Berbari, E. J. "Principles of Electrocardiography."

The Biomedical Engineering Handbook: Second Edition.

Ed. Joseph D. Bronzino

Boca Raton: CRC Press LLC, 2000

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Principles of Electrocardiography

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The electrocardiogram (ECG) is the recording on the body surface of the electrical activity generated by heart. It was originally observed by Waller in 1889 [1] using his pet bulldog as the signal source and the capillary electrometer as the recording device. In 1903, Einthoven [2] enhanced the technology by employing the string galvanometer as the recording device and using human subjects with a variety of cardiac abnormalities. Einthoven is chiefly responsible for introducing some concepts still in use today, including the labeling of the various waves, defining some of the standard recording sites using the arms and legs, and developing the first theoretical construct whereby the heart is modeled as a single time-varying dipole. We also owe the *EKG* acronym to Einthoven's native Dutch language, where the root word *cardio* is spelled with a *k*.

In order to record an ECG waveform, a differential recording between two points on the body are made. Traditionally, each differential recording is referred to as a *lead*. Einthoven defined three leads numbered with the Roman numerals I, II, and III. They are defined as

$$I = V_{LA} - V_{RA}$$

$$II = V_{LL} - V_{RA}$$

$$III = V_{LL} - V_{LA}$$

where RA = right arm, LA = left arm, and LL = left leg. Because the body is assumed to be purely resistive at ECG frequencies, the four limbs can be thought of as wires attached to the torso. Hence lead I could be recorded from the respective shoulders without a loss of cardiac information. Note that these are not independent, and the following relationship holds: II = I + III.

The evolution of the ECG proceeded for 30 years when F.N. Wilson added concepts of a "unipolar" recording [3]. He created a reference point by tying the three limbs together and averaging their potentials so that individual recording sites on the limbs or chest surface would be differentially recorded with the same reference point. Wilson extended the biophysical models to include the concept of the cardiac source enclosed within the volume conductor of the body. He erroneously thought that the central terminal was a true zero potential. However, from the mid-1930s until today, the 12 leads composed of the 3 limb
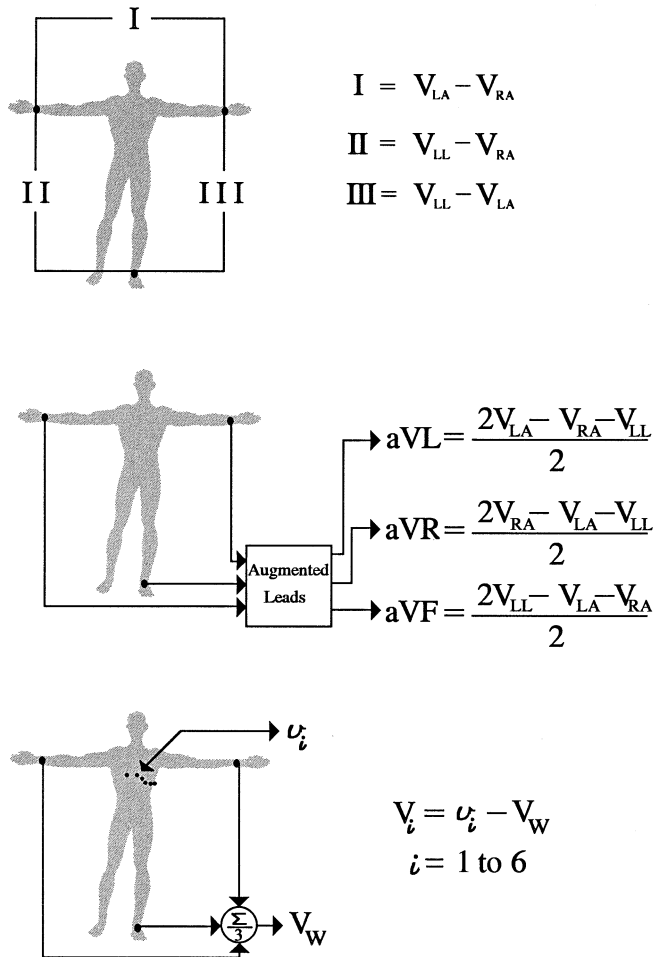
$$I = V_{LA} - V_{RA}$$

$$II = V_{LL} - V_{RA}$$

$$III = V_{LL} - V_{LA}$$

$$aVL = \frac{2V_{LA} - V_{RA} - V_{LL}}{2}$$

$$aVR = \frac{2V_{RA} - V_{LA} - V_{LL}}{2}$$

$$aVF = \frac{2V_{LL} - V_{LA} - V_{RA}}{2}$$

$$V_i = v_i - V_W$$

$$i = 1 \text{ to } 6$$

FIGURE 13.1   The 12-lead ECG is formed by the 3 bipolar surface leads: I, II, and III; the augmented Wilson terminal referenced limb leads: aV_R, aV_L, and aV_F; and the Wilson terminal referenced chest leads: V_1, V_2, V_3, V_4, V_5, and V_6.

