AHA/ACC/HRS Scientific Statement

Recommendations for the Standardization and Interpretation of the Electrocardiogram

Part I: The Electrocardiogram and Its Technology

A Scientific Statement From the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society

Endorsed by the International Society for Computerized Electrocardiology

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***Abstract*—**This statement examines the relation of the resting ECG to its technology. Its purpose is to foster understanding of how the modern ECG is derived and displayed and to establish standards that will improve the accuracy and usefulness of the ECG in practice. Derivation of representative waveforms and measurements based on global intervals are described. Special emphasis is placed on digital signal acquisition and computer-based signal processing, which provide automated measurements that lead to computer-generated diagnostic statements. Lead placement, recording methods, and waveform presentation are reviewed. Throughout the statement, recommendations for ECG standards are placed in context of the clinical implications of evolving ECG technology. **(*Circulation*. 2007;115:1306-1324.)**

Key Words: AHA Scientific Statements ■ electrocardiography ■ computers ■ diagnosis ■ electrophysiology ■ intervals ■ potentials ■ tests

In the century since the introduction of the string galvanometer by Willem Einthoven,[1] the electrocardiogram (ECG) has become the most commonly conducted cardiovascular diagnostic procedure and a fundamental tool of clinical practice.[2,3] It is indispensable for the diagnosis and prompt initiation of therapy in patients with acute coronary syndromes and is the most accurate means of diagnosing intraventricular conduction disturbances and arrhythmias. Its interpretation may lead to the recognition of electrolyte abnormalities, particularly of serum potassium and calcium, and permit the detection of some forms of genetically mediated electrical or structural cardiac abnormalities. The ECG is routinely used to monitor patients treated with antiarrhythmic and other drugs, in the preoperative assessment of patients undergoing noncardiac surgery, and in screening individuals in high-risk occupations and, in some

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The American Heart Association, the American College of Cardiology, and the Heart Rhythm Society make every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

This statement was approved by the American Heart Association Science Advisory and Coordinating Committee on October 26, 2006, by the American College of Cardiology Board of Trustees on October 12, 2006, and by the Heart Rhythm Society on September 6, 2006.

This article has been copublished in the March 13, 2007, issue of the *Journal of the American College of Cardiology* and in the March 2007 issue of *Heart Rhythm*.

Copies: This document is available on the World Wide Web sites of the American Heart Association (www.americanheart.org) and the American College of Cardiology (www.acc.org). A single reprint is available by calling 800-242-8721 (US only) or writing the American Heart Association, Public Information, 7272 Greenville Ave, Dallas, TX 75231-4596. Ask for reprint No. 71-0389. To purchase additional reprints, call 843-216-2533 or e-mail kelle.ramsay@wolterskluwer.com.

***Circulation* is available at http://www.circulationaha.org** **DOI: 10.1161/CIRCULATIONAHA.106.180200**

cases, for participation in sports. As a research tool, it is used in long-term population-based surveillance studies and in experimental trials of drugs with recognized or potential cardiac effects.

Indications for use of the ECG were summarized in a joint American Heart Association (AHA)/American College of Cardiology report in 1992.[4] Because of its broad applicability, the accurate recording and precise interpretation of the ECG are critical. The establishment of and adherence to professionally developed and endorsed evidence-based standards for all phases of the ECG procedure is an important step in ensuring the high level of precision required and expected by clinicians and their patients.[5] However, there has not been a comprehensive updating of ECG standards and criteria since 1978.[6–14] Since 1978, there have been many advances in the technology of electrocardiography; in the understanding of the anatomic, pathological, electrophysiological, and genetic information underlying ECG findings; and in the clinical correlations of ECG abnormalities. One of the most important changes in electrocardiography is the widespread use of computerized systems for storage and analysis. Many if not most ECGs in the United States now are recorded by digital, automated machines equipped with software that measures ECG intervals and amplitudes, provides a virtually instantaneous interpretation, and often compares the tracing to those recorded earlier by the same system. However, different automated systems may have different technical specifications that result in significant differences in the measurement of amplitudes, intervals, and diagnostic statements.[15,16]

For these reasons, the AHA initiated an updating of guideline statements for standardization and interpretation of the ECG. The project has been endorsed by the American College of Cardiology, the Heart Rhythm Society, and the International Society for Computerized Electrocardiology. The purposes of this project are as follows: (1) to review the status of techniques currently used to record and interpret the ECG and to identify opportunities for modification; (2) to simplify and unify the various descriptive, diagnostic, and modifying terminologies currently used in order to create a common and more easily applied lexicon; and (3) to identify the weaknesses of the descriptive, interpretative, and comparative algorithms and recommend changes that incorporate the newly recognized factors referred to above.

The chairman (L.S.G.) was selected by the Electrocardiography and Arrhythmias Committee of the Council on Clinical Cardiology of the AHA. He formed an advisory group to assist in setting goals and to recommend other writing group members. The committee met on 5 occasions to discuss goals, identify specific areas that required updating, and review progress. A smaller working/writing group with a group leader was chosen for each topic. This is the first of 6 articles written in response to the AHA mandate. It is followed by a glossary of descriptive, diagnostic, and comparative statements that attempts to minimize repetitive and noninformative statements. Additional articles, to be published subsequently, will discuss the ECG interpretation of intraventricular conduction disturbances, abnormalities of ventricular repolarization, hypertrophy, and ischemia/infarction.

The ECG and Its Technology

The purposes of this statement are (1) to examine the relation of the resting ECG to its technology, (2) to increase understanding of how the modern ECG is derived and recorded, and (3) to promote standards that will improve the accuracy and usefulness of the ECG in practice. Special emphasis will be placed on the digital recording methods and computer-based signal processing that are used in current electrocardiographs to provide automated measurements that lead to computer-generated diagnostic statements. The writing group recognizes that technical details of the processing and recording of ECGs may be unfamiliar to clinicians. Accordingly, a major purpose of this document is to provide clinicians with insight into the generally missing link between technology and its consequences for clinical ECG interpretation. The evolution and application of ECG technology have profound clinical implications, as exemplified by the demonstration that measurements made by different automated ECG systems from reference ECG data can vary enough to alter diagnostic interpretation.[15,17] Sensitivity and specificity of computer-based diagnostic statements are improving, but at the same time, it remains evident that physician overreading and confirmation of computer-based ECGs is required.[15,16,18]

Previous Standards and Reviews

A number of recommendations for the standardization of ECG recording and guidelines for ECG interpretation in the computer era have appeared during the past several decades. The most recent comprehensive AHA recommendations for the standardization of leads and general technical requirements of ECG instruments were published in 1975.[5] In 1978, task forces of the American College of Cardiology produced a collection of reports on optimal electrocardiography,[7] which addressed standardization of terminology and interpretation,[13] the development of databases,[6] the quality of ECG records,[12] computers in diagnostic cardiology,[9] the use of ECGs in practice,[10] cost-effectiveness of the ECG,[11] and a discussion of future directions.[14] In Europe, international common standards for quantitative electrocardiography (CSE) evolved from the work of Willems and colleagues.[19–22] The CSE studies were designed to reduce the wide variation in wave measurements obtained by ECG computer programs and to assess and improve the diagnostic classification of ECG interpretation programs.[22] Given the expanding use of computer-based ECG systems and evolving technology, recommendations for bandwidth and digital signal processing standards during automated electrocardiography were formulated in 1990 by a committee of the AHA.[23] In 1991, recommendations of the 1975 and 1990 AHA documents were incorporated into a summary document on diagnostic ECG devices that was developed by the Association for the Advancement of Medical Instrumentation (AAMI) and approved by the American National Standards Institute (ANSI).[24] This document was reaffirmed by ANSI in 2001. Other statements have addressed related issues of ECG utilization and physician competence in interpretation of the ECG.[16,18,25–27]

The ECG Signal and Its Processing

Automated analysis of the digital 12-lead ECG involves signal analysis and diagnostic classification.[28] Processing of the ECG occurs in a series of steps, each of which requires adherence to methodological standards. These steps include (1) signal acquisition, including filtering; (2) data transformation, or preparation of data for further processing, including finding the complexes, classification of the complexes into "dominant" and "nondominant" (ectopic) types, and formation of an average or median complex for each lead; (3) waveform recognition, which is the process for identification of the onset and offset of the diagnostic waves; (4) feature extraction, which is the measurement of amplitudes and intervals; and (5) diagnostic classification. Diagnostic classification may be heuristic (ie, deterministic, or based on experience-based rules) or statistical in approach.[29]

