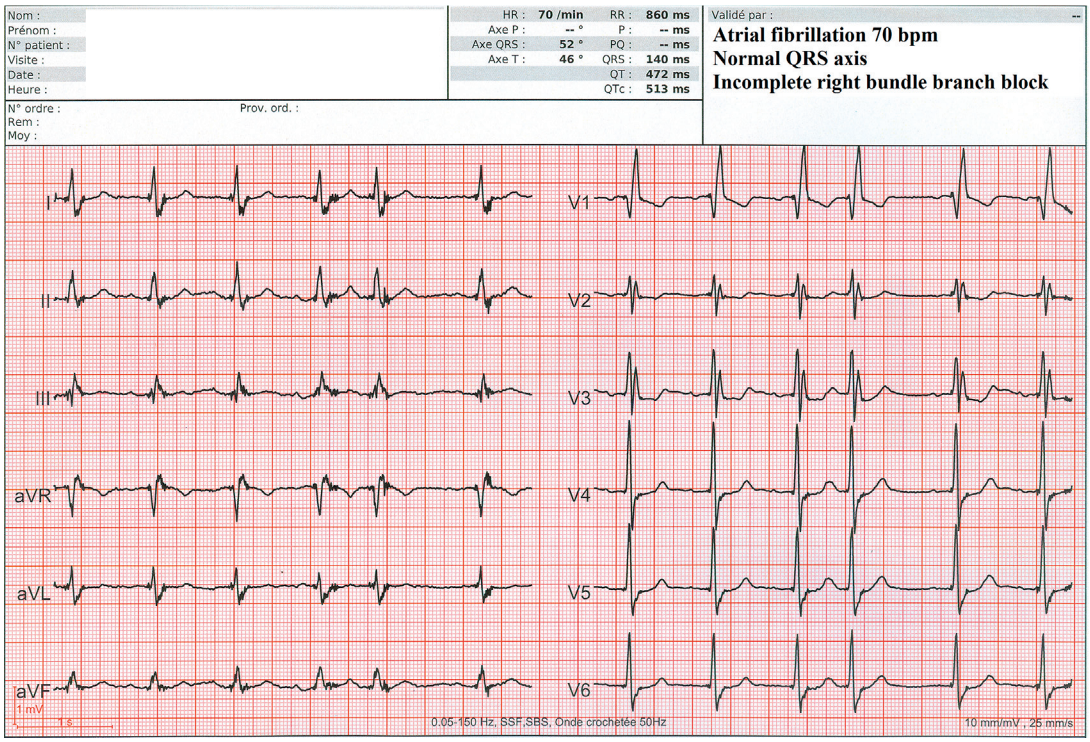
trained to recognize STEMI (25). Preferably, the ECG review should be supplemented by the characteristics of the patient's symptoms, the past medical history, and comparison with previous ECGs to improve CIE diagnostic accuracy and help in the decision process (**Central Illustration**) (27).

Bosson et al. (27) recently showed that ECG artifacts and nonischemic causes of ST-segment elevation, such as early repolarization, were the most common reasons for incorrect algorithm interpretation of STEMI. Minimizing ECG artifacts by training paramedics on how to recognize and avoid them is critical in improving the performance of software (27).

For the future, electrocardiograph manufacturers are asked to equip their machines with switching systems allowing the arrangement of limb leads in their anatomically contiguous sequence (23), which may help to make the correct diagnosis. Algorithms should be further refined to display the spatial orientation of the ST-segment deviation vector in the frontal and transverse planes, and to help in locating the culprit vessel as well as the site of occlusion (23). These algorithms should also help clinicians to recognize, in acute coronary settings, culprit lesion sites resulting in a large ischemic area that require rapid reperfusion, as in left main obstruction, proximal left anterior descending artery occlusion, and multivessel disease, or in situations in which the ECG interpretation is complicated by conduction disorders (e.g., complete left bundle branch block or paced rhythms) (28). Recording additional right-sided precordial leads should also be suggested in inferoposterior infarctions to make the distinction between a right or circumflex coronary artery occlusion (6,23). Incorporating sex, age, race, and prior ECG findings into algorithms could also increase the sensitivity of a STEMI diagnosis (**Central Illustration**) (23–25).

