A New Simple Model for the Synthesis of the Electrocardiogram

By HERMAN N. UHLEY, M.D.

SUMMARY

This paper reports the development of a simple, inexpensive apparatus that can be constructed and programmed to simulate normal as well as abnormal depolarization and repolarization of the heart and to reproduce an electrocardiogram. The device utilizes a modulated light beam, a series of differential photocells, a patch cord programmer, and a synthesizer consisting of an array of dipoles in a saline conductor. Changes occurring on a cellular level are simulated and programmed and in proper temporal sequence to the multiple dipoles, thereby forming a resultant spatial generator of QRS and T complexes.

Additional Indexing Words: Depolarization Dipoles Teaching device Repolarization Analog computer Genesis of electrocardiogram

IN RECENT YEARS there has been considerable interest in the mode and sequence of activation of the heart chambers.1-5 Detailed studies by Scher and Young,6 using intramural multipolar electrodes, have provided three-dimensional plots of the activation process. In addition attempts have been made to simulate ventricular depolarization, generally by using data based on Scher’s activation sequence in dogs.7-10 Such research, however, requires expensive computers and consequently has its limitations.

The purpose of this paper is to report the development of a simple, inexpensive apparatus that can be easily constructed and programmed to simulate normal as well as abnormal depolarization and repolarization and to reproduce a vectorcardiogram, a standard 12-lead electrocardiogram, or an electrocardiogram with any other lead system.

Methods

The underlying principle of the apparatus involves the conversion of light energy into electromotive forces.11 The apparatus (fig. 1) consists of (a) a wave-form generator, (b) a programmer, (c) synthesizer, and (d) a recorder.

The wave-form generator is made up of (1) a cyclic modulator, and (2) five sequentially activated differential photocell circuits.

The cyclic light modulator allows five shaped beams of light to fall cyclically on a bank of photocells (fig. 1a). The shape and duration of the light beams that fall on the cells are controlled by the slots of tapering shape in the side of the cylinder. The cylinder base is fixed to the top of a revolving phonograph turntable. A light within the cylinder projects through the slots with each revolution of the turntable, and the modulated beams fall on the respective photocells.

In the differential photocell circuit two photocells are used in each differential photocell circuit. Five differential photocell circuits are arranged so that they are sequentially activated by the revolving beams of light. Figure 2 shows the outputs from the five photocell circuits used in generating the electrocardiogram of figure 3.

The programmer is a patch network that allows selection of any of the five sequentially activated photocell circuit outputs and distribution of the voltage to a particular dipole source in the synthesizer (fig. 1b). Table 1 indicates the program format used to obtain the electrocardiogram of figure 3 based on the observed activation of the normal dog.8
The synthesizer is a saline-filled tank containing 35 dipoles (fig. 1c). The dipoles are the exposed 2-mm tips of pairs of insulated wires held in fixed spatial relation by 1 mm apart by means of five thin formica discs. Three of the discs are circular with a hole in the center and represent the base, middle, and apical cross sections of the left ventricle. Two semicircular pieces represent superior and inferior cross sections of the right ventricular mural wall. In effect, these five pieces of formica merely maintain the proper orientation of the 35 dipoles. The dipoles are perpendicular to the surface of the heart model and are located in the assumed septal, anterior, and posterior positions of the three left ventricular cross sections and anterior and posterior positions of the right ventricular cross sections. Thus, at any given position on a left ventricular disc, there is an epicardial (outer) electrode, myocardial (middle) electrode, and endocardial (inner) electrode. The septal epicardial electrodes of the left ventricular discs actually form the right septal endocardial electrodes. In the right ventricular mural position there are endocardial (inner) and epicardial (outer) electrodes.

The electrode wires physically serve to hold the formica discs in place. They resemble the ventricular conduction system and its distribution within the two chambers. The dipoles, which encompass a volume of approximately 4 inches by 4 inches by 3½ inches, are submerged in a volume conductor formed by a cylindrical plexiglass tank 19 inches high and 12 inches in diameter containing a saline solution (25 mEq/L). The heart was positioned vertically with the right ventricle in the anterior position. The center of the mid-formica ring was approximately in line with the V₆ electrode.

The recorder is a conventional electrocardiogram which is connected to terminals within the tank in positions corresponding to the shoulders and pelvis for the limb leads and the characteristic V₁ to V₆ positions for the chest leads (fig. 1d). These terminals can be arranged otherwise to produce orthogonal leads and vectorcardiograms.

The apparatus works as follows: The waveform generator motor turns a cylinder encompassing a light bulb. The configuration of the slit in the cylinder allows the light to be cast out from within the cylinder so that a period of darkness is followed by the sudden appearance of light which gradually recedes into darkness again. When this cyclically modulated light pattern falls on the differential photocells, the electrical energy developed is a function of the difference in light intensity between the two cells. Thus the circuit develops a sudden voltage in one direction as the light hits the first cell of the pair, followed by return of the voltage to the base line as the light hits both cells. This is followed by a gradual increase in voltage in the opposite direction as the first cell is in darkness again, and finally a

**Figure 1**

Diagram of the various components used in the model. The modulated light beams activate the photocells sequentially resulting in five output voltages from the differential photocell circuits. The programmer distributes the voltages in proper temporal sequence to the synthesizer (dipoles in the saline conductor). The resultant voltages are recorded on the electrocardiogram.
### Table 1