The ECG Signal

The standard 12-lead ECG records potential differences between prescribed sites on the body surface that vary during the cardiac cycle; it reflects differences in transmembrane voltages in myocardial cells that occur during depolarization and repolarization within each cycle. The ECG was regarded by Einthoven et al[30] as originating in a stationary, time-dependent single-dipole source that can be represented by a vector, the heart vector. In this model, voltage in any lead was explained by projection of the heart vector onto the straight line that defined the lead axis. Burger et al[31,32] expanded this concept by treating the lead axes as vectors. A lead vector, in addition to having a direction that is not the same as that of the lead axis, also has a length. Voltage in a lead is not merely the projection of the heart vector on the lead axis but also its projection on the lead vector times the length (ie, the "strength") of the lead vector. Direction and strength of a lead vector depend on the geometry of the body and on the varying electric impedances of the tissues in the torso.[31,32] Pairs of electrodes (or a combination of electrodes serving as 1 of the 2 electrodes) and the tracings that result from their use are known as leads. Placement of electrodes on the torso is distinct from direct placement on the heart, because the localized signal strength that occurs with direct electrode contact is markedly attenuated and altered by torso inhomogeneities that include thoracic tissue boundaries and variations in impedance. At any point in time, the electrical activity of the heart is composed of differently directed forces. Accordingly, the potential at any point on the body surface represents the instantaneous uncanceled electrical forces of the heart, where cancellation also is dependent on torso inhomogeneities. For further reading, see the comprehensive analysis of lead theory by Horacek in 1989.[33] As electrodes move farther away from the heart, signal strength decreases together with lead strength. According to solid angle theory, signal magnitude can be related to both spatial and nonspatial factors.[34] Nonspatial factors include the magnitude of transmembrane potential difference across a boundary within the heart. Spatial factors include the projected boundary of the difference in potential relative to the area of a sphere of unit size; this will increase with the absolute size of the area but decrease with distance of the electrode from the heart. Simultaneously active wave fronts within the heart may confound the seeming simplicity of these models.

The fundamental frequency for the QRS complex at the body surface is ≈10 Hz, and most of the diagnostic information is contained below 100 Hz in adults, although low-amplitude, high-frequency components as high as 500 Hz have been detected and studied. The QRS of infants often contains important components as high as 250 Hz.[35] The fundamental frequency of T waves is approximately 1 to 2 Hz.[23] Filtering of the ECG signal to within the band between 1 to 30 Hz produces a stable ECG that is generally free of artifact, but this bandwidth is unacceptable for diagnostic recording because it produces distortions of both high- and low-frequency components of the signal. The high-frequency components of the ECG signal define the most rapidly changing parts of the signal, including Q waves and notched components within the QRS complex. Because QRS amplitude measurement depends on accurate detection of the peak of an R wave, an inadequate high-frequency response results in systematic underestimation of signal amplitude and in smoothing of notches and Q waves. On the other hand, an inadequate low-frequency response can result in important distortions of repolarization. Accordingly, the transfer functions of the filtering algorithms of analog and digital electrocardiographs have a major effect on the resulting ECG.

ECG Signal Processing

Processing of the ECG signal by a digital electrocardiograph involves initial sampling of the signal from electrodes on the body surface. Next, the digital ECG must eliminate or suppress low-frequency noise that results from baseline wander, movement, and respiration and higher-frequency noise that results from muscle artifact and power-line or radiated electromagnetic interference.[36] As a result, the ECG signal at the body surface must be filtered and amplified by the electrocardiograph. Digital filters can be designed to have linear phase characteristics, and this avoids some of the distortion introduced by classic analog filters. Once filtered, individual templates are constructed for each lead from data sampled generally from dominant complexes, from which amplitude and duration measurements are made. Global measurements are made from individual lead data or from mathematical combinations of simultaneously acquired individual lead data. Measurement error has an important effect on the accuracy of ECG diagnostic statements.[37] Reference is made to the comprehensive analysis of technical factors that affect the ECG by Zywietz.[38] In the present statement, factors that affect the processing of the ECG signal will be discussed in terms of technology, clinical implications, and recommendations.

Sampling of the ECG Signal

Technology

Direct-writing electrocardiographs, which were preponderant until the 1970s, recorded signals that were analog, that is, continuous, in nature. Nearly all current-generation ECG machines convert the analog ECG signal to digital form before further processing. Analog-to-digital conversion in modern digital ECGs generally occurs at the front end, such

as the lead cable module. The initial sampling rate during analog-to-digital conversion at the front end is higher than the sampling rate that is used for further processing of the ECG signal. Oversampling was originally introduced to detect and represent pacemaker stimulus outputs, which are generally <0.5 ms in duration. Front-end sampling has been performed at rates from 1000 to 2000 per second, but newer converters can routinely sample at 10 000 to 15 000 per second or even higher; other converters are adaptive in sampling rate, with output that is proportional to the energy detected.

Clinical Implications

The initial sampling rate used by the computer to transform the analog electrical signal to a series of discrete digital points (generally described in the unit of samples per second, or imprecisely as a sampling rate of *x* Hz) is most often many times greater than required for further processing of the ECG signal. This is known as "oversampling." Pacemaker stimulus outputs are generally shorter in duration than 0.5 ms, and therefore, they cannot be reliably detected by ordinary signal processing technique at 500 to 1000 Hz. Accordingly, a primary benefit of oversampling is the detection of narrow pacemaker pulses. Pacemaker detection is not reliably or accurately performed in all current systems. Oversampling can also improve signal quality at the high-frequency cutoff. Separate from difficulties caused by pacemaker spike duration, the very small amplitudes of modern bipolar pacemaker stimulus outputs are often too small to be recognized on the standard ECG, a problem that requires resolution without introducing artificially enhanced pacemaker signals into the tracing.

Recommendations

Oversampling by a significant multiple of the upper-frequency cutoff is recommended to provide recommended bandwidth in the digitized signal. Manufacturers should continue to develop improved algorithms for the identification and quantitative presentation of pacemaker stimulus outputs and for their preservation during ECG storage and retrieval. Low-amplitude pacemaker stimulus outputs should not be artificially increased in amplitude to aid recognition, because this would distort the form of the recorded ECG. Instead, it is recommended that manufacturers incorporate a separate representation of detected pacemaker stimulus outputs into 1 row only of the standard output tracing that would aid the identification of atrial, ventricular, and biventricular pacing signals. The selected row might be a rhythm strip that accompanies the standard 3 rows of lead signals in 4 columns, or in the absence of a rhythm row, 1 of the standard rows might be selected for this purpose.

Low-Frequency Filtering

Technology

The heart rate, in beats (cycles) per minute (bpm), when divided by 60 (seconds per minute) forms a lower bound for the frequency content in Hertz (Hz, cycles per second). In practice, this is unlikely to be lower than 0.5 Hz, which corresponds to a heart rate of 30 bpm; heart rates below 40 bpm (0.67 Hz) are uncommon in practice.[23] However, with traditional analog filtering, a 0.5-Hz low-frequency cutoff introduces considerable distortion into the ECG, particularly with respect to the level of the ST segment.[39,40] This distortion results from phase nonlinearities that occur in areas of the ECG signal where frequency content and wave amplitude change abruptly, as occurs where the end of the QRS complex meets the ST segment. Digital filtering provides methods for increasing the low-frequency cutoff without the introduction of phase distortion.[23] This can be accomplished with a bidirectional filter by a second filtering pass that is applied in reverse time,[41] that is, from the end of the T wave to the onset of the P wave. This approach can be applied to ECG signals that are stored in computer memory, but it is not possible to achieve continuous real-time monitoring without a time lag. Alternatively, a zero phase shift can be achieved with a flat step response filter,[42] which allows the reduction of baseline drift without low-frequency distortion.

Clinical Implications

Low-frequency noise, such as that produced by respiration, causes the tracing to wander above and below the baseline. A low-frequency cutoff at 0.5 Hz, which was once widely used in ECG rhythm monitors, reduces baseline drift due to the generally lower frequency of respiratory motion but can result in marked distortion of repolarization that may produce artifactual ST-segment deviation.[39] The 1975 AHA recommendations included a 0.05-Hz low-frequency cutoff for diagnostic electrocardiography.[5] This recommendation preserves the fidelity of repolarization, but it does not eliminate the problem of baseline drift. Baseline drift suppression is necessary for coherent alignment of the sequential complexes that many modern ECG systems use in the formation of a representative PQRST complex, which is sometimes called a template; otherwise, baseline wander can distort template amplitudes. Newer digital filters can correct baseline drift while preserving the fidelity of ST-segment levels, and these digital methods obligate revision of prior standards required for analog filters.

