DIAGNOSTIC ELECTROCARDIOGRAPHY AND VECTORCARDIOGRAPHY

Second Edition

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NOTICE

Medicine is an ever-changing science. As new research and clinical experience broaden our knowledge, changes in treatment and drug therapy are required. The editors and the publisher of this work have made every effort to ensure that the drug dosage schedules herein are accurate and in accord with the standards accepted at the time of publication. Readers are advised, however, to check the product information sheet included in the package of each drug they plan to administer to be certain that changes have not been made in the recommended dose or in the contraindications for administration. This recommendation is of particular importance in regard to new or infrequently used drugs.

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PREFACE

The scope and aims of this second edition of "Diagnostic Electrocardiography and Vectorcardiography" remain the same as those of the first edition: to provide a practical textbook, concise enough for the beginner but comprehensive enough to furnish more detailed information and serve as a ready reference for the more advanced student and the electrocardiographic interpreter. As in the previous edition, conventional electrocardiography, vectorelectrocardiography, and oscilloscopic vectorcardiography have been incorporated and integrated within the text to help the reader bridge the gap between them.

The entire text has been revised, updated, and expanded. Most chapters have been enlarged to provide more complete coverage of the subject matter. At least 150 new illustrations have been added. Some of the more recent advancements in electrocardiography that have been included in the text are as follows: present-day concepts of the anatomy and physiology of the conduction system and the electrophysiology of the arrhythmias; the monofascicular, bifascicular, and trifascicular blocks and bilateral bundle branch block; His bundle electrocardiography; sinoventricular rhythm; sinus node dysfunction: the "sick sinus" and bradycardia-tachycardia syndromes; reentrant paroxysmal supraventricular tachycardia; fascicular beats and rhythms; the Wedensky phenomena; and pacemaker electrocardiography.

Each chapter has been made reasonably complete, which has led to some repetition in the text, but has obviated to a great extent the need for cross references to other pages or chapters. A complete bibliography has not been given, but selected references are listed at the end of each chapter. In choosing them, I have given preference to the more recent literature and to review articles. Those who seek a more comprehensive bibliography will usually find it in the papers that have been cited.

The major emphasis throughout the book is on electrocardiographic and vectorcardiographic diagnosis. The criteria listed in the text represent the consensus of competent authorities. However, I have attempted to indicate areas in which there is controversy or diversity of opinion or in which the diagnostic standards are not entirely adequate.

Several physicians have graciously provided illustrations in the original text and in the current edition. I am deeply indebted to Drs. Leonard S. Dreifus, Henry J. L. Marriott, Joseph Synyder, and especially to William P. Nelson and Ray Pryor for their courtesy in this regard.

All the new diagrams and drawings in the present edition are the work of Ms. Sara Gustafson. The photography was performed by Ms. Peggy Perlmeter. I am grateful to them for their splendid spirit of cooperation and the technical excellence of their work. Mr. Sheldon Luper, head of the Medical Illustration Department at General Rose Memorial Hospital, kindly made the facilities of his department available to me.

In the preparation of the book, I have had the generous support of the administrative staff and board of trustees of General Rose Memorial Hospital.

I am very much indebted to Mrs. Diane Yacovetta who typed the entire manuscript and to Mrs. Dorothy F. Goldberg and her staff of technicians at General Rose Memorial Hospital who recorded many of the tracings in the text and mounted them for photography.

My deepest gratitude and thanks go to my wife, Charlotte, whose patience and forbearance made the writing of this book an enjoyable task rather than a burdensome chore. Without her understanding and encouragement, neither this nor any of my other books would have been written.

H. Harold Friedman

CONTENTS

CHAPTER 1

ELECTROPHYSIOLOGY

Knowledge of basic electrophysiologic principles is essential to a proper understanding of clinical electrocardiography and to the correct interpretation of the electrocardiogram.

A simple approach to the electrophysiology of the heart is through a consideration of the electrical properties of individual cardiac muscle fibers during the resting state and during the processes of depolarization and repolarization.