leads, 3 leads in which the limb potentials are referenced to a modified Wilson terminal (the augmented leads [4]), and 6 leads placed across the front of the chest and referenced to the Wilson terminal form the basis of the standard 12-lead ECG. Figure 13.1 summarizes the 12-lead set. These sites are historically based, have a built-in redundancy, and are not optimal for all cardiac events. The voltage difference from any two sites will record an ECG, but it is these standardized sites with the massive 90-year collection of empirical observations that have firmly established their role as the standard. Figure 13.2 is a typical or stylized ECG recording from lead II. Einthovin chose the letters of the alphabet from P to U to label the waves and to avoid conflict with other physiologic waves being studied at the turn of the century. The ECG signals are typically in the range of ±2 mV and require a recording bandwidth of 0.05 to 150 Hz. Full technical specification for ECG equipment has been proposed by both the American Heart Association [5] and the Association for the Advancement of Medical Instrumentation [6].

There have been several attempts to change the approach for recording the ECG. The vectorcardiogram used a weighted set of recording sites to form an orthogonal *xyz* lead set. The advantage here was minimum lead set, but in practice it gained only a moderate degree of enthusiasm among physicians.
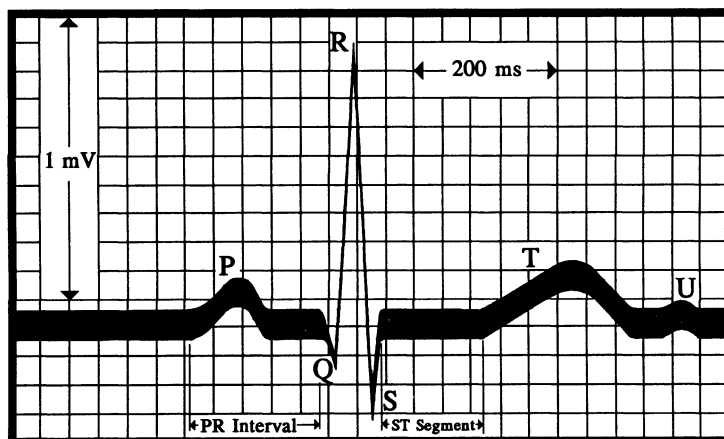
FIGURE 13.2 This is a stylized version of a normal lead II recording showing the P wave, QRS complex, and the T and U waves. The PR interval and the ST segment are significant time windows. The peak amplitude of the QRS is about 1 mV. The vertical scale is usually 1 mV/cm. The time scale is usually based on millimeters per second scales, with 25 mm/s being the standard form. The small boxes of the ECG are 1 × 1 mm.

Body surface mapping refers to the use of many recording sites (>64) arranged on the body so that isopotential surfaces could be computed and analyzed over time. This approach still has a role in research investigations. Other subsets of the 12-lead ECG are used in limited-mode recording situations such as the tape-recorded ambulatory ECG (usually 2 leads) or in intensive care monitoring at the bedside (usually 1 or 2 leads) or telemetered within regions of the hospital from patients who are not confined to bed (1 lead). The recording electronics of these ECG systems have followed the typical evolution of modern instrumentation, e.g., vacuum tubes, transistors, integrated chips, and microprocessors.

Application of computers to the ECG for machine interpretation was one of the earliest uses of computers in medicine [7]. Of primary interest in the computer-based systems was replacement of the human reader and elucidation of the standard waves and intervals. Originally this was performed by linking the ECG machine to a centralized computer via phone lines. The modern ECG machine is completely integrated with an analog front end, a 12- to 16-bit analog-to-digital (A/D) converter, a computational microprocessor, and dedicated input-output (I/O) processors. These systems compute a measurement matrix derived from the 12 lead signals and analyze this matrix with a set of rules to obtain the final set of interpretive statements [8]. Figure 13.3 shows the ECG of a heartbeat and the types of measurements that might be made on each of the component waves of the ECG and used for classifying each beat type and the subsequent cardiac rhythm. The depiction of the 12 analog signals and this set of interpretive statements form the final output, with an example shown in Fig. 13.4. The physician will overread each ECG and modify or correct those statements which are deemed inappropriate. The larger hospital-based system will record these corrections and maintain a large database of all ECGs accessible by any combination of parameters, e.g., all males, older than age 50, with an inferior myocardial infarction.

