Basic Knowledge of Electrocardiogram (ECG)

51

Rui Zeng

51.1 Section 1: The First Sight of ECG

This is a normal standard 12-leads ECG (Fig. 51.1). What can you see when you get a first sight of this ECG?

First, you will find that there are a lot of square boxes; Second, you will find that there are many confusing waves; Finally, you may also find that there are some Roman numerals(I, II, III) as well as some combinations of letters and numbers (aVR, aVL, aVF, V_1, V_2, V_3, V_4, V_5, V_6).

Therefore, in order to fully appreciate the world of ECG, we first need to accomplish some preparation, in other words, to get familiar with ECG. Let's start with the boxes.

51.1.1 What's the Connotation of the Boxes?

All the boxes are squares with 1 mm on a side. The horizontal line of the boxes (horizontal ordinate) represents time. The length of time in each box can vary, depending on the constant speed of the graph paper. Normally when the graph paper moves at a constant speed of 25 mm/s, one box represents 0.04 s (40 ms); when the graph paper moves at a constant speed of 50 mm/s, then one small box represents 0.02 s (20 ms), and the rest can be done in the same fashion. The vertical line of the box (vertical ordinate), otherwise, represents voltage, 0.1 mV per small box normally (Fig. 51.2).

Every 25 boxes (5 × 5) contribute to a large box, so the large box is also a square, each of which represents 0.2 s (200 ms) on the horizontal ordinate and 0.5 mV on the vertical ordinate (Fig. 51.2).

This chapter is reprinted with permission from: Rui Zeng, Dingke Wen, Zhanhao Su et al, Basic Knowledge of ECG. In the book: Graphics-sequenced interpretation of ECG. ISBN: 978-981-287-953-0. Springer, 2016.

R. Zeng (✉)
Department of Cardiology, Sichuan University, Chengdu, China

51.1.2 What Are the Confusing Waves?

After boxes, we came to see the confusing waves. Before we explain the waves, we should review some basic cardiac electrophysiology.

The electrical impulses is derived from a special pacemaking area in the right atrium called sinoatrial (SA) node and then triggers the contraction of heart in course of its gradual conduction. Figure 51.3 shows the whole process of how the impulse is produced by the SA node and spread to the entire heart. The impulse would first move through right and left atrium, then reach the atrioventricular (AV) node through the conduction of internodal pathways. After the impulse having reached the AV node, the depolarization would be delayed for a while. Finally the impulse moves to stimulate the ventricular muscle through the bundles of His and the left and right bundle branches. It's noteworthy that the SA node has no stable resting potential and it has automaticity, meaning it possess the feature of automatic depolarization and repolarization thus acting as the pacemaker of the heart. Normally, the cardiac muscles, conduction system aside, are unable to depolarize automatically, they can only be stimulated by the impulse from the other part of the heart.

51.1.2.1 The Depolarization and Repolarization of Heart

When at resting state, for a cardiac muscle cell specifically, the positively charged ions are located at the outer side of the cell membrane and the negatively charged ions are located at the inner side of the cell membrane, therefore rendering the cell at a state of equilibrium described as positive outside and negative inside or polarized (Fig. 51.4a). When the cell membrane is stimulated by the outer electric activity, the negatively charged ions move inward, to alter the state to negative outside and positive inside. This process is called depolarization (Fig. 51.4b). At the recovery phase of cardiac muscle cells, the positively charged ions, again, move back to the outside of the cell membrane, and the negatively charged ions move to the inside. Thereby the cell returns to a

© Springer Nature Singapore Pte Ltd. and People's Medical Publishing House 2020

X.-H. Wan, R. Zeng (eds.), *Handbook of Clinical Diagnostics*, https://doi.org/10.1007/978-981-13-7677-1_51