Recommendation

To reduce artifactual distortion of the ST segment, the 1990 AHA document recommended that the low-frequency cutoff be 0.05 Hz for routine filters but that this requirement could be relaxed to 0.67 Hz or below for linear digital filters with zero phase distortion.[23] The ANSI/AAMI recommendations of 1991, affirmed in 2001, endorsed these relaxed limits for low-frequency cutoff for standard 12-lead ECGs, subject to maximum allowable errors for individual determinants of overall input signal reproduction.[24] These standards continue to be recommended.

High-Frequency Filtering

Technology

The digital sampling rate (samples per second) determines the upper limit of the signal frequency that can be faithfully represented. According to the Nyquist theorem, digital sampling must be performed at twice the rate of the desired high-frequency cutoff. Because this theorem is valid only for an infinite sampling interval, the 1990 AHA report recommended sampling rates at 2 or 3 times the theoretical minimum.[23] A series of studies have now indicated that data

at 500 samples per second are needed to allow the 150-Hz high-frequency digital filter cutoff that is required to reduce amplitude error measurements to ≈1% in adults.[43,44] Greater bandwidth may be required for accurate determination of amplitudes in infants.[35,45,46] The European CSE group recommended that waveforms should be recognized if they have amplitudes of at least 20 μV and durations of at least 6 ms.[23] This implies a high-frequency response in the range of 150 Hz. A 2001 Dutch report showed that in order to keep amplitude errors <25 μV in >95% of the cases, a bandwidth up to 250 Hz is needed for pediatric cases and up to 150 Hz for adolescents.[35]

Clinical Implications

The higher the frequencies contained in the filtered signal, the more accurate will be the measurement of rapid upstroke velocity, peak amplitude, and waves of small duration.[44] Inadequate high-frequency response reduces the amplitude of QRS measurements and the ability to detect small deflections. Because digital ECGs have a temporal resolution in milliseconds and an amplitude resolution in microvolts, recommendations for the high-frequency response of ECGs have evolved over the years. A high-frequency cutoff of 100 Hz was considered adequate by the AHA in 1975 to maintain diagnostic accuracy during visual inspection of direct-writing tracings by electrocardiographers.[5] Even so, it has long been recognized that higher-frequency components of the QRS complex are present[47,48] and that these components may have clinical significance in patients with various forms of heart disease.[49–51] To measure routine durations and amplitudes accurately in adults, adolescents, and children, an upper-frequency cutoff of at least 150 Hz is required; an upper-frequency cutoff of 250 Hz is more appropriate for infants. An obvious consequence of these high-frequency recommendations is that reduction of noise by setting the high-frequency cutoff of a standard or monitoring ECG to 40 Hz will invalidate any amplitude measurements used for diagnostic classification.[52]

Recommendations

The ANSI/AAMI standard of 1991, reaffirmed in 2001, recommended a high-frequency cutoff of at least 150 Hz for all standard 12-lead ECGs.[24] The ANSI/AAMI document also details maximum allowable errors for individual determinants of overall input signal reproduction, which extend beyond the scope of the present report but are important guidelines for manufacturers.[24] These most recent limits continue to be recommended for adolescents and for adults, with extension of the high-frequency cutoff to 250 Hz in children,[35] subject to demonstration of fidelity testing by individual manufacturers according to standard methods.[23] Electrocardiographs should automatically alert the user when a suboptimal high-frequency cutoff, such as 40 Hz, is used, and a proper high-frequency cutoff should automatically be restored between routine standard ECG recordings.

Formation of a Representative Single-Lead Complex

Technology

QRS waveform amplitudes and durations are subject to intrinsic beat-to-beat variability and to respiratory variability between beats. Accordingly, the ANSI/AAMI standards recommend using the largest-amplitude deflection in each lead as representative of the magnitude for that measurement.[24] Measurements from digitized records are more reproducible than those from analog tracings.[53] Digital electrocardiographs can reduce or eliminate unwanted beat-to-beat variations within leads by forming "templates" for individual leads that serve as representative complexes. Willems et al[54] have shown that programs that analyzed an averaged beat showed significantly less variability than programs that measured every complex or a selected beat; similar findings have been reported by Zywietz and colleagues.[55] Single-lead average or median-complex templates may be derived from selected, accurately aligned complexes. One algorithm combines techniques to use the median values of several averaged cycles. Methods vary for the accurate alignment of normal PQRST complexes for these purposes but generally involve template matching and cross-correlation algorithms that exclude nondominant waveforms. Alignment is critical to the success of the measurement process that follows template formation. Noise, measured as RMS (root mean square) residual error in aligned representative complexes, can affect measurements of duration and compromise the tradeoff between sensitivity and specificity for infarction criteria, among other diagnoses.[56] Residual error is reduced by incorporation of more complexes into the representative complex. Zywietz[43] has demonstrated that noise levels in constructed complexes can be reduced to below 5 μV to allow deflections of 20 μV to be estimated with no more than 10% error. However, not all variability between complexes is due to noise, and a study using the CSE database has suggested that the diagnostic value of a representative complex may be improved under some circumstances by consideration of the classification of individual complexes.[57] Although fidelity standards for other ECG features are contained in the 1990 AHA document,[23] no fidelity standard exists for accuracy of representative beat construction.

Clinical Implications

Some biological beat-to-beat variation undoubtedly exists in the electrical activity of the heart, separate from respiratory variability, which is recorded in the surface ECG. For special purposes, such as the detection of QRS and T-wave alternans, it may be desirable to retain the ability to examine these beat-to-beat changes. For routine recording of the ECG, however, reduction of noise by formation of a single and stable representative complex for analysis of each lead results from exclusion of cycle-to-cycle change. Digital electrocardiographs can adjust for respiratory variability and decrease beat-to-beat noise to improve the measurement precision in individual leads by forming a representative complex for each lead. Automated measurements are made from these representative templates, not from measurement of individual complexes. Average complex templates are formed from the average amplitude of each digital sampling point for selected complexes. Median complex templates are formed from the median amplitude at each digital sampling point. As a result, measurement accuracy is strongly dependent on the fidelity with which representative templates are formed.

Recommendations

Digital electrocardiographs must provide beat alignment that allows selective averaging or formation of a representative complex with fidelity adequate for diagnostic ECG computer programs. Fidelity standards for construction of representative complexes need to be developed.

Global Measurement From Simultaneously Acquired Leads

Technology

Some, but not all, digital electrocardiographs utilize the time coherence of simultaneously acquired representative complexes to derive "global" measurements of intervals. Temporal superposition of complexes permits the earliest onset and latest offset of waveforms to be identified for measurement of intervals that are more accurate than can be obtained from single leads. This can be done by searching for the earliest and latest time points of rapid voltage change across temporally aligned individual complexes. Alternatively, a spatial vector magnitude may be created for multiple leads, as exemplified for 3 leads by $(x^2+y^2+z^2)^{1/2}$, and fiducial points may be determined from this magnitude function. An equally useful function can be derived as $|\Delta x|+|\Delta y|+|\Delta z|$, where Δx is the amplitude difference between 2 consecutive samples in lead x, etc, which is a spatial velocity function. When only several selected representative complexes are included in the global measurement, intervals may still be underestimated if earliest onset and latest offset times are not detected. Conversely, global measurements may overstate intervals by inclusion of single-lead information that would not be visually accepted by a human overreader. Differences in measurements may also result from differences in the method of lead alignment or template formation and from differences in definition of waveform onset and offset by different algorithms of different manufacturers. The importance of this phenomenon is seen in determination of the QT interval, where different approaches to definition of T-wave offset can confound reproducibility.[58,59] It is in this context that differences in ECG measurement performance of different computer-assisted analysis programs must be placed.[15,17]