Repolarization. ***QT interval.*** Precise QT interval measurement is another challenge for computerized algorithms, as the reliability of QT measurements has long been considered to be limited. Miller et al. (29) showed that diagnostic accuracy of screening ECGs in long QT syndrome was unsatisfactory and failed to identify at-risk family members. Significant progress

FIGURE 3 **Misdiagnosis of Atrial Fibrillation**

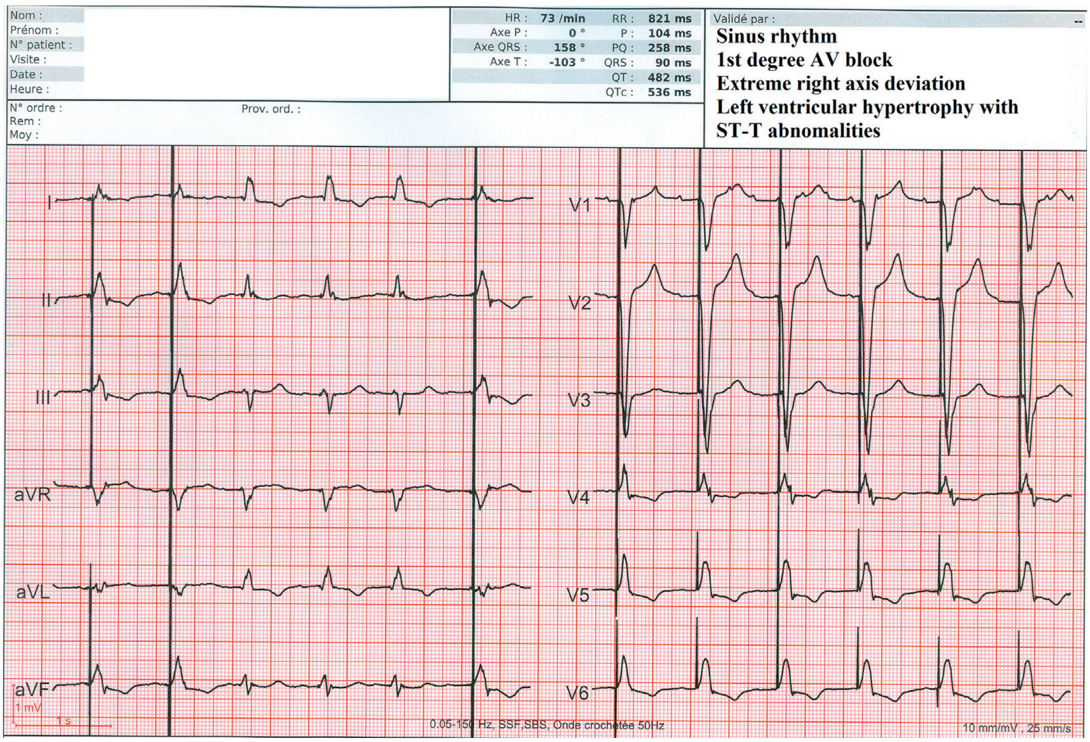


Normal sinus rhythm recorded during a checkup. The poor quality of the electrocardiogram made the fellow trust the wrong automated diagnosis of atrial fibrillation (AF) despite readily visible P waves. bpm = beats per minute.