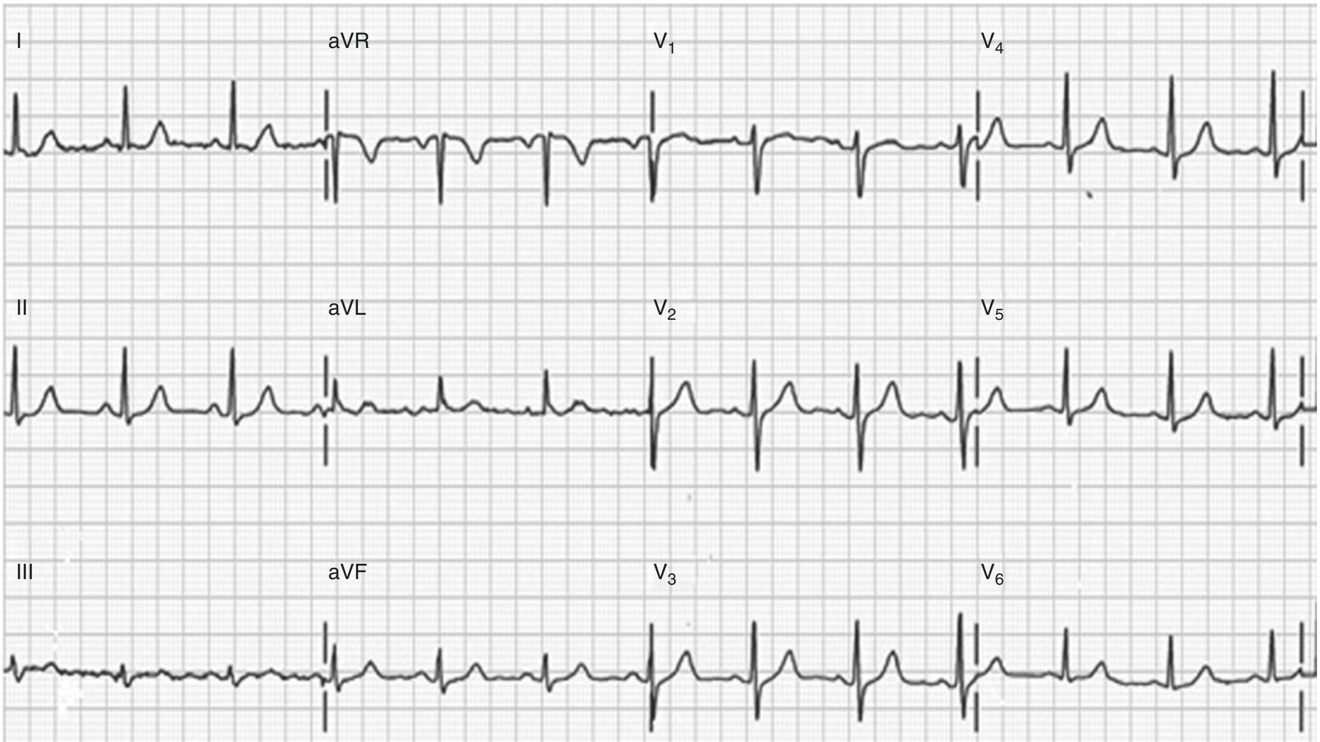


Fig. 51.1 Normal standard 12-leads ECG

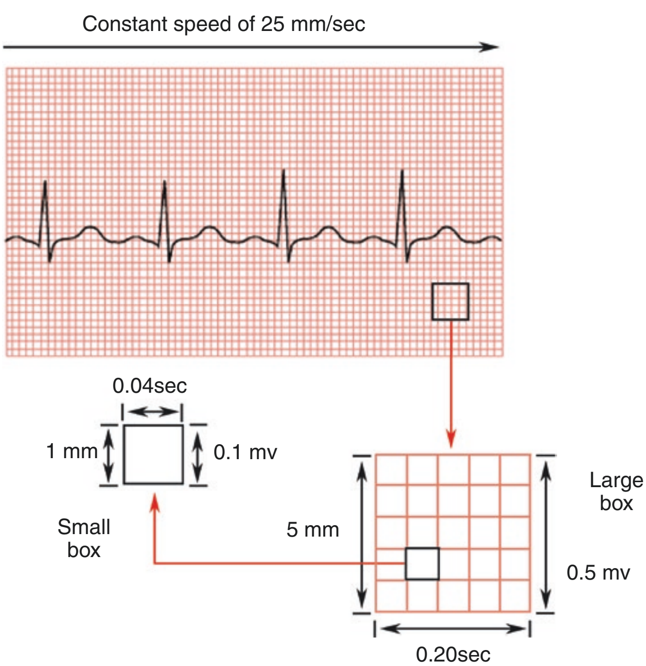


Fig. 51.2 The connotation of the boxes at 25 mm/s paper speed

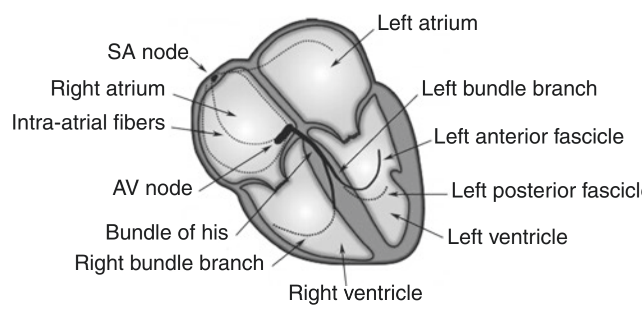


Fig. 51.3 Cardiac electrical conduction

state of outward whereas the positively charged ions move electrical equilibrium. This process is called repolarization (Fig. 51.4c). When the depolarization wave moves toward the electrodes, the galvo-recorder would detect and record a wave that is upward (positive) (Fig. 51.5a). When the depolarization wave moves away from the electrodes, the galvo-recorder would record a downward (negative) wave (Fig. 51.5b). And when the depolarization wave has some distance from the location of electrodes, a small deflection would be recorded (Fig. 51.5c); that is one of the reasons for low voltage occurrence in the ECG.

51.1.2.2 Resting Potential of Myocardial Cell

The resting potential of cardiac muscle cell is the potential difference between the inside and outside of the cell membrane when the cardiac muscle cell is not stimulated by the outside electrical activities (at the resting state). The theory can be explained as follows: At resting state, the concentration of K^+ inside the cell is 30 times higher than that of the outside (the concentration of Na^+ outside the cell is 30 times