There are hundreds of interpretive statements from which a specific diagnosis is made for each ECG, but there are only about five or six major classification groups for which the ECG is used. The first step in analyzing an ECG requires determination of the rate and rhythm for the atria and ventricles. Included here would be any conduction disturbances either in the relationship between the various chambers or within the chambers themselves. Then one would proceed to identify features that would relate to the presence or absence of scarring due to a myocardial infarction. There also may be evidence of acute events that would occur with ischemia or an evolving myocardial infarction. The ECG has been a primary tool for evaluating chamber size or enlargement, but one might argue that more accurate information in this area would be supplied by noninvasive imaging technologies.
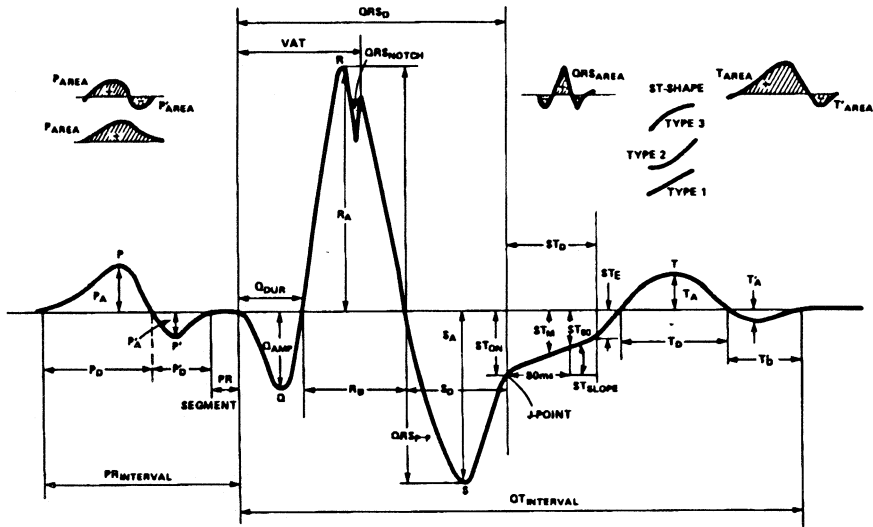
FIGURE 13.3 The ECG depicts numerous measurements that can be made with computer-based algorithms. These are primarily durations, amplitudes, and areas. (*Courtesy of Hewlett Packard Company, Palo Alto, Calif.*)
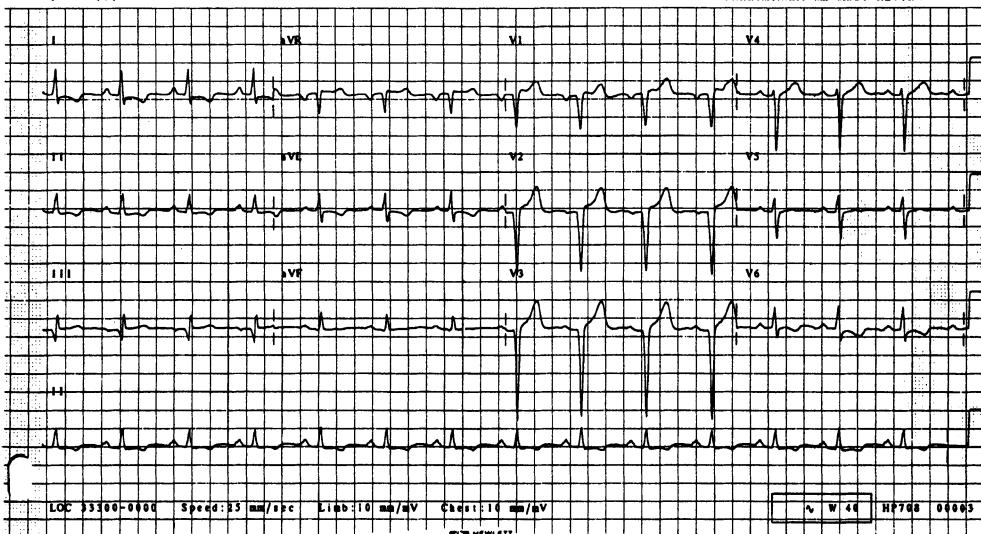