has been made since then, with newer algorithms for QT measurements in good-quality tracings, but measurement errors remain in abnormal or poor-quality ECGs (30). The automatically measured global QT interval is generally longer than the QT interval measured in any individual lead by as much as 30 to 40 ms (9-31). As previously described, individual lead measurements tend to underestimate the true QT interval, as the onset or offset of waveforms may be isoelectric in a specific lead, whereas the lead with the earliest QRS onset may be different from that with the latest T-wave end (3,7,31). Superimposing individual tracings or points used to derive the QT interval should help the physician to obtain the correct value (3). A QT interval may be within or outside of the accepted normal values depending on the measurement method (visual or automatic) used. Central databases with high-quality ECGs using comparable methodology will be the only way to distinguish normal from abnormal values in specific populations (31). Differences in QT measurements between algorithms from the same manufacturer may exist, stressing the importance of using an electrocardiograph equipped with the same algorithm when measuring QT interval values during ECG surveillance in patients with long QT syndrome treated with drugs potentially affecting the QT interval (32,33). The same rule should be applied during serial comparisons in drug testing or for regulatory authorities in their evaluation of a possible proarrhythmic risk of a new drug (32,33). Recently Garg and Lehmann (34) drew attention to the fact that the algorithmic diagnosis did not display a prolonged QT interval in 52.5% of patients with a prolonged QT interval. This was attributed to ECG waveform-based criteria included in the tested algorithm (34). A similar behavior could occur (but not yet be published) with the algorithms of other manufacturers (**Figure 2**). The under-reporting of prolonged QTc interval in patients on methadone was also recognized (33). Before definitively concluding that the displayed QTc interval is correct, both systematic checking of the actual QTc value and visual validation of QT interval prolongation are strongly recommended (9,32-34).

Early repolarization. The early repolarization pattern is a widely prevalent condition, lately linked with an increased risk of arrhythmic death (35). Recent

FIGURE 4 Unrecognized Pacing Activity



Failure to recognize both atrial flutter and ventricular pacing activity. AV = atrioventricular.

development of sensitive algorithms may allow automatic detection of early repolarization in the general population, which could provide useful information for research programs or future large registries established to more precisely define individuals at risk of dying suddenly (35–38).

Left ventricular hypertrophy. The use of echocardiography, magnetic resonance imaging, or computerized tomography questioned the value of the ECG in diagnosing LVH. However, its lower cost and ease of use still justify its place in daily practice, epidemiological studies, and clinical trials (39). Over the years, different, initially simple electrocardiographic criteria were used for the diagnosis of LVH. Recently, more complex criteria, based on products of voltage and QRS duration, QRS area, or composite use of several criteria, have been published. However, no single diagnostic criterion can be recommended (39) due to their low sensitivity and specificity. CIE may help ECG readers save time in applying all criteria validated for identifying LVH and adjusted for noncardiac factors such as age, sex, race, and body habitus. The final interpretation should specify which diagnostic criteria were used and which were abnormal (39) (**Central Illustration**).

CIE as a screening tool. Berge et al. (40) showed, in 595 professional soccer players, that abnormal ECGs were more than twice as common after computer-based measurements than after visual measurements. The investigators appropriately suggest that this may justify redefining or adjusting reference values for abnormalities, as previously done for automatic QRS width and QT interval measurements (10–12,31). These observations raise the more general question of the influence of the technique used for ECG interpretations (visual diagnostic or automated measurements), not only in athletes in whom ECG screening value is controversial, but also in other populations (31). Homogeneity in ECG interpretation techniques is mandatory to ensure coherent results in research or epidemiological studies using ECG screening (40–42).

ARTIFACTS. Artifacts are well known to lower ECG diagnostic accuracy (**Figure 3**). To allow algorithms to perform at their best, quality recording is essential. Nurses and technicians in charge of ECG recordings should be well taught about the importance of correct preparation of the patient by cleaning the skin and using electrodes with contact gel. Periodic retraining in proper lead positioning of the different leads should also be routinely organized. Next, algorithms should alert for improper filter use and for any interchange of limb lead connections or precordial electrode misplacements (**Central Illustration**) (6). Paramedics involved in ECG recordings should also be educated to immediately alert the physician or the bedside nurse when a critical diagnosis is given by the machine (15).