Clinical Implications

The capability for simultaneous 12-lead data acquisition by modern digital electrocardiographs obligates major reconsideration of measurement standards and reference values for intervals that were originally derived from analog, single-channel recordings. When the vector orientation of any lead is approximately perpendicular to the heart vector during the initial or terminal portion of an ECG waveform, an isoelectric component of the initial or terminal component of the waveform will be recorded in that lead at that time. Because there can be no accurate time alignment of leads in single-channel recordings, duration measurements from individual leads will in most cases fail to detect the earliest onset or the latest offset of waveforms. As a result, measurements from single leads will systematically underestimate durations of components of the PQRST complex.[21] Simple demonstration of this phenomenon is seen in the measurement of QT dispersion that results from isoelectric components of the T wave in some leads of the normal ECG.[60,61]

Measurement from simultaneous leads provides a method for identification of the earliest onset and latest offset of waves that are used for duration measurements. Waveform measurements taken from temporally aligned lead information will be systematically greater than the corresponding measurements made from single leads or measurements averaged from several leads. P-wave and PR-interval durations, QRS duration, and QT interval in population studies will be greater when measured from temporally aligned multiple leads or from a spatial vector lead template than when measured from individual leads. In addition, global measurement can affect Q-wave durations that determine the ECG diagnosis of myocardial infarction. Accordingly, redefinition is required of population-based criteria for first-degree atrioventricular block, P-wave duration, Q-wave duration in infarction (relative to the earliest onset of the QRS complex), QRS duration, and QT intervals measured from simultaneous lead technology. Several studies of normal limits of ECG measurements derived from simultaneously recorded 12-lead ECGs have already been published.[62–66] Global measurement of the QT interval is desirable for routine electrocardiography, but global QT measurement remains problematic even when derived from temporally aligned complexes. This is due in part to differences in the currently available algorithms that are used to define and to identify the end of the T wave, which can affect measurements.[59] Until reproducible methodology is established in this area, comparative analyses of ECGs must recognize the potential effect of different algorithms on resulting simultaneous lead measurements. Special situations, such as QT monitoring in drug trials, may continue to require alternative methods of QT measurement from single or multiple leads.

Recommendations

Global measurements of intervals should be obtained from time-coherent data in multiple leads to detect the earliest onset and latest offset of waveforms. For routine purposes, global measurements of P-wave duration, PR interval, QRS duration, and QT duration should be stated on the ECG report. A comparative study is needed of global measurements made by different methods from a reference standard. Differences in global measurement algorithms and methods should be minimized to promote standardization, but these differences must be accounted for in comparative studies within individuals and between individuals. Attention must be paid to definition of normal ECG ranges in children and adolescents, as well as in adults, with stratification for specific age groups, sex, and race. Where methods vary, algorithm-specific normal ranges for intervals need to be derived. With respect to QT interval, the end of the T wave as determined globally should match with a well-defined T-wave offset in at least 1 of its component individual leads. Alternative methods of QT measurement from single or multiple leads may be prescribed for special purposes such as drug evaluation, but it is inappropriate for studies involving serial comparison of the QT interval to use differing methods of QT measurement within trials.

Data Compression for Transmission, Storage, and Retrieval of ECGs

Technology

Digitized at 500 samples per second, 10 seconds of a single lead of ECG record requires ≈10 kB of memory. Accordingly, 10 seconds of an uncompressed 12-lead ECG digitized at recommended standards would occupy about 80 to 100 Kb of memory, in addition to memory needed for template complexes and demographic data. Several methods of ECG data compression have been used to reduce processing time and to minimize the memory required for permanent data storage.[67,68] Techniques include fast Fourier, discrete cosine, and wavelet transforms, as well as hybrid compression methods.[69–73] These methods can provide compression ratios of 8:1 to 10:1 with resulting root mean square errors that range from <0.5% to >2%.[69,70,74] Compression ratio is generally inversely related to root mean square error, so that a recent algorithm was able to provide a 20:1 compression ratio but with a root mean square error of 4%.[70] Because compression affects high-frequency components of the ECG to a greater extent than low-frequency components, at least 1 algorithm has used bimodal decimation of the signal in which QRS complexes are kept at 500 samples per second while the rest of the recording is compressed to lower sampling rates.[75] Compression of data may occur before or after signal processing, but in either case, compression occurs before transfer of the signal to central storage systems and affects all retrieved records. Accordingly, the 1990 AHA report recommended that the fidelity of retrieved compressed data should be within 10 μV for corresponding samples.[23] As computer networks increase transmission speed and storage capacity, lossless compression techniques may supersede other compression methods for some applications.

Clinical Implications

Compression of ECG data can speed transmission and retrieval of records that are stored in central databases and minimize memory required for storage. Algorithms based on a variety of mathematical transforms can compress data by a factor of ≈8, with signal fidelity preserved within about a 2% overall error. However, the error may not be uniform throughout the ECG cycle. Data compression affects high-frequency (short duration) signals more than the smoother low-frequency signal. Therefore, compression has greater potential to alter measurements within the QRS complex, such as pacemaker spikes, Q-wave duration, and R-wave amplitude, than to alter other signals such as the ST segment and the T wave. In some cases, a noncompressed ECG taken at the bedside may differ from the tracing later retrieved from the stored, compressed file, which may also affect serial comparison of original and retrieved tracings when ECG waveforms are reanalyzed.[76] Furthermore, differences in compression methodology may affect comparison of retrieved tracings from different manufacturers in the same way that different filters and different use of time-coherent templates affect measurements of the ECG signal. These differences will be minimal when compressed tracings adhere to established or newer standards of fidelity to the original signal,[23,73] and they can be eliminated with newer methods of lossless compression (in which no loss of ECG data occurs).

Recommendation

Compression algorithms should perform in a manner that allows retrieved data to adhere to the fidelity standards established in the 1990 AHA statement with reference to the original signal.

Standard Leads

Location of Standard Limb and Precordial Electrodes

Technology

The standard 12-lead ECG[5,24] consists of 3 limb leads (leads I, II, and III), 3 augmented limb leads in which the Goldberger modification of the central terminal of Wilson serves as a derived indifferent electrode that is paired with the exploring electrode (leads aVR, aVL, and aVF), and 6 precordial leads in which the Wilson central terminal serves as a derived indifferent electrode that is paired with the exploring electrode (V_1 through V_6). All leads are effectively "bipolar," and the term "unipolar" in description of the augmented limb leads and the precordial leads lacks precision. Reference is made to the comprehensive study of lead systems for various types of electrocardiography by Macfarlane.[77] Skin preparation by cleaning and gentle abrasion before electrode application can reduce noise and improve the quality of the recorded ECG.[78–80] Historically, limb lead electrodes have been attached at the wrists and the ankles, with the patient in the supine position, generally with a pillow under the head. For routine 12-lead recording, the AHA statement of 1975 recommended placement of the 4 limb lead electrodes on the arms and legs distal to the shoulders and hips,[5,81] and thus not necessarily on the wrists and ankles. Evidence exists that different placement of electrodes on the limbs can alter the ECG, a phenomenon that appears to be more marked with respect to the left arm electrode.[81] Therefore, reevaluation of the magnitude of changes due to variation in limb electrode placement in clinical practice is required, as discussed below. Six electrodes are placed on the chest in the following locations: V_1, fourth intercostal space at the right sternal border; V_2, fourth intercostal space at the left sternal border; V_3, midway between V_2 and V_4; V_4, fifth intercostal space in the midclavicular line; V_5, in the horizontal plane of V_4 at the anterior axillary line, or if the anterior axillary line is ambiguous, midway between V_4 and V_6; and V_6, in the horizontal plane of V_4 at the midaxillary line.

Clinical Implications

Skin preparation and electrode placement have important effects on the ECG, and patient positional change, such as elevation and rotation, can change recorded amplitudes and axes. It has been widely accepted for many years that ECG amplitudes, durations, and axes are independent of the distal or more proximal location of the limb electrodes. As a result, routine recording of the ECG from the upper arm rather than from the wrist to "reduce motion artifact" has become popular and is facilitated by the development of disposable tab electrodes. However, one study has shown that electrode placement along the limbs can affect ECG voltages and

durations, most importantly in the limb leads.[81] Whether these differences are large enough to alter routine diagnostic criteria, such as voltage for left ventricular hypertrophy or Q-wave duration for inferior infarction, is unknown. Further confounding this situation is the variability in electrode placement that might have been present during the actual derivation of the diagnostic criteria involved, because studies during the past several decades have rarely described electrode placement in detail.