RESTING OR POLARIZED STATE (FIG. 1-1)

For the purposes of this discussion, a hypothetical cardiac muscle fiber or cell is immersed in a homogeneous volume conductor such as normal saline in order to simulate conditions as they exist within the body. When the muscle strip is at *rest,* or is in the *polarized state,* a series of positive charges line the outer surface of the cell membrane and a corresponding number of negative charges line its inner surface. Each pair of positive and negative charges is called a *dipole,* or *doublet.* Current flow between the two layers of charges is prevented by the high electrical resistance of the cell membrane during the resting state.

DEPOLARIZATION (FIG. 1-2)

Stimulation of the muscle cell causes the electrical resistance to be lowered at the site of stimulation, which permits an electric current to flow across the

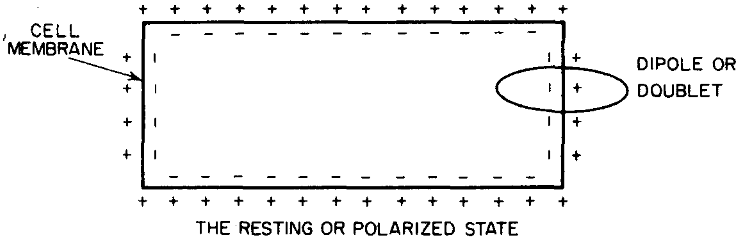
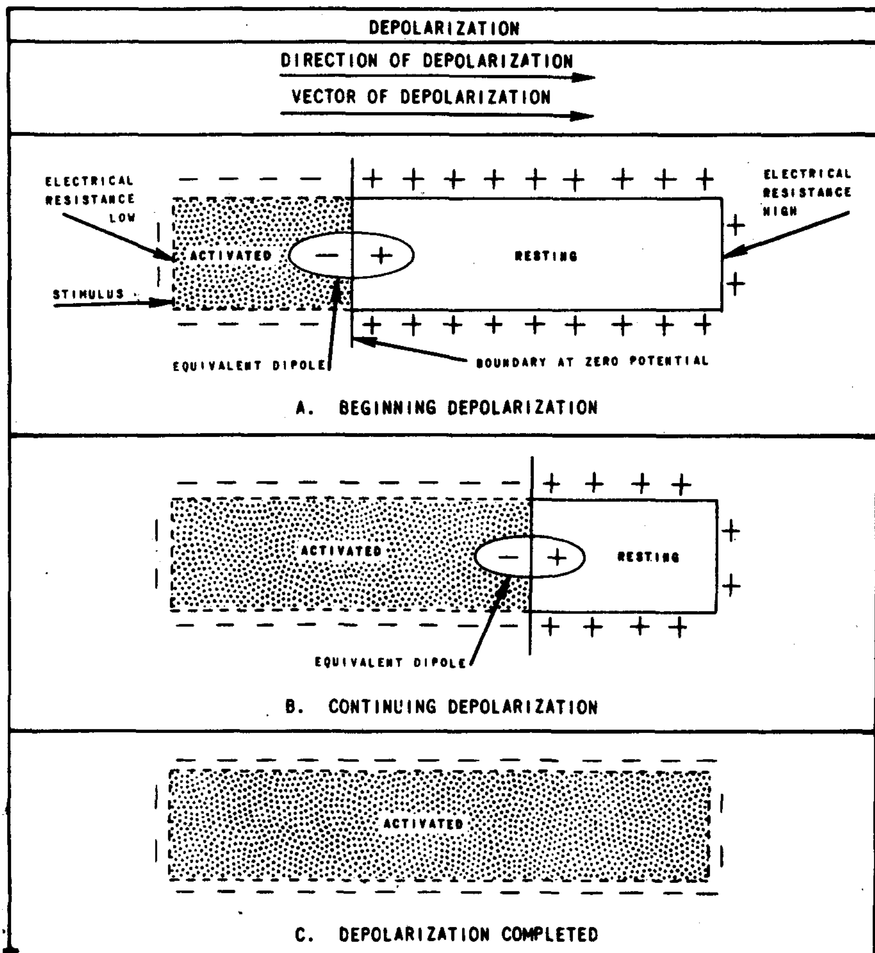


Fig. 1-1 The resting or polarized state. Described in text.