FIGURE 13.4 This is an example of an interpreted 12-lead ECG. A 2-1/2-s recording is shown for each of the 12 leads. The bottom trace is a continuous 10-s rhythm strip of lead II. Patient information is given in the top area, below which is printed the computerized interpretive statements (*Courtesy of the Hewlett Packard Company, Palo Alto, Calif.*)

More recently, the high-resolution ECG has been developed, whereby the digitized ECG is signal-averaged to reduce random noise [9,10]. This approach, coupled with postaveraging high-pass filtering, is used to detect and quantify low-level signals (~1.0 μV) not detectable with standard approaches. This computer-based approach has enabled the recording of events that are predictive of future life-threatening cardiac events [11,12].

13.1   Physiology

The heart has four chambers; the upper two chambers are called the *atria,* and the lower two chambers are called the *ventricles.* The atria are thin-walled, low-pressure pumps that receive blood from the venous circulation. Located in the top right atrium are a group of cells that act as the primary pacemaker of the heart. Through a complex change of ionic concentration across the cell membranes (the current source), an extracellular potential field is established which then excites neighboring cells, and a cell-to-cell propagation of electrical events occurs. Because the body acts as a purely resistive medium, these potential fields extend to the body surface [13]. The character of the body surface waves depends on the amount of tissue activating at one time and the relative speed and direction of the activation wavefront. Therefore, the pacemaker potentials that are generated by a small tissue mass are not seen on the ECG. As the activation wavefront encounters the increased mass of atrial muscle, the initiation of electrical activity is observed on the body surface, and the first ECG wave of the cardiac cycle is seen. This is the P wave, and it represents activation of the atria. Conduction of the cardiac impulse proceeds from the atria through a series of specialized cardiac cells (the A-V node and the His-Purkinje system) which again are too small in total mass to generate a signal large enough to be seen on the standard ECG. There is a short, relatively isoelectric segment following the P wave. Once the large muscle mass of the ventricles is excited, a rapid and large deflection is seen on the body surface. The excitation of the ventricles causes them to contract and provides the main force for circulating blood to the organs of the body. This large wave appears to have several components. The initial downward deflection is the Q wave, the initial upward deflection is the R wave, and the terminal downward deflection is the S wave. The polarity and actual presence of these three components depend on the position of the leads on the body as well as a multitude of abnormalities that may exist. In general, the large ventricular waveform is generically called the QRS complex regardless of its makeup. Following the QRS complex is another short relatively isoelectric segment. After this short segment, the ventricles return to their electrical resting state, and a wave of repolarization is seen as a low-frequency signal known as the T wave. In some individuals, a small peak occurs at the end or after the T wave and is the U wave. Its origin has never been fully established, but it is believed to be a repolarization potential.

13.2   Instrumentation

The general instrumentation requirements for the ECG have been addressed by professional societies through the years [5,6]. Briefly, they recommend a system bandwidth between 0.05 and 150 Hz. Of great importance in ECG diagnosis is the low-frequency response of the system, because shifts in some of the low-frequency regions, e.g., the ST segment, have critical diagnosis value. While the heart rate may only have a 1-Hz fundamental frequency, the phase responses of typical analog high-pass filters are such that the system corner frequency must be much smaller than the 3-dB corner frequency where only the amplitude response is considered. The system gain depends on the total system design. The typical ECG amplitude is ±2 mV, and if A/D conversion is used in a digital system, the enough gain to span the full range of the A/D converter is appropriate.

To first obtain an ECG the patient must be physically connected to the amplifier front end. The patient-amplifier interface is formed by a special bioelectrode that converts the ionic current flow of the body to the electron flow of the metallic wire. These electrodes typically rely on a chemical paste or gel with

a high ionic concentration. This acts as the transducer at the tissue-electrode interface. For short-term applications, silver-coated suction electrodes or "sticky" metallic foil electrodes are used. Long-term recordings, such as for the monitored patient, require a stable electrode-tissue interface, and special adhesive tape material surrounds the gel and an Ag^+/Ag^+Cl^- electrode.

