

THE BIOMEDICAL ENGINEERING HANDBOOK
FOURTH EDITION

Biomedical Engineering Fundamentals

Edited by
Joseph D. Bronzino
Donald R. Peterson

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Principles of Electrocardiography

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45.1 Introduction

The electrocardiogram (ECG) is the recording of the electrical activity generated by the heart on the body surface. 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] improvised the technology by using the string galvanometer as the recording device and employing 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 writing in German where the root word “cardio” is spelled with a “k.”

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:

$$\begin{aligned} \text{I} &= V_{\text{LA}} - V_{\text{RA}} \\ \text{II} &= V_{\text{LL}} - V_{\text{RA}} \\ \text{III} &= V_{\text{LL}} - V_{\text{LA}} \end{aligned}$$

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 $\text{II} = \text{I} + \text{III}$ holds.

For 30 years the evolution of the ECG proceeded when F.N. Wilson [3] added concepts of a “unipolar” recording. He created a reference point by tying the three limbs together and averaging their potentials so that individual recording sites on the limbs or the chest surface would be differentially recorded with the same reference point. Wilson extended the biophysical models to include the concept of the

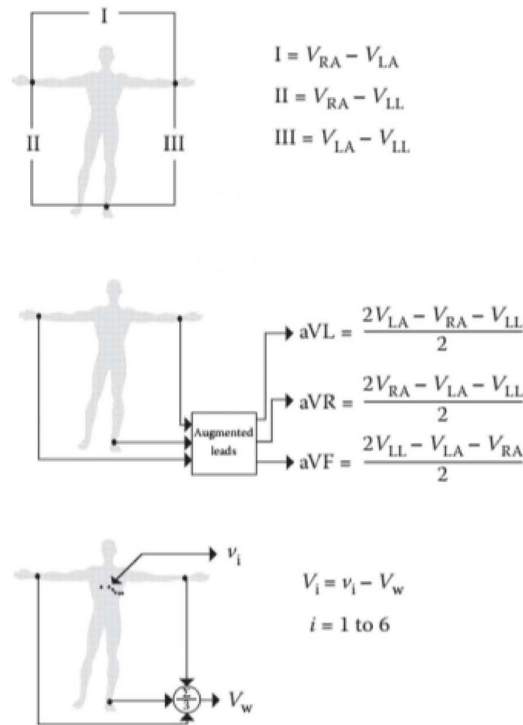


FIGURE 45.1 The 12-lead ECG is formed by the three bipolar surface leads: I, II, and III; the augmented Wilson terminal referenced limb leads: aVR, aVL, aVF; and the Wilson terminal referenced chest leads: V_1 , V_2 , V_3 , V_4 , V_5 , and V_6 .

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 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 45.1 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 has firmly established their role as the standard. Figure 45.2 is a typical or stylized ECG recording from lead II. Einthoven chose the letters of the alphabet from P–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 0.05–150 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 vector cardiogram 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. 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 digitally stored 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, for example, vacuum tubes, transistors, ICs, and microprocessors.