Fig. 1-2 The process of depolarization. Described in text.



membrane. The positive charge at this point migrates across the membrane toward the interior of the cell, and its corresponding negative charge moves to the surface of the strip. Because the muscle fiber is an excitable tissue, the stimulus is propagated through the cell without additional stimulation. Along the entire length of the muscle strip, each successive pair of positive and negative charges crosses the cell membrane until the cell is completely *activated*, or *depolarized*. At any given instant during depolarization, there is a boundary between resting and depolarized muscle. This boundary is at zero potential. The greatest positivity lies immediately in front of the zero line; the greatest negativity, immediately behind it. The depolarization process may be represented by a series of dipoles consisting of positive charges in advance of negative charges traversing the surface of the cell from the site of stimulation to the opposite end of the cell. Moreover, the whole series of dipoles may be represented by a *single equivalent dipole*. Since the cell is immersed in a homogeneous volume conductor, the flow of current creates an electric field in the conductor. Potential differences therefore exist between any points located on opposite sides of the zero line within the volume conductor.

REPOLARIZATION (FIG. 1-3)

Following depolarization, the muscle strip remains in the activated state for a brief interval and then slowly returns to the polarized state. During the time that the muscle cell remains in the activated state, no current flows, and the potential differences and the electric field disappear. Restoration of the resting state is called *repolarization*. Repolarization may take place in the same direction as depolarization (e.g., that which occurs in normal atrial muscle) or in the opposite direction from depolarization (e.g., that which occurs in normal ventricular muscle). In either case, during repolarization, the high electrical resistance of the membrane, with a layer of positive charges on the outer surface of the cell membrane and a corresponding layer of negative charges along its inner surface, is restored. The repolarization process may be represented by a series of dipoles, consisting of negative charges in advance of positive charges, traversing the surface of the cell from the site at which repolarization began to the opposite end of the cell. As in the case of depolarization, the whole series of dipoles may be represented by a single equivalent dipole. The flow of current during repolarization creates an electric field in the surrounding medium. Potential differences therefore exist between any points located on opposite sides of the zero line within the conductor.

LEADS (FIG. 1-4)

A *galvanometer* may be used to record the electrical potentials produced by a muscle strip during depolarization and repolarization. This instrument