At any given time, the patient may be connected to a variety of devices, e.g., respirator, blood pressure monitor, temporary pacemaker, etc., some of which will invade the body and provide a low-resistance pathway to the heart. It is essential that the device not act as a current source and inject the patient with enough current to stimulate the heart and cause it to fibrillate. Some bias currents are unavoidable for the system input stage, and recommendations are that these leakage currents be less than 10 μA per device. This applies to the normal setting, but if a fault condition arises whereby the patient comes in contact with the high-voltage side of the alternating current (ac) power lines, then the isolation must be adequate to prevent 10 μA of fault current as well. This mandates that the ECG reference ground not be connected physically to the low side of the ac power line or its third-wire ground. For ECG machines, the solution has typically been to AM modulate a medium frequency carrier signal (≈400 kHz) and use an isolation transformer with subsequent demodulation. Other methods of signal isolation can be used, but the primary reason for the isolation is to keep the patient from being part of the ac circuit in the case of a patient-to-power-line fault. In addition, with many devices connected in a patient monitoring situation, it is possible that ground loop currents will be generated. To obviate this potential hazard, a low-impedance ground buss is often installed in these rooms, and each device chassis will have an external ground wire connected to the buss. Another unique feature of these amplifiers is that they must be able to withstand the high-energy discharge of a cardiac defibrillator.

Older-style ECG machines recorded one lead at a time and then evolved to three simultaneous leads. This necessitated the use of switching circuits as well as analog weighting circuits to generate the various 12 leads. This is usually eliminated in modern digital systems by using an individual single-ended amplifier for each electrode on the body. Each potential signal is then digitally converted, and all the ECG leads can be formed mathematically in software. This would necessitate a 9-amplifier system. By performing some of the lead calculations with the analog differential amplifiers, this can be reduced to an 8-channel system. Thus only the individual chest leads V_1 through V_6 and any 2 of the limb leads, e.g., I and III, are needed to calculate the full 12-lead ECG. Figure 13.5 is a block diagram of a modern digital based ECG system. This system uses up to 13 single-ended amplifiers and a 16-bit A/D converter, all within a small lead wire manifold or amplifier lead stage. The digital signals are optically isolated and sent via a high-speed serial link to the main ECG instrument. Here the 32-bit CPU and DSP chip perform all the calculations, and a hard-copy report is generated (Fig. 13.4). Notice that each functional block has its own controller and that the system requires a real-time, multitasking operating system to coordinate all system functions. Concomitant with the data acquisition is the automatic interpretation of the ECG. These programs are quite sophisticated and are continually evolving. It is still a medical/legal requirement that these ECGs be overread by the physician.

13.3   Applications

Besides the standard 12-lead ECG, there are several other uses of ECG recording technology that rely on only a few leads. These applications have had a significant clinical and commercial impact. Following are brief descriptions of several ECG applications which are aimed at introducing the reader to some of the many uses of the ECG.

The Ambulatory ECG

The ambulatory or Holter ECG has an interesting history, and its evolution closely followed both technical and clinical progress. The original, analog, tape-based, portable ECG resembled a fully loaded backpack and was developed by Dr. Holter in the early 1960s [14]. It was soon followed by more compact devices
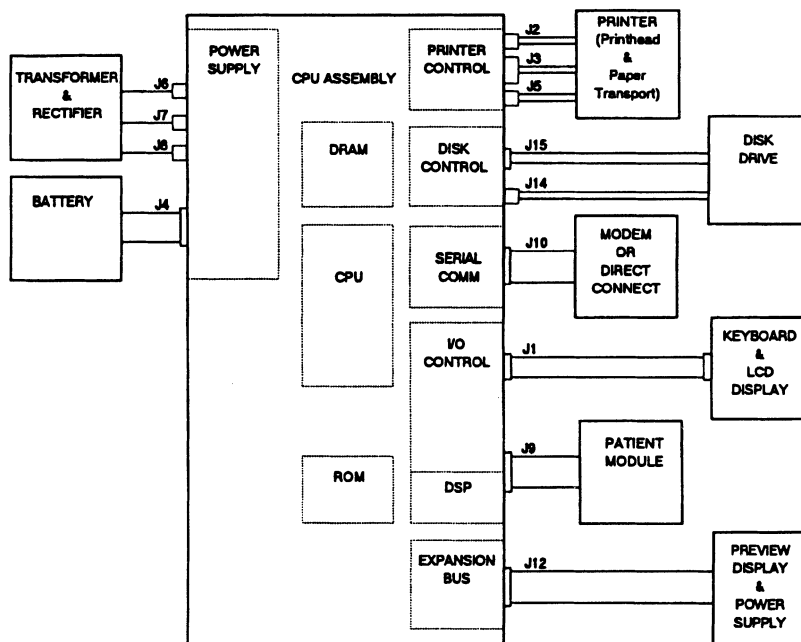
FIGURE 13.5 This is a block diagram of microprocessor-based ECG system. It includes all the elements of a personal computer class system, e.g., 80386 processor, 2 Mbytes of RAM, disk drive, 640 × 480 pixel LCD display, and battery operable. In addition, it includes a DSP56001 chip and multiple controllers which are managed with a real-time multitasking operating system. (*Courtesy of the Hewlett Packard Company, Palo Alto, Calif.*)