From the time of their initial standardization by a joint committee of the AHA and the Cardiac Society of Great Britain and Ireland,[82,83] the normal precordial electrode positions have been relatively horizontal in orientation. When precordial electrodes are positioned without reference to the underlying bony landmarks, the placement pattern often is erroneously vertical in orientation.[84] Mapping data document the often profound alterations in waveforms that can result from precordial electrode misplacement.[85,86] A common error is superior misplacement of V_1 and V_2 in the second or third intercostal space. This can result in reduction of initial R-wave amplitude in these leads, approximating 0.1 mV per interspace, which can cause poor R-wave progression or erroneous signs of anterior infarction.[87] Superior displacement of the V_1 and V_2 electrodes will often result in rSr′ complexes with T-wave inversion, resembling the complex in lead aVR. It also has been shown that in patients with low diaphragm position, as in obstructive pulmonary disease,[88,89] V_3 and V_4 may be located above the ventricular boundaries and record negative deflections that simulate anterior infarction. Another common error is inferior placement of V_5 and V_6, in the sixth intercostal space or even lower, which can alter amplitudes used in the diagnosis of ventricular hypertrophy. Precordial lead misplacement explains a considerable amount of the variability of amplitude measurements that is found between serial tracings.[90] Some residual disagreement persists in current guidelines and texts on the standard for location of V_5 and V_6, with some sources retaining an early recommendation that these leads follow the course of the fifth intercostal space rather than the horizontal plane of V_4. In addition, it is common to refer to the anterior axillary line as an anatomic marker for the placement of V_5. These alternatives are discouraged because the course of the intercostal space is variable and the definition of an anterior axillary line only vague. Placement of precordial electrodes in women with large breasts remains problematic. Electrodes are most commonly placed beneath the breast, which should reduce amplitude attenuation caused by the higher torso impedance in women and, intuitively, would seem to favor reproducibility of positioning during routine practice. Conversely, one study has suggested that reproducibility of ECG measurements is slightly increased when electrodes are positioned on top of the breast.[91] Another study using precisely ascertained electrode placement has suggested that precordial potential attenuation by the breast is very small.[92] Yet another study has found attenuation only in V_3 and an increase in voltage in V_5 and V_6[93] when electrodes are placed over the breast; this may result from V_5 and V_6 being correctly placed at the level of V_4 rather than more inferiorly when V_4 is positioned under the breast. Clearly, the magnitude of this effect in ordinary ECGs will depend greatly on the care with which electrodes are ordinarily placed and also on breast size, breast shape, and small changes in patient position. Similar considerations apply in relation to subjects with breast implants and in subjects who are obese.

Recommendations

Technicians and other medical personnel responsible for the recording of ECGs should have periodic retraining in skin preparation, proper electrode positioning, and proper patient positioning. All leads are effectively "bipolar," and the differentiation between "bipolar" and "unipolar" in the description of the standard limb leads, the augmented limb leads, and the precordial leads is discouraged. Neither term should be used. Studies to clarify the effect of distal versus proximal limb lead electrode placement on ECG magnitudes and durations are required. Validity of test performance criteria for current diagnostic algorithms may be dependent on placement of limb leads in the same positions that were used for criteria development. Pending resolution of this issue, all ongoing studies used for criteria development must clearly document electrode placement with precision. The horizontal plane through V_4 is preferable to the fifth intercostal interspace for the placement of V_5 and V_6 and should be used for placement of these electrodes. Definition of V_5 as midway between V_4 and V_6 is conducive to greater reproducibility than occurs for the anterior axillary line, and this should be used when the anterior axillary line is not well defined. In the placement of V_6, attention should be directed to the definition of the midaxillary line as extending along the middle, or central plane, of the thorax. For the time being, it is recommended that electrodes continue to be placed under the breast in women until additional studies using electrodes placed on top of the breast are available.

Derivation of the Standard Limb Leads and Relationships Among Leads

Technology

The 4 limb electrodes define the standard frontal plane limb leads that were originally defined by Einthoven. With the right leg electrode acting as an electronic reference that serves to improve common mode (unwanted noise) rejection, 3 pairs of electrodes exist. Within each pair, 1 electrode is established as the positive end of the lead in the sense that current flow toward that electrode is inscribed in an upward (positive) direction. The other electrode of the pair would inscribe the exactly opposite waveform. Lead I is defined as the potential difference between the left arm and the right arm (LA-RA), lead II is defined as the potential difference between the left leg and the right arm (LL-RA), and lead III is defined as the potential difference between the left leg and the left arm (LL-LA). In each case, net current flow toward the first electrode of the pair is defined as a positive voltage deflection in the recorded waveform. According to Kirchhoff's law, the sum of the voltage gains and voltage drops in a closed circuit is equal to zero. Therefore, lead II=lead I+lead III at any instant in the cardiac cycle. This relationship is known as Einthoven's law.

Clinical Implications

From 3 pairs of limb electrodes, 6 waveforms may be obtained, 3 of which are defined as the standard limb leads by establishing 1 of each pair as the electrode toward which net current flow will inscribe an upward (positive) voltage deflection on the ECG. The opposite waveforms, by definition, are mirror images of the standard limb leads. In this sense, the electrical activity defined by a lead pair can be examined from either perspective. Distinction of single electrodes from established "poles" is highlighted by selection of the LA electrode as the positive end of the LA-RA pair for lead I but not as the positive end of the LL-LA pair for lead III. Einthoven's law indicates that any 1 of the standard limb leads can be mathematically derived from the other 2 leads. As a consequence, the 3 standard limb leads contain only 2 independent pieces of information. Even though limb lead placement is often represented in terms of the apices of an equilateral triangle, known as the Einthoven triangle, Einthoven's law is entirely independent of any assumptions about geometric placement of the 3 electrodes. These considerations notwithstanding, redundant leads promote the appreciation of spatial morphological characteristics of the ECG and aid in its interpretation, such as calculation of axis, and consideration of the information from the perspective of both ends of the available leads can be clinically useful, particularly in the evaluation of ST-segment shifts during acute myocardial infarction.

Recommendation

Users should recognize the redundancy of information in the standard limb leads. Redundancy notwithstanding, the information contained in different perspectives from multiple leads can be used to improve recognition of ECG abnormalities.

Derivation of the Augmented Limb Leads and the Precordial Leads

Technology

An electrode potential can also be obtained as an average (or weighted average) of the potentials at 2 or more body surface locations, which creates a potential that is different from each of the contributing electrodes alone. Wilson and colleagues[94] devised a central terminal based on the limb electrodes to serve as a new reference potential. The Wilson central terminal (WCT) is obtained as an average potential of the RA, LA, and LL electrodes, so that the potential at WCT=(RA+LA+LL)/3. Kirchhoff's law does not require that the potential at WCT be zero or that it remain constant throughout the cardiac cycle. Potential differences between WCT and RA, LA, and LL, respectively, defined new frontal plane limb leads VR, VL, and VF. Wilson called these electrode pairs the "unipolar" limb leads. Wilson's VR, VL, and VF leads had relatively low amplitudes because the potential at the exploring site was also included in the central terminal. By removing the single exploring potential from the central terminal, Goldberger produced the "augmented unipolar" limb leads, so-called because they mathematically are 50% larger in amplitude with respect to recordings that use the Wilson central terminal.[95,96] The Goldberger central terminals for the augmented limb leads are now obtained as (LA+LL)/2 for aVR, (RA+LL)/2 for aVL, and (RA+LA)/2 for aVF. Lead aVL therefore represents the potential difference between the left arm and the modified terminal of Goldberger and is given by LA−(RA+LL)/2, which can be reduced to (lead I−lead III)/2. Similarly, lead aVR is RA−(LA+LL)/2, which can be reduced to −(lead I+lead II)/2, and lead aVF is LL−(LA+RA)/2, which can be reduced to (lead II+lead III)/2. These derived leads provide new vectorial perspective within the frontal plane. It should be noted that aVR+aVL+aVF=0 at any point in the cardiac cycle. The 6 standard precordial leads are based on potential differences between an exploring electrode on the chest wall and the original WCT. Each precordial lead, symbolized as V_i, represents the potential difference given by V_i−WCT.