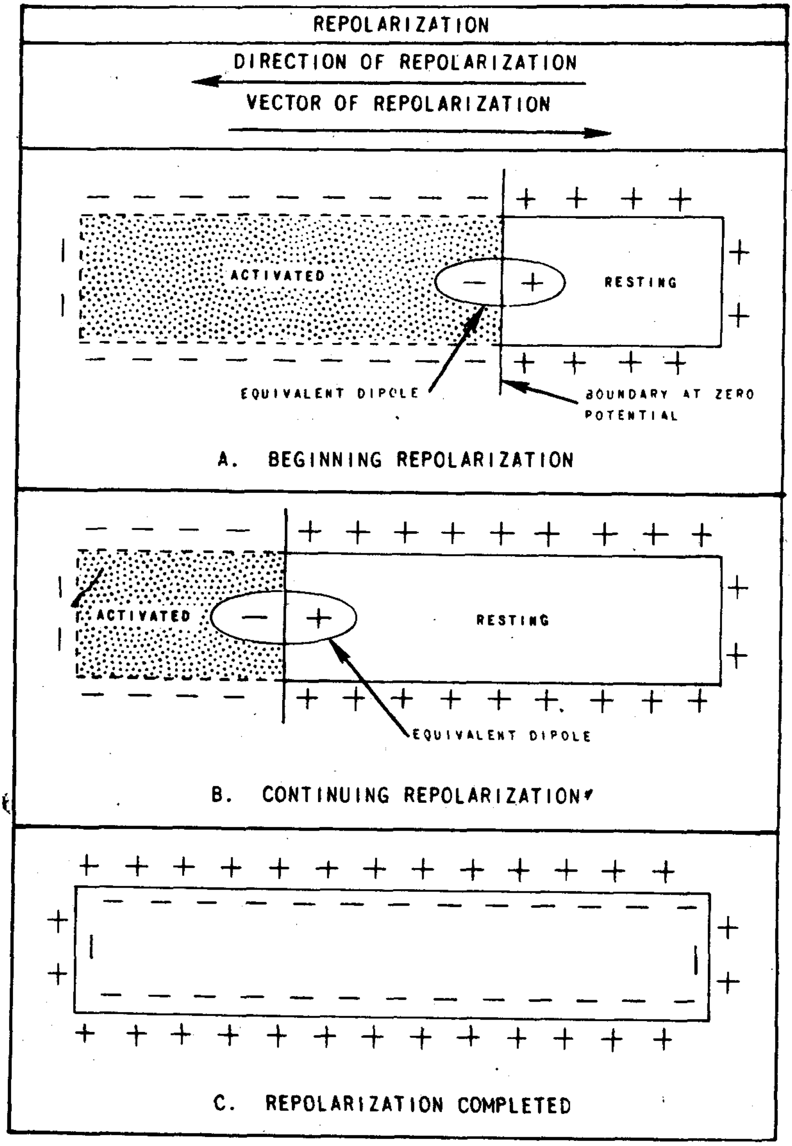


Fig. 1-3 The process of repolarization. Described in text.

has two terminals: one is connected to a positive electrode, and the other to a negative electrode. The galvanometer records the difference in potential between the two electrodes. An *electrocardiograph,* which is essentially a modified galvanometer, operates in similar fashion. When the electrodes are placed at different points in an electrical field, they form a *lead.* A hypothetical line joining the sites of the two electrodes is called the *axis of* the lead. *Bipolar leads* are those in which both positive and negative electrodes are located in areas of electric potential. *Unipolar leads* are those in which the negative electrode, called the *indifferent electrode,* is at zero potential. The positive electrode of a unipolar lead is called the *exploring electrode.*

Bipolar leads record the potential difference between the two electrode sites but give no information concerning the electric forces actually present beneath each electrode. Unipolar leads (which, in the strict sense, are really bipolar) similarly record the potential difference between the exploring electrode and the indifferent electrode. However, since the latter is at zero potential, a unipolar lead, in effect, records the potential variations taking place beneath the exploring electrode.

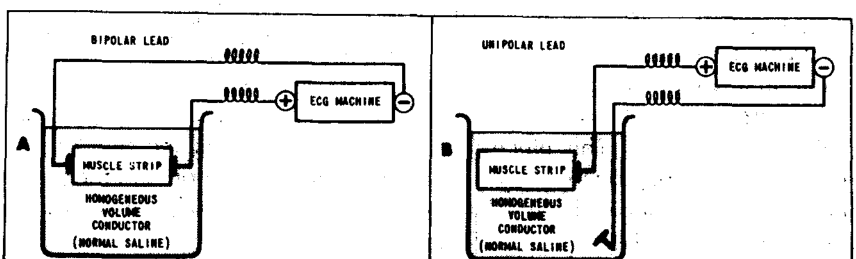
Unipolar leads may be employed to record the electrical activity of a hypothetical muscle strip. The graphic record of the electrical forces generated by a muscle cell is called an *electrogram.* Similarly, the graphic record of the electrical potentials produced by the heart is called an *electrocardiogram.* By convention, in both the electrogram and the electrocardiogram, positive forces cause the inscription of upward deflections; negative forces, downward deflections.

POTENTIALS RECORDED BY UNIPOLAR LEADS DURING DEPOLARIZATION AND REPOLARIZATION

The potentials recorded by a unipolar lead during depolarization and repolarization of a muscle strip are dependent on the location of the exploring electrode, the distance between the exploring electrode and the muscle strip, and the orientation of the axis of the lead with respect to the direction of depolarization and repolarization. These factors will now be considered.

In the discussion which follows, a hypothetical muscle strip from the left ventricle, extending from endocardium to epicardium, is immersed in a large-volume conductor. The indifferent electrode is placed in the conduc-

Fig. 1-4 Bipolar and unipolar leads. In bipolar leads the positive and negative electrodes are located in areas of electrical potential. In unipolar leads, the negative electrode, because it is located at a great distance from the source of electromotive forces, is at zero potential.