that could be worn on the belt. The original large-scale clinical use of this technology was to identify patients who developed heart block transiently and could be treated by implanting a cardiac pacemaker. This required the secondary development of a device that could rapidly play back the 24 hours of tape-recorded ECG signals and present to the technician or physician a means of identifying periods of time where the patient's heart rate became abnormally low. The scanners had the circuitry not only to play back the ECG at speeds 30 to 60 times real time but also to detect the beats and display them in a superimposed mode on a CRT screen. In addition, an audible tachometer could be used to identify the periods of low heart rate. With this playback capability came numerous other observations, such as the identification of premature ventricular complexes (PVCs), which lead to the development of techniques to identify and quantify their number. Together with the development of antiarrhythmic drugs, a marriage was formed between pharmaceutical therapy and the diagnostic tool for quantifying PVCs. ECG tapes were recorded before and after drug administration, and drug efficacy was measured by the reduction of the number of PVCs. The scanner technology for detecting and quantifying these arrhythmias was originally implemented with analog hardware but soon advanced to computer technology as it became economically feasible. Very sophisticated algorithms were developed based on pattern-recognition techniques and were sometimes implemented with high-speed specialized numerical processors as the tape playback speeds became several hundred times real time [15]. Unfortunately, this approach using the ambulatory ECG for identifying and treating cardiac arrhythmias has been on the decline because the rationale of PVC suppression was found to be unsuccessful for improving cardiac mortality. However, the ambulatory ECG is still a widely used diagnostic tool, and modern units often have built-in microprocessors with considerable amounts of random access memory and even small disk drives with capacities greater than 400 Mbytes. Here the data can be analyzed on-line, with large segments of data selected for storage and later analysis with personal computer-based programs.

Patient Monitoring

The techniques for monitoring the ECG in real time were developed in conjunction with the concept of the coronary care unit (CCU). Patients were placed in these specialized hospital units to carefully observe their progress during an acute illness such as a myocardial infarction or after complex surgical procedures. As the number of beds increased in these units, it became clear that the highly trained medical staff could not continually watch a monitor screen, and computerized techniques were added that monitored the patient's rhythm. These programs were not unlike those developed for the ambulatory ECG, and the high-speed numerical capability of the computer was not taxed by monitoring a single ECG. The typical CCU would have 8 to 16 beds, and hence the computing power was taken to its limit by monitoring multiple beds. The modern units have the CPU distributed within the ECG module at the bedside, along with modules for measuring many other physiologic parameters. Each bedside monitor would be interconnected with a high-speed digital line, e.g., Ethernet, to a centralized computer used primarily to control communications and maintain a patient database.