Clinical Implications

The augmented limb leads and the precordial leads use a derived electrode to serve as the opposing electrode of the lead pair. Wilson made a reasonable assumption that the potential oscillations of his central terminal would be small compared with those of the exploring electrode and that his "unipolar" leads therefore would largely reflect the potential variation under the exploring electrode. Later investigators have often mistakenly taken this to mean that these leads reflect electrical activity only of cardiac regions in the vicinity of the exploring electrode. This fails to recognize that the potential at the exploring electrode is determined by all cardiac sources electrically active at a given instant of cardiac excitation and repolarization cycle. Even though the augmented limb leads provide vectorial insight within the frontal plane, each of these leads can also be mathematically derived from any 2 of the standard limb leads, as demonstrated above; accordingly, they do not contain new information but rather provide new views of cardiac electrical activity. This calculation is mathematically independent of any assumption about the equilateral nature of the Einthoven triangle. As a consequence, the 6 frontal plane leads, consisting of the 3 standard limb leads and the 3 augmented limb leads, actually contain only 2 independent measured signals. In practice, modern electrocardiographs measure potential differences for 2 pairs of limb lead electrodes and use these measurements to mathematically derive the third standard limb lead and each of the augmented limb leads. Although redundancy exists within the 6 frontal plane leads, visualization of multiple leads promotes appreciation of spatial aspects of the ECG that can be important to clinical interpretation. Unlike the mathematical relationships between the frontal plane limb leads, each of the precordial electrodes provides uniquely measured potential differences at the recording site with reference to the central terminal. Because the exploring precordial electrodes are not connected in a closed electrical loop like the extremity electrodes, the precordial leads are independent of each other; none can be calculated precisely from other information in the ECG. Therefore, the "standard" 12-lead ECG actually contains 8 independent pieces of information: 2 measured potential differences from which the 4 remaining limb leads can be calculated and the 6 independent precordial leads.

Recommendations

The augmented limb leads of the frontal plane and the precordial leads result from derived electrode pairs and should not be described as "unipolar." Users should recognize the derived and redundant nature of the 3 augmented limb leads, but these are retained because multiple leads facilitate the clinical interpretation of the ECG.

Simultaneous Lead Presentation

Technology

With analog single-channel ECG recorders, each lead is recorded sequentially by means of a switching mechanism that connects applied electrodes in the prescribed combinations. Digital electrocardiographs are able to record the 8 channels of independent information simultaneously, with 4 of the limb leads being derived from the other 2. Alignment of separate channel writers must be precise to within 10 ms,[24] and ideally less. The most commonly used output format involves lead separation based on rows and columns. For standard-sized paper, at 25 mm/s recording speed, four 2.5-second columns can be presented sequentially on the page, with no time disruption between different columns. Each column therefore represents successive 2.5-second intervals of a continuous 10-second record. In the most traditional simultaneous lead format, the first column records rows representing simultaneous leads I, II, and III; the second column records rows representing simultaneous aVR, aVL, and aVF; the third column represents simultaneous leads V_1, V_2, and V_3; the fourth column represents simultaneous leads V_4, V_5, and V_6. Additional rows may be available for 1, 2, or 3 leads of 10-second continuous recordings for rhythm analysis. Alternatively, additional rows may be utilized to present two 5-second recordings of 6 simultaneous limb leads and 6 simultaneous precordial leads, or 12 rows of simultaneous leads.

Clinical Implications

The major advantage of simultaneous lead acquisition is that it allows precise temporal alignment of waveforms from different leads, which results in spatial-temporal insights that have diagnostic value.[97] By way of example, the temporal alignment of waveforms in aVR and aVL can aid in the diagnosis of fascicular block in the presence of infarction,[98] whereas simultaneous views of P-wave and QRS waveforms in multiple leads can add information of value in the interpretation of arrhythmias and in the diagnosis of myocardial infarction.[99]

Recommendation

Standard tracings obtained with digital electrocardiographs should provide accurate temporal alignment of multiple leads, with maximum misalignment of no more than 10 ms, and ideally as little as is practically feasible. The printed tracing may present temporally aligned groups of leads in different formats according to preference.

Alternative Information Format From Standard Leads

Technology

The Cabrera or orderly sequence reorients the frontal plane leads into a progressive anatomic array that extends logically and sequentially in the same way that the precordial leads progress sequentially from V_1 through V_6.[100,101] With inverted aVR (−aVR or maVR) used to represent the signal between leads II and I, the sequence becomes, from right to left, III, aVF, II, −aVR, I, and aVL, or from left to right, aVL, I, −aVR, II, aVF, and III. In addition to improved spatial quantification of acute infarction, the Cabrera sequence facilitates calculation of the frontal plane axis.[102] This presentation, when in sequence with the precordial leads, has also been termed the panoramic display.[103]

Clinical Implications

Whether presented serially from single-channel recorders or in standard array from simultaneous-lead–acquisition devices, the sequence of limb lead presentation on ECG recordings is historical, not anatomic. Thus, whereas V_1 through V_6 progress leftward and slightly inferiorly across the precordium, the frontal plane limb leads follow no regular order that allows individual leads to be compared easily with anatomically directly adjacent leads. For example, lead aVF represents the potential difference from a vector perspective that is between lead III and lead II, but this is not easily appreciated from the standard array. Similarly, leads I and aVL are progressively counterclockwise, in the anatomic sense, from lead II. Lead aVR is often thought of as an intracavitary lead that looks toward the atria from the apex of the ventricles, but inversion of aVR can be considered to represent a perspective that lies anatomically within the counterclockwise progression from lead II to lead I.[101] Use of inverted aVR has been reported to improve the diagnostic classification and estimation of risk associated with acute inferior and lateral myocardial infarction.[104]

Recommendations

Routine use of the Cabrera sequence for display of the limb leads can be highly recommended as an alternative presentation standard. For display in a format of 4 columns of 3 leads, a left-to-right sequence (aVL to III) is logical because it is closer to traditional placement of limb lead I at the upper left. To maintain consistency, the left-to-right sequence is also recommended for horizontal display of the limb leads. However, it is recognized that the current limb lead array is so deeply entrenched in ECG tradition that change might take years to become generally accepted. At present, manufacturers should be encouraged to make this display available as a routine option in new electrocardiographs.

Alternative Lead Applications

Torso and Other Modified Placement of the Limb Leads

Technology

Noise from motion of the arms and legs during ambulatory and exercise electrocardiography can be reduced by placement of the limb leads on the torso. In these diagnostic applications, 12-lead ECGs have been recorded with the Mason-Likar lead position,[105] in which the arm electrodes are placed in the infraclavicular fossae medial to the deltoid insertions and the left leg electrode is placed midway between the costal margin and iliac crest in the left anterior axillary

line. More recent applications of the Mason-Likar monitoring position place the arm electrodes over the outer clavicles.[81,106] The precordial electrodes are placed in the standard positions. An alternative modification of limb lead placement developed for bicycle ergometry applies the arm electrodes to the upper outer arm and the leg electrodes to the anterior iliac crest.[107] Torso limb leads are sometimes used to reduce motion artifact from the arms and legs during recording in infants.

Clinical Implications

Noise from motion of the limbs during routine ambulation and during exercise makes standard limb lead electrode placement impractical for ECG monitoring. Typical monitoring applications include bedside hard-wired or telemetered observation of rhythm and ST segments, quantitative ambulatory electrocardiography, and ECG recording during diagnostic exercise testing.[108] Rhythm diagnosis is not adversely affected by monitoring lead placement; however, tracings that use torso electrodes differ in important ways from the standard 12-lead ECG. In addition to body position differences that affect the ECG,[109] monitoring electrodes placed on the trunk do not provide standard limb leads, and distortion of the central terminal alters the augmented limb leads and the precordial leads.[110,111] Tracings with Mason-Likar and other alternative lead placement may affect QRS morphology more than repolarization compared with the standard ECG; these differences can include false-negative and false-positive infarction criteria.[81,112] Motion artifact of the limbs is a particular problem for routine recording in neonates, infants, and young children, in whom torso leads are sometimes used; the clinical significance of the resulting differences remains to be established.

Recommendations

ECGs recorded with torso placement of the extremity electrodes cannot be considered equivalent to standard ECGs for all purposes and should not be used interchangeably with standard ECGs for serial comparison. Evaluation of the effect of torso placement of limb leads on waveform amplitudes and durations in infants is required. Tracings that use torso limb lead placement must be clearly labeled as such, including 12-lead tracings derived from torso limb lead placement in neonates or in young children and during ambulatory and exercise electrocardiography in adults. Furthermore, tracings recorded in the sitting or upright position should not be considered equivalent to standard supine ECGs.