tor at a site remote from the muscle fiber. Since in large-volume conductors electromotive force is inversely proportional to the cube of the distance between the source of the potential and the electrode, it can be assumed that the indifferent electrode is at zero potential. Exploring electrodes are placed at three points on the surface of the cell: one at each end of the cell and the third at its midportion. Each electrode is connected to a different recording channel in the galvanometer. The potential variations of the muscle cell are recorded by each lead on a moving paper or film. By standardization it is possible to determine the magnitude of the voltages from the amplitude of the deflections. Similarly, since the paper moves at a given speed, it is possible to measure the duration of the waves, complexes, and intervals. As in the case of normal ventricular myocardium, the direction of depolarization is from endocardium to epicardium, and the direction of repolarization is from epicardium to endocardium. By convention, the deflections produced by depolarization of ventricular muscle are called *QRS complexes;* those produced by repolarization are called *T waves.*

EFFECT OF THE LOCATION OF THE EXPLORING ELECTRODE ON THE POTENTIAL VARIATIONS OF UNIPOLAR LEADS (FIG. 1-5)

Epicardial Leads

During the resting state, no current flows and the baseline remains isoelectric. When the muscle strip is stimulated, the activation process begins. An equivalent dipole with a positive charge in advance of a negative charge travels toward the electrode. The electrode, facing the positive side of the dipole, begins to record an upstroke. The positivity becomes more intense as the dipole approaches the electrode. This is represented by the gradual upward slope of the deflection. The peak of the deflection signals the arrival of the dipole at the epicardial end of the cell directly beneath the electrode. With complete activation of the muscle strip at this moment, the dipole disappears and the deflection returns precipitously to the baseline. This deflection is called an *R wave.* The muscle strip remains in the activated state for a brief period during which the entire surface of the strip has the same negative potential. During this interval, therefore, the baseline remains isoelectric. This portion of the baseline is called the *S-T segment.*

With the onset of repolarization, an equivalent dipole with a negative charge in advance of a positive charge appears at the epicardial end of the muscle strip and travels to the endocardial end in a direction away from the exploring electrode. This electrode always faces the positive side of the dipole. Since repolarization takes longer than depolarization and the magnitude of the potentials produced at any given instant is less, a small, wide, upright deflection, the T wave, is inscribed.

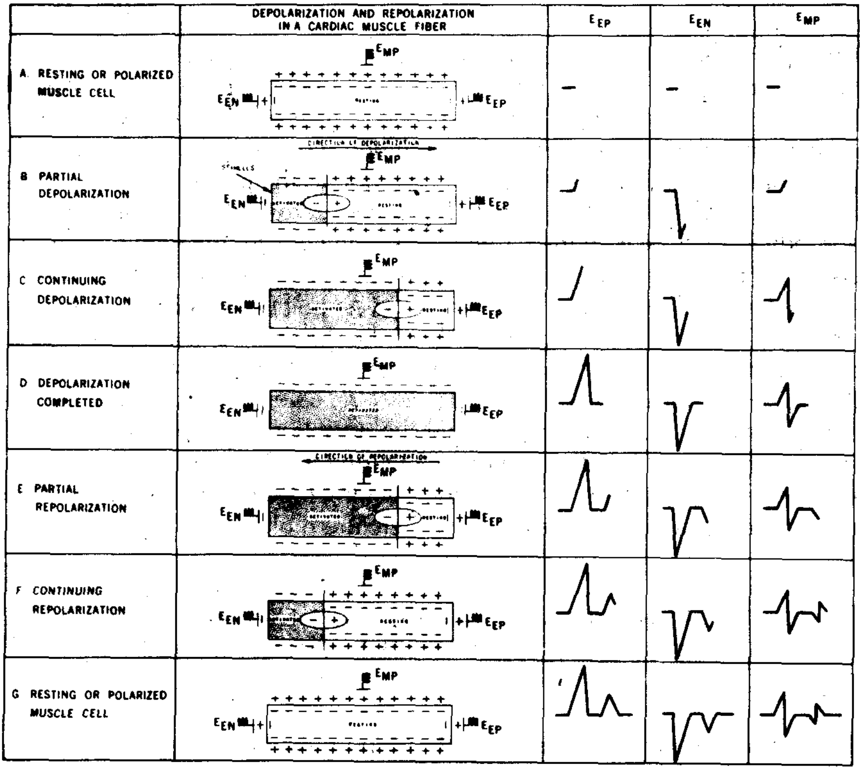


Fig. 1-5 The potentials recorded by unipolar leads during depolarization and repolarization of a cardiac muscle fiber. Described in text. E_{EP}, epicardial lead; E_{EN}, endocardial lead; E_{MP}, a lead at the midpoint of the muscle strip.