Format of Dipole Connections Used to Obtain the Electrocardiogram of Figure 3

<table>
<thead>
<tr>
<th>Dipoles connected to output no. 1</th>
<th>Dipoles connected to output no. 2</th>
<th>Dipoles connected to output no. 3</th>
<th>Dipoles connected to output no. 4</th>
<th>Dipoles connected to output no. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-septal-endocardial</td>
<td>Mid-septal-epicardial*</td>
<td>Base-anterior-endocardial</td>
<td>Base-anterior-myocardial</td>
<td>Base-posterior-epicardial</td>
</tr>
<tr>
<td>Mid-septal-myocardial</td>
<td>Base-septal-endocardial</td>
<td>Base-posterior-myocardial</td>
<td>Base-septal-myocardial</td>
<td>Base-septal-epicardial</td>
</tr>
<tr>
<td>Mid-posterior-endocardial</td>
<td>Base-posterior-endocardial</td>
<td>Mid-posterior-epicardial</td>
<td>Right base-posterior epicardial</td>
<td></td>
</tr>
<tr>
<td>Mid-anterior-endocardial</td>
<td>Mid-posterior-myocardial</td>
<td>Mid-posterior-epicardial</td>
<td></td>
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</tr>
<tr>
<td>Apex-septal-endocardial</td>
<td>Apex-anterior-myocardial</td>
<td>Apex-posterior-epicardial</td>
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</tr>
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<td>Apex-posterior-endocardial</td>
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<tr>
<td>Apex-anterior-endocardial</td>
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<td>Right apex-anterior endocardial</td>
<td>Right base-posterior endocardial</td>
<td>Right base-anterior epicardial</td>
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</tr>
</tbody>
</table>

* Electrodes reversed (positive pole toward left ventricular cavity).
regression of the voltage slowly toward the base line as the remaining cell is slowly cut off from the light source. Thus, the effect of the differential photocell circuit is to produce an abrupt change in voltage (depolarization) followed by a period of quiescence and a slow movement of voltage in the opposite direction (repolarization) with a return to normal.* In this manner the rotating, shaped beam of light simulates the activation process on a cellular level by developing voltage corresponding to the supposed underlying ionic movements or current flows (in other words, the rapid sodium influx, followed by the slower potassium efflux). The output of this differential circuit is referred to as output no. 1. Outputs 2, 3, 4, and 5, occurring at successively later intervals of time, are obtained by using a similar differential photocell circuit with the cells placed at appropriate points in the pathways of the rotating beams of light (fig. 1a). Thus, it is possible to simulate the successive activation of tissue or a moving wave front. The programmer merely picks up the voltage occurring at each successive period of time and distributes it to the proper anatomic point in the dipole heart system lying within the volume conductor (fig. 1b). Thus, the synthesizer serves in effect to combine the voltages of the 35 dipoles, as the dipoles are sequentially and properly activated by the programmer within the volume conductor (fig. 1c). The final stage is the recording of the resultant voltages obtained from the tank by the ECG machine (fig. 1d).

**Discussion**

A model of the activation process must contain two essential prerequisites: (1) It must simulate the specific current flow produced by the activation process at a given point (that is, the local depolarization-repolarization process). (2) It must simulate the proper sequential appearance of the current changes at various anatomic sites in the heart (that is, the proper sequence of actual activation).

The first postulate is met by the wave-form generator. The differential photocell circuit with the modulated light beam creates the electrical effect of the activation wave approaching, passing, and leaving a given locus. The abrupt appearance and gradual disappearance of the light beam is perhaps analogous to the membrane changes, which result in a rapid influx of sodium ions and a subsequent efflux of potassium ions from the myocardial cell. It creates, via the differential photocell circuit, the abrupt rise, fall, and subsequent slow voltage in the opposite direction with a return to the original base line and is analogous in a general sense to current flows secondary to the sodium and potassium conductance changes.

The second postulate, namely the proper sequential appearance at the anatomic sites of the heart, is achieved by a distribution

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*While it is recognized that differences in the action potential exist in different locations in the myocardium, the repolarization sequence in this report was not specifically modified but followed the programmed depolarization sequence (fig. 2).
network. This network is merely a patch system that is programmed by connecting the dipoles contained in the three-dimensional conductor to the appropriate output of the five sequentially activated differential photocell circuits. If the spatially arranged dipoles are programmed into the proper temporal sequence,¹,²,⁶ one can simulate the activation process, and a resultant wave form is synthesized within the volume conductor, which may be recorded as a conventional electrocardiogram (or vectorcardiogram).

As can be seen in figure 3, an electrocardiographic pattern is obtained resembling that of a mammalian heart. While the pattern is perhaps not perfect, it does contain QRS and T complexes that are in proper orientation and generally consistent with the canine electrocardiogram.¹³ Certain technical refinements, such as increasing the number of dipoles, accounting for inhomogeneity, of the torso, and improving torso contour, will no doubt produce better electrocardiograms.

The advantages of this system over other methods, particularly over sophisticated computer systems are: (1) that it provides an easy means, starting with an analog of changes on a cellular level, for simulating the activation of the heart and obtaining electrocardiograms, and (2) that the apparatus employed is relatively simple to construct and inexpensive; its cost is about $50.00. This device, which is in effect a "homemade analog computer," enables one to study both the depolarization and the repolarization process and to simulate various types of normal and abnormal activation encountered in clinical conditions. Such studies are now in progress.

Figure 3

Example of a standard 12-lead electrocardiogram from the apparatus programmed according to the activation sequence of the normal dog.⁶
References


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