Reduced Lead Sets

Technology

It is possible to mathematically construct a synthesized 12-lead ECG from reduced lead sets. These syntheses can approximate but not duplicate the tracing obtained by the standard leads. The Frank lead system was devised as a lead set suitable for obtaining reproducible orthogonal lead information that could be used for vectorcardiography.[5] The system involves 7 electrodes, 5 of which are applied at points in the horizontal plane that intersect the fifth intercostal space at the left sternal border: A at the left midaxillary line, C on the anterior left chest wall halfway between E and A, E at the mid sternum anteriorly, I at the right midaxillary line, and M at the mid spine posteriorly. In addition, electrode H is placed at the junction of the neck and torso posteriorly, and electrode F is placed on the left foot. Orthogonal lead information is constructed from modeled weighting of lead voltages. The EASI lead system is a reduced 5-lead set that uses the E, A, and I electrodes from the Frank lead system and adds an electrode, S, at the top of the mid sternum, along with a ground reference electrode to provide orthogonally oriented signals.[113] In addition to orthogonal data, transfer coefficients have been developed for the EASI lead system that produce synthesized 12-lead ECGs.[114] Advantages of the EASI lead system for patient monitoring applications are the absence of limb electrodes, which allows the patient to move around without intolerable noise in the ECG signal, elimination of the need to determine intercostal spaces, and avoidance of the breast.

Clinical Implications

Because monitoring applications of reduced lead sets are widespread and 12-lead reconstruction algorithms are available in practice, it is important that the derived nature of these tracings is appreciated. The Frank lead system and other vectorcardiographic lead systems produce the orthogonal X, Y, and Z components of the heart vector. These can be combined into 3-dimensional vectorcardiographic loops displayed in 2-dimensional planes (frontal, horizontal, and sagittal); they can be directly examined as ECG voltage-time records as well. A number of transformations of orthogonal data can be used to produce a synthesized 12-lead ECG, but the generalized transfer coefficients used in these estimations are subject to individual variability in torso shape and heterogeneities of impedance. Patient-specific transformations derived from comparison with a baseline 12-lead ECG can improve the accuracy of subsequent synthesized tracings. Torso inhomogeneities also limit the fidelity of synthesized 12-lead tracings derived from EASI leads. An advantage of EASI leads is the relative anatomic simplicity of electrode placement. Tracings synthesized from the EASI leads have been shown to have useful correlative value with the standard 12-lead ECG[115,116]; however, it is recognized that these synthesized tracings can differ in interval duration and amplitude from the corresponding standard ECGs. Whether synthesized 12-lead tracings provide practical advantage and adequate reproduction of ST-segment shifts to be a substitute for standard tracings during acute ischemic syndromes is a matter of intense current investigation.[117] Whether the accuracy of these transformations for the monitoring of repolarization changes can facilitate drug trials in ambulatory subjects is also under study.

Recommendations

Synthesized 12-lead ECGs are not equivalent to standard 12-lead ECGs and cannot be recommended as a substitute for routine use. All 12-lead tracings derived by synthesis from reduced lead sets must be clearly labeled as such. Although synthesized ECGs that use the EASI lead system may be demonstrably adequate for some purposes, such as monitoring of rhythm, they cannot be considered equivalent to

standard 12-lead recordings or recommended at present as an alternative for routine use.

Expanded Lead Sets

Technology

Hybrid lead systems, incorporating 3 Frank leads with the standard 12 leads, can be used by some electrocardiographs. Expanded lead sets include the multiple-electrode arrays used for body surface mapping of the electrical activity of the heart. Torso arrays include wraparound electrodes in multiple horizontal and vertical lines. Details of these arrays are beyond the scope of the present report. Studies of body surface maps recorded from large electrode arrays have provided useful information about localization of ECG information on the thorax, but their complexity precludes their use as a substitute for the standard 12-lead ECG for routine recording purposes. Additional chest leads may be useful for investigation of acute infarction. Four additional precordial leads have been identified for use in this clinical setting (V_3R, V_4R, V_5R, and V_6R), each of which is placed on the right side in mirror image to the standard precordial placement of electrodes. Within this right-sided array of electrodes, standard V_1 can be considered equivalent to V_2R, and standard V_2 can be considered equivalent to V_1R. Examination of additional posterior chest leads has been proposed for the identification of ST-elevation events in the posterior wall, including V_7 (at the posterior axillary line), V_8 (below the scapula), and V_9 (at the paravertebral border), each in the same horizontal plane as V_6.[118–120]

Clinical Implications

Although acute right ventricular infarction can sometimes be recognized from ST-segment elevation in V_1, studies dating from the early 1980s have demonstrated that additional right-sided precordial leads have value for the diagnosis of acute right ventricular infarction in patients with inferior infarction.[121–123] In this setting, ST-segment elevation exceeding 0.1 mV in 1 or more of the right precordial leads is moderately sensitive and specific for right ventricular injury and has been associated with underlying right ventricular dysfunction[124,125] and greater in-hospital complications.[126] Acute infarction of the posterior wall of the left ventricle theoretically can be diagnosed from reciprocal ST-segment depression evident in precordial leads V_1 through V_3, and it appears that both the additional right-sided and additional posterior leads can be reconstructed from the standard ECG leads.[127] (Alternate description of this territory as anatomically inferolateral rather than posterior will be discussed elsewhere.) Additional leads have not provided increased sensitivity for infarction in all studies[128]; however, ST-segment elevation over the posterior left chest has been reported to be the only site of ST elevation found in some cases of posterior infarction.[118] Recent guidelines for intervention in acute coronary syndromes differ in important ways for ST-elevation and for non–ST-elevation infarction.[129] In this sense, anterior ST depression during infarction from a spatial vector perspective may be electrocardiographically equivalent to posterior ST elevation, but it may be quite different in terms of a literal interpretation of treatment guidelines that requires "ST elevation" in an intervention algorithm. Even so, ST elevation in posterior leads in acute posterior infarction is often <1 mm in amplitude, and because of lead orientation, proximity effect, and torso inhomogeneity, it may not be equivalent in absolute magnitude to the ST depression present in anterior leads. ST elevation in 1 or more of the posterior leads has moderate sensitivity and high specificity for posterior wall infarction,[130] but the value of these additional findings for the prediction of increased in-hospital complications is unresolved.[126,131]

Recommendations

Because treatment of infarction may vary with right ventricular involvement, recording of additional right-sided precordial leads during acute inferior-wall left ventricular infarction is recommended. Routine recording of these leads in the absence of acute inferior infarction is not recommended. The use of additional posterior precordial leads can be recommended in settings in which treatment will depend on documentation of ST elevation during infarction or other acute coronary syndrome. Routine recording of these additional leads in the absence of an acute coronary syndrome is not recommended. As ST-segment vectors become increasingly used for improved diagnostic classification of myocardial infarction, the addition of a frontal plane ST-segment axis to the currently measured P-wave, QRS, and T-wave axes in the ECG header data is recommended.

Lead Switches and Misplacements

Limb Lead and Precordial Lead Switches

Technology

Lead switches (or more correctly, electrode cable switches) occur when a dedicated lead wire and electrode combination is misplaced or when there is erroneous attachment of a dedicated lead wire to individually placed electrodes. Color coding of lead wires is a feature of manufacturing standards for electrocardiographs,[24] but even so, it is possible to misconnect lead wires at the cable terminal. Time-coherent P-wave morphology can be used to clarify lead switches,[132] and these principles should be applicable to computer algorithms. Computer algorithms that are adaptable to computer-assisted electrocardiographs are capable of detecting lead switches.[133–137]

Clinical Implications

Lead switches are really switches of the cable connections of 2 or more properly placed electrodes. This can result in erroneous pairing within the standard limb leads or within the pairing of an exploring lead with the central terminal. When an electrode that is switched involves the central terminal, all leads may be affected. Lead switches affect 2 or more of the standard leads, thereby distorting the ECG recording. Limb lead switches can result in false-positive and false-negative signs of ischemia.[138] Some of these changes can be recognized by an alert technician or correctly interpreted by the reviewing physician, particularly when previous ECGs are available, whereas others may go unrecognized or require repeat recording of the ECG.[139] Transposition of the left and

right arm lead wires produces inversion of limb lead I, with a switch of leads II and III and a switch of leads aVR and aVL, whereas aVF remains unaltered. Because the central terminal is unaffected, there are no changes in the precordial leads. In normal situations, lead I is generally similar to V_6 with respect to the morphology of the P wave and QRS direction. A clue to distinction of these findings from those present in a patient with mirror-image dextrocardia is that lead misplacement results in an important discordance between lead I and V_6. As a corollary, the ECG in a patient with mirror-image dextrocardia may be "normalized" by purposely reversing the left and right arm lead wires and using mirror-image right-sided precordial leads. Transposition of the right arm and right leg lead wires is also easy to recognize, because lead II now records the nearly zero potential difference that exists between the 2 legs,[140,141] which results in very low amplitude only in lead II, with inverted symmetry between standard lead I and lead III. Transposition of the left arm and left leg lead wires is more difficult to recognize because the main effects are an often subtle shift in axis and inversion of lead III; it can be suspected from changes in P-wave morphology in the limb leads,[138] although the specificity of this approach has been challenged.[137] Suspected lead switches may be confirmed by reference to a prior or subsequent tracing with correct lead placement. Transposition of lead wires to V_1 and V_2, to V_2 and V_3, or within all 3 leads can cause a reversal of R-wave progression that simulates anteroseptal wall infarction, but this artifact often can be recognized by distorted progression of the precordial P waves and T waves in the same leads.