Endocardial Leads

When an exploring electrode is placed at the endocardial end of the muscle strip, the electrode faces the negative aspect of the moving dipole throughout depolarization, and a downward deflection will be recorded. The greatest negativity occurs at the onset of depolarization, since the electrode is closest to the dipole at this time. The slope of the forward limb of the deflection is, therefore, steeply downward, and its nadir is reached almost immediately. During the remainder of depolarization, the dipole moves away from the exploring electrode, so that the negativity at the electrode decreases. The hind limb of the deflection therefore shows a gradual return to the isoelectric level. This single, negative deflection is called a *QS complex*. During the time the muscle remains in the activated state, an isoelectric baseline is written. During repolarization, the electrode faces the negative aspect of the approaching dipole and a downward T wave is recorded.

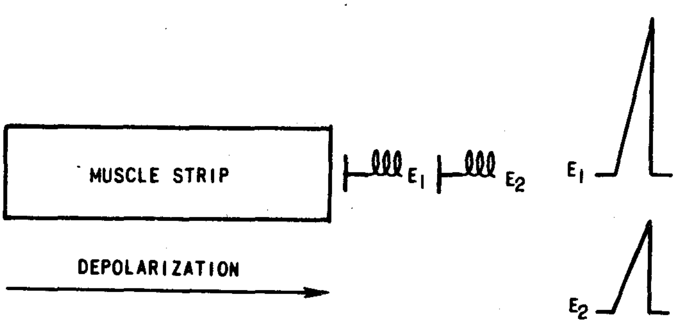
Other Leads

When an exploring electrode is placed over the center of the muscle strip, the electrode faces the positive side of the approaching dipole at the onset of depolarization and an upstroke is inscribed. The upstroke continues to be written and reaches its maximum amplitude when the dipole arrives at a point directly beneath the electrode. As soon as the positive charge passes beneath the electrode, the potential becomes zero and the deflection falls abruptly from its peak to the baseline. A moment later the dipole begins to travel away from the electrode. The deflection continues sharply downward from the baseline and reaches its lowest point immediately, since the electrode now faces the negative side of the dipole. As the dipole moves away from the electrode, the negativity at the electrode decreases. The deflection thus returns gradually to the isoelectric level. This diphasic deflection is called an *RS complex*. While the muscle remains in the activated state, an isoelectric baseline is written. During repolarization, the electrode first faces the negative side of the approaching dipole and later its positive side. The T wave that is recorded is therefore diphasic.

EFFECT OF THE DISTANCE BETWEEN THE EXPLORING ELECTRODE AND THE MUSCLE STRIP ON THE POTENTIAL VARIATIONS OF UNIPOLAR LEADS (FIG. 1-6)

Since electromotive force is inversely proportional to the cube of the distance in a large-volume conductor, the potential decreases rapidly as the distance between the exploring electrode and the muscle strip increases.

Fig. 1-6 The effect of the distance between the exploring electrode and the muscle strip upon the amplitude of the deflections recorded by unipolar leads. As the exploring electrode is moved away from the muscle cell, there is a marked decrement in voltage. Compare the potentials recorded by exploring electrodes E_1 and E_2.