High-Resolution ECG

High-resolution (HR) capability is now a standard feature on most digitally based ECG systems or as a stand-alone microprocessor-based unit [16]. The most common application of the HRECG is to record very low level (~1.0-μV) signals that occur after the QRS complex but are not evident on the standard ECG. These "late potentials" are generated from abnormal regions of the ventricles and have been strongly associated with the substrate responsible for a life-threatening rapid heart rate (ventricular tachycardia). The typical HRECG is derived from 3 bipolar leads configured in an anatomic *xyz* coordinate system. These 3 ECG signals are then digitized at a rate of 1000 to 2000 Hz per channel, time aligned via a real-time QRS correlator, and summed in the form of a signal average. Signal averaging will theoretically improve the signal-to-noise ratio by the square root of the number of beats averaged. The underlying assumptions are that the signals of interest do not vary, on a beat-to-beat basis, and that the noise is random. Figure 13.6 has four panels depicting the most common sequence for processing the HRECG to measure the late potentials. Panel *a* depicts a 3-second recording of the *xyz* leads close to normal resolution. Panel *b* was obtained after averaging 200 beats and with a sampling frequency of 10 times that shown in panel *a*. The gain is also 5 times greater. Panel *c* is the high-pass filtered signal using a partially time-reversed digital filter having a second-order Butterworth response and a 3-dB corner frequency of 40 Hz [12]. Note the appearance of the signals at the terminal portion of the QRS complex. A common method of analysis, but necessarily optimal, is to combine the filtered *xyz* leads into a vector magnitude, that is, $(\mathbf{X}^2 + \mathbf{Y}^2 + \mathbf{Z}^2)^{1/2}$. This waveform is shown in panel *d*. From this waveform, several parameters have been derived such as total QRS duration (including late potentials), the RMS voltage value of the terminal 40 ms, and the low-amplitude signal (LAS) duration from the 40-μV level to the end of the late potentials. Abnormal values for these parameters are used to identify patients at high risk of ventricular tachycardia following a heart attack.

13.4   Conclusions

The ECG is one of the oldest instrument-bound measurements in medicine. It has faithfully followed the progression of instrumentation technology. Its most recent evolutionary step, to the microprocessor-based system, has allowed patients to wear their computer monitor or has provided an enhanced, high-resolution ECG that has opened new vistas of ECG analysis and interpretation.
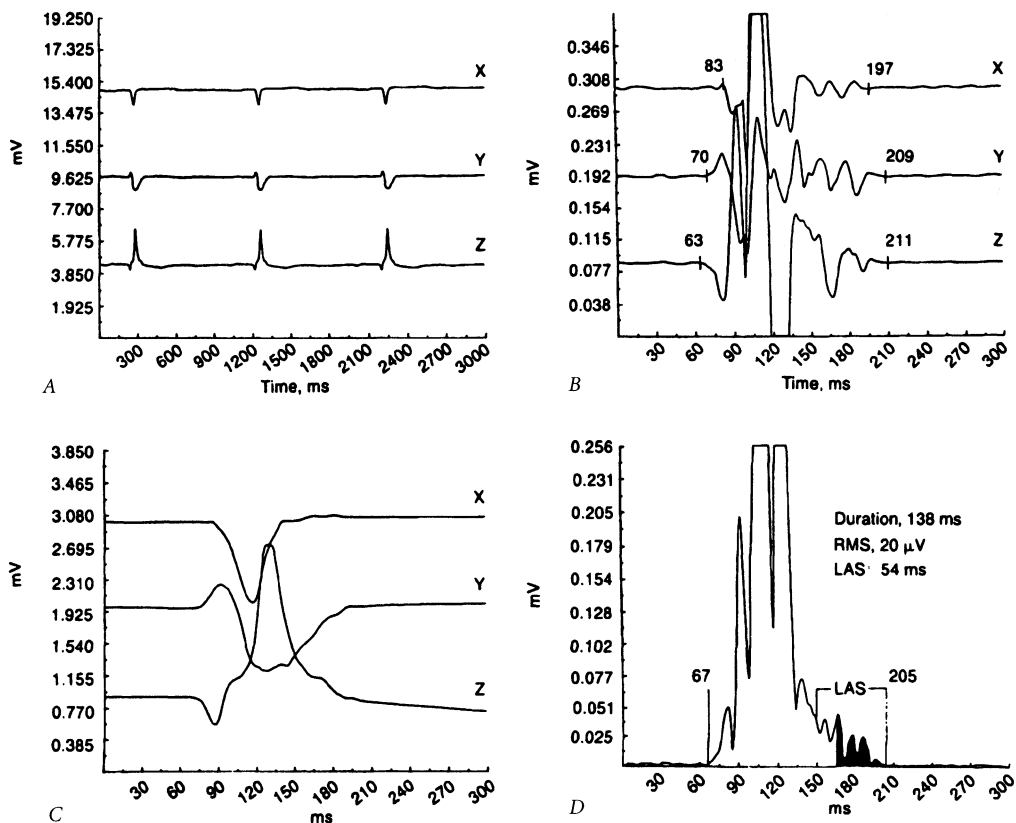
FIGURE 13.6 The signal-processing steps typically performed to obtain a high-resolution ECG are shown in panels A through D. See text for a full description.

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