PRACTICAL ASPECTS. Provided that the ECG quality is good, computerized interpretation gives a correct measurement of the basic parameters. Computer-assisted ECG interpretation decreased analysis time by up to 24% to 28% for experienced readers (5). Also, computerized archives allow rapid access to serial ECG comparisons. Besides indicating differences between ECGs, it improves interpretation accuracy, for example, in acute coronary syndromes (43).

CIE has the goal of improving patient care by displaying information helpful to reducing medical errors, facilitating physicians' reading, and reducing costs (44,45). However, computer-based analysis of the ECG may lead to erroneous diagnosis with useless, inappropriate, or even dangerous care of the patient. These potentially harmful consequences stress the requirement for continuous development in software and systematic over-reading of the ECG (5,6).

The correct interpretation of an ECG remains a challenge for physicians with a low level of knowledge (**Figure 3**) (45). Internal medicine residents have a low overall proficiency and self-perceived confidence in interpreting ECGs. They also find their training insufficient (45–47). Cardiologists as primary readers more often correct the misinterpreted ECGs, as compared with internists or others specialists (48). In the United States, cardiology fellows are requested to interpret approximately 3,000 to 3,500 ECGs during their standard 3-year training program to acquire competence in ECG interpretation (49). Training to review, edit, and amend ECGs generated by the computerized system that provides preliminary interpretation is part of their training (49).

The consensus is to consider CIE only as an adjunct to, and not a substitute for, the electrocardiographer. Consequently, all computer-based reports should be systematically over-read (5,6). It requires training of physicians and health personnel to validate (or not) the automated interpretation and early detection of errors (49,50). Knowledge of the strengths and limitations of CIE is a prerequisite for avoiding blind trust in software interpretations (5). Automated interpretation may influence physicians' ECG reading. It improves their diagnostic abilities when the interpretation is correct, but increases the probability of errors when the proposed diagnosis is incorrect, and negatively influences the decision making of the physician in charge of the patient (44,50,51). It has been roughly estimated that these misdiagnoses may account for up to 10,000 adverse effects or avoidable deaths worldwide annually (16). Additionally, level of expertise, training of the physician, time constraints, or fatigue are other main causes of diagnostic errors in ECG interpretation (21,48,52).

No single method of teaching appears most effective in obtaining ECG interpretation skills (53,54). However, repeated assessments, tested by a final examination, increase medium-term retention of ECG interpretation skills, whatever the instruction format. Continuous ECG training, coupled with appropriate examinations should also be done at the postgraduate level (55).

Standardization in applied algorithms and uniformization of diagnostic criteria and statements have been proposed (56). It would lead to worldwide uniformity of ECG interpretation and facilitate the development of a uniform teaching curriculum in electrocardiography.

The ECG is a noninvasive, powerful, and cost-effective tool when interpreted by the proper specialist, but hospitals may have difficulties in finding the resources to offer the ECG standard of care and comply with advised guidelines (16). A formal process of over-reading of all ECGs by cardiologists, or ECG-trained and ECG-tested physicians or paramedics, should be the rule and routinely applied in hospitals and clinics (5,16). Ideally, a clear delivery and routing system has to be organized, with over-reading of the ECG and rapid transmission to the patient's chart (16). When not possible, an alternative approach would be collaboration with an outside, centralized ECG interpretation service (16).

CONCLUSIONS

Significant progress was made in the development of ECG algorithms for use in the CIE. However, limitations are still present, requiring standardization, with continuous improvement in applied software and uniformization of ECG diagnostic criteria and statements. Systematic over-reading of CIE is mandatory. To provide patients with the best standard of care, critical knowledge in ECG interpretation remains necessary, and can only be acquired by continuous education and active ECG training. It also requires the implementation of new ECG information. Close cooperation between clinical ECG experts and CIE manufacturers is needed to optimize CIE performance.

ADDRESS FOR CORRESPONDENCE: Dr. Jürg Schläpfer, Department of Cardiology, Lausanne University Hospital, Rue du Bugnon 44, 1011 Lausanne, Switzerland. E-mail: jurg.schlaepfer@chuv.ch.

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