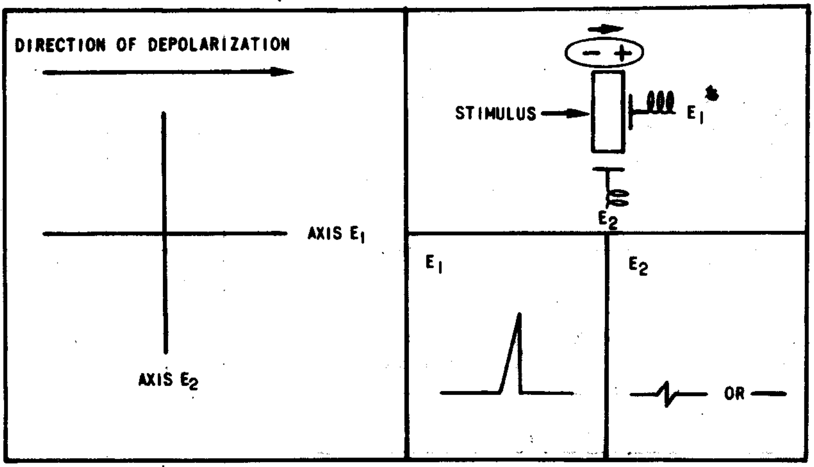


Fig. 1-7 The relationship between the lead axis and the magnitude of the deflections recorded by unipolar leads. The axis of E_1 is parallel to the direction of depolarization, which results in a large deflection. The E_2 axis is perpendicular to the direction of current flow. Either no deflection or a small diphasic deflection is recorded by this lead.

RELATIONSHIP BETWEEN THE LEAD AXIS AND THE MAGNITUDE OF DEFLECTIONS RECORDED BY UNIPOLAR LEADS (FIG. 1-7)

The amplitude of a deflection is maximal when the direction of electrical forces is parallel to the axis of the lead. As the angle between the two decreases from a straight angle to a right angle, the amplitude of the deflection becomes smaller. When the flow of electrical forces is perpendicular to the axis of a lead, no significant deflection is recorded.

EFFECT OF SIMULTANEOUS STIMULATION OF TWO MUSCLE STRIPS ON THE POTENTIAL VARIATIONS OF UNIPOLAR LEADS (FIGS. 1-8, 1-9)

When excitation spreads simultaneously in the same direction through two identical muscle strips lying end to end, the potentials recorded by an exploring electrode placed at the outer end of the muscle fibers will be greater than that inscribed by each muscle strip alone.

When excitation spreads simultaneously in opposite directions through two identical muscle strips lying end to end, the potentials will tend to neutralize each other. However, an exploring electrode placed at the epicardial end of the second muscle strip will record a small upright deflection because of its proximity to the positive charge of the equivalent dipole traversing the adjacent strip. The amplitude of the deflection is lower than it would have been if the potentials in the second muscle strip had not been opposed by those produced in the first.

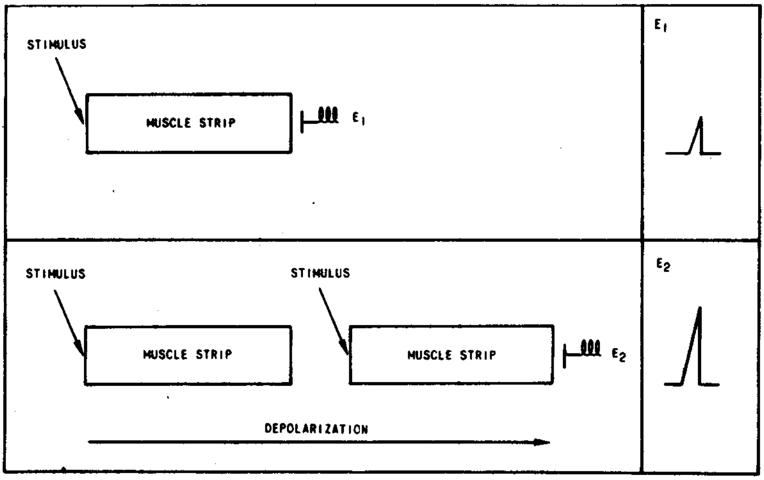


Fig. 1-8 Simultaneous stimulation of two muscle strips in the same direction results in a larger deflection than would be recorded during the depolarization of a single muscle fiber.

INTRINSIC DEFLECTION (FIG. 1-10)

The *intrinsic deflection* is the deflection that signifies activation of muscle directly beneath the exploring electrode of a unipolar lead. All deflections preceding or following the intrinsic deflection are called *extrinsic deflections*.

FACTORS AFFECTING THE PROCESSES OF DEPOLARIZATION AND REPOLARIZATION (FIG. 1-11)

Effects of a Change in the Speed or Direction of Depolarization on the Direction of Repolarization

A change in the direction of repolarization may be secondary to a reduction in conduction velocity. For example, if a conduction defect is present in a

Fig. 1-9 Simultaneous stimulation of two muscle strips in opposite directions results in a small positive deflection recorded by exploring lead E. Explained in text.