Recommendations

Medical personnel responsible for the recording of routine ECGs should receive training on the avoidance of lead switches and guidelines for their recognition. Lead-switch detection algorithms should be incorporated into digital electrocardiographs along with alarms for abnormally high lead impedance, and suspected misplacements should be identified to the person recording the ECG in time to correct the problem. If not corrected before recording, a diagnostic statement alerting the reader to the presence of different types of lead switches should be incorporated into preliminary interpretive reports.

Lead Misplacement

Technology

ECG amplitudes and duration measurements vary with precordial lead placement, which often ranges widely from the recommended anatomic sites.[84,142] The early work of Kerwin et al[143] demonstrated that reproducibility of precordial lead placement to within 1 cm occurred only in about half of men and in even fewer women. Placement accuracy during routine electrocardiography appears to have decreased further with time. A recent study documented that fewer than two thirds of routinely applied precordial electrodes were applied within 1.25 inch of the designated landmark, but errors were not distributed randomly.[84] A more vertical distribution of precordial electrodes than required resulted from superior misplacement of V_1 and V_2 electrodes in more than half of cases and inferior-leftward misplacement of left precordial electrodes in more than one third.

Clinical Implications

Lead placement variability between recordings is an important reason for poor reproducibility of precordial ECG amplitude measurements.[86,90,144] Reproducibility of duration measurements is generally better than reproducibility of amplitudes.[145] It has been established that variation in precordial lead placement of as little as 2 cm can result in important diagnostic errors, particularly those that involve statements about anteroseptal infarction and ventricular hypertrophy.[142] Precordial lead misplacement can alter computer-based diagnostic statements in up to 6% of recordings.[85]

Recommendations

Periodic retraining in proper lead positioning of the precordial leads should be routine for all personnel who are responsible for the recording of ECGs. Serial tracings in acute or subacute care settings should make use of some form of skin marking to promote reproducibility of lead placement when it is not possible to leave properly applied electrodes in place.

Computerized Interpretation of the ECG

Technology

Two computer-based processes are required for diagnostic digital ECG programs that provide diagnostic interpretation. The first stage is preparation of the signal for analysis by the processing methods discussed above. As discussed in prior sections of this statement, the fidelity of measurements used in diagnostic algorithms is determined by the technical issues that affect signal processing.[9,23,28,42,146] These signal-processing methods include signal preparation (sampling, filtering, and template formation), feature extraction, and measurement.[147–151] Time-coherent simultaneous lead data and the construction of representative template complexes are critical to the reliability of feature extraction and measurement; global measurements of duration may be systematically smaller when time-coherent data are not used. The second stage of analysis applies diagnostic algorithms to the processed ECG. Diagnostic algorithms may be heuristic (experience-based rules that are deterministic) or statistical (probabilistic) in structure. Heuristic diagnostic algorithms were originally designed to incorporate discrete measurement thresholds into a decision tree or boolean combinations of criteria.[152–155] Statistical diagnostic algorithms circumvent problems of diagnostic instability that are associated with small serial changes around discrete partitions by adding a probability statement to the diagnosis. These may be based on bayesian logic.[156] Other statistical methods use discriminant function analysis, which can use continuous ECG parameters in addition to discrete variables to produce a point score.[157,158] These algorithms tend to be more reproducible than earlier heuristic methods, even though they still may result in discrete thresholds for diagnostic statements. Neural nets differ from conventional discriminant function analysis in the way they are trained, in the resulting classifier, and in their derived decision boundaries.[133,159,160] Statistical methods de-

pend on a database of well-documented cases to find the optimal ECG parameters to use. Such a database must be large enough that the results are statistically reliable. The database must contain sufficient cases with varying degrees of abnormality, ranging from mild to severe cases, and a representative distribution of common confounding conditions.[6,9,17,161] The statistics of well-documented populations have been used to develop diagnostic algorithms that no longer simply mimic the human reader.[162] Similarly, it has also been shown that the addition of vector loop criteria (or the equivalent information deduced from simultaneous leads) improves 12-lead ECG diagnoses.[97,98]

Clinical Implications

Given the potentially profound effects of technical factors on ECG measurements, it is not surprising that identical diagnostic algorithms might perform differently when applied to ECG signals that undergo processing by different methods. Adherence to methodological standards will minimize these differences, promote uniformity of measurement and interpretation, and facilitate serial comparison of tracings. Even with adherence to standards, small systematic differences in measurements might be expected between diagnostic instruments that use different processing methods, particularly with respect to diagnostically important global measures of QRS duration and QT interval. A 1985 study by the European CSE group demonstrated that measurement differences among 10 standard ECG systems could be large enough to alter diagnostic conclusions[17]; however, no recent studies have directly compared template and global measurements made with the current generation of commercially available standard ECG recording systems. Beyond the technical issues of measurement fidelity, evaluation of the performance of ECG programs is difficult.[9,15,17,163] Programs may be compared with diagnoses of an expert cardiologist or consensus of expert cardiologists or with diagnoses ascertained by independent data. The CSE group evaluated 15 ECG and vectorcardiographic analysis programs against a reference database that included documented cases of ventricular hypertrophy and myocardial infarction,[15] diagnoses that are strongly dependent on accurate measurement of amplitudes and durations and should favor computer analysis. Overall, the percentage of ECGs correctly classified by the computer programs (median 91.3%) was lower than that for the cardiologists (median 96.0%), whereas important differences in overall accuracy were found between different algorithms. Salerno et al[18] reviewed 13 reports of computer ECG program performance and showed that these programs generally perform less well than expert readers with respect to individual diagnoses. Even so, this report found that computer assistance was able to improve the diagnostic performance of less expert readers.

Recommendations

Computer-based interpretation of the ECG is an adjunct to the electrocardiographer,[164] and all computer-based reports require physician overreading. Accurate individual templates should be formed in each lead before final feature extraction and measurement used for diagnostic interpretation. Time-coherent data from multiple leads should be used to detect the earliest onset and latest offset of waveforms of global measurements used for diagnostic interpretation. Deterministic and statistical or probabilistic algorithms should be based on well-constructed databases that include varying degrees of pathology and an appropriate distribution of confounding conditions. Such algorithms should be validated with data that have not been used for development. Programs using complex diagnostic algorithms should document in reference material those measurements that are critical to the diagnostic statement, which might include synthesized vector loop or other novel measurements. Serial comparisons of sequential ECGs should be done by trained observers regardless of whether the ECG program provides a serial comparison. Assessment of the performance of different algorithms will be facilitated by use of a standardized glossary of interpretive statements.

Summary

The present document outlines the relation of the modern digital electrocardiograph to its technology. Individual features of ECG processing and recording are considered in terms of their clinical implications. Recommendations focus on progress toward optimal use of the ECG. It is hoped that the standards set out in this document will provide a further stimulus to the improvement of ECG recording and interpretation.

Disclosures

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This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (1) the person receives $10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (2) the person owns 5% or more of the voting stock or share of the entity, or owns $10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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This table represents the relationships of reviewers that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all reviewers are required to complete and submit.

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Recommendations for the Standardization and Interpretation of the Electrocardiogram: Part I: The Electrocardiogram and Its Technology: A Scientific Statement From the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society Endorsed by the International Society for Computerized Electrocardiology

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Circulation. 2007;115:1306-1324; originally published online February 23, 2007;
doi: 10.1161/CIRCULATIONAHA.106.180200
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Print ISSN: 0009-7322. Online ISSN: 1524-4539