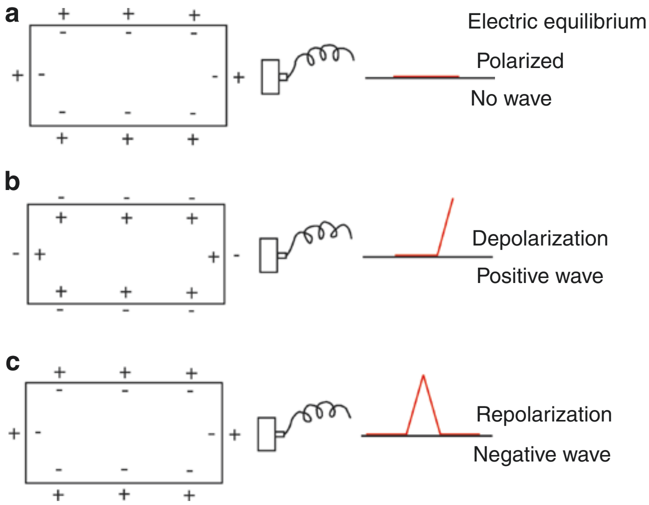


Fig. 51.4 Polarization, depolarization and repolarization of cardiac muscle cell

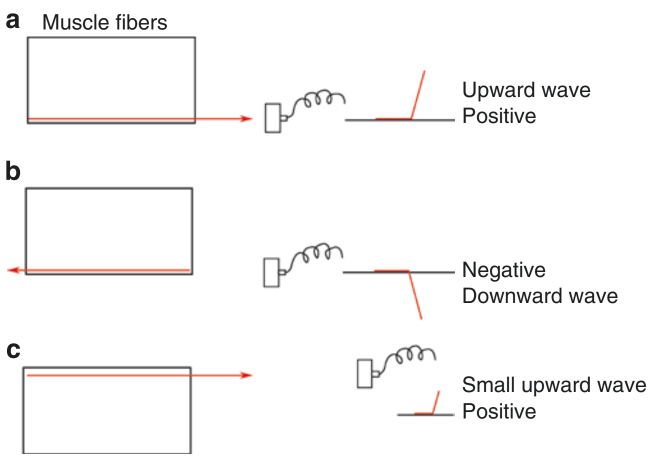


Fig. 51.5 Relationship between current flow direction and ECG wave pattern

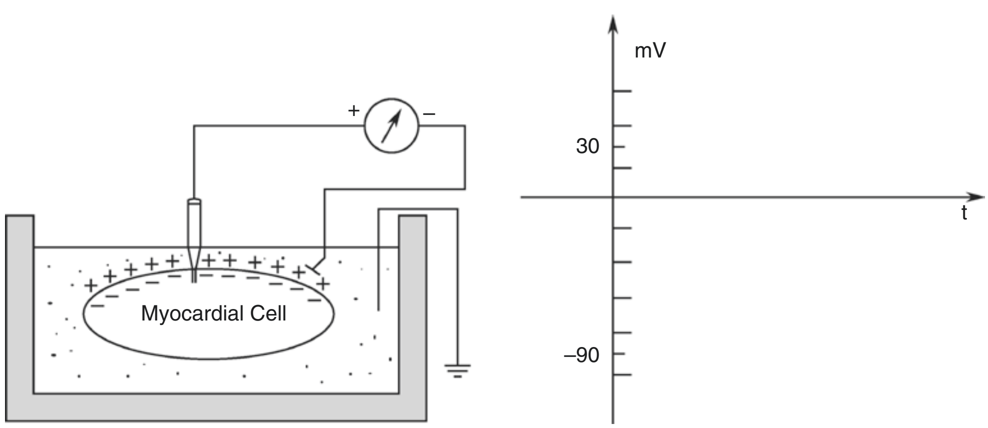
higher than that of the inside). In addition, the cell membrane has a relatively high permeability to K^+, and a relatively low permeability to Na^+ and organic negatively charged ions A^-. As a result, K^+ could diffuse from inside of the membrane to the outside under the concentration difference (concentration gradient) whereas the negatively charged ions A^- could not diffuse with K^+ in the opposite direction. With the process of K^+ moving out, the membrane would slowly form a potential difference which is negative inside and positive outside. Such potential difference would slow down the process of K^+ further moving out, until reaching a point when the potential difference and the concentration difference of K^+ balance out. Then the moving stops and this potential difference between the inside and outside of the membrane is called the resting potential (Fig. 51.6). Normally, the resting potential of cardiac muscle cell is −90 mV.

51.1.2.3 Action Potential of Cardiac Muscle Cell

If the cell is stimulated properly on the basis of resting potential, a rapid and transient fluctuation of the membrane potential will be triggered. Such fluctuation in the membrane is called action potential. Action potential is the sign of cardiac excitation.

Action potential of cardiac muscle cell can be divided into four phases (Fig. 51.7) as phase 0, phase1, phase2, and phase 3 according to the change of potential. The mechanism is as follows: when the cardiac cell receives a certain level of stimuli, the stimuli would trigger the opening of Na^+ channel in the cell membrane and increase of Na^+ inflow. Under the dual effect of both the electric gradient and the concentration gradient, Na^+ move inside the cell membrane rapidly and result in a rapid increase of potential inside which is higher than the outside (+30 mV). The cell membrane is then at a positive inside and negative outside

Fig. 51.6 Resting potential of cardiac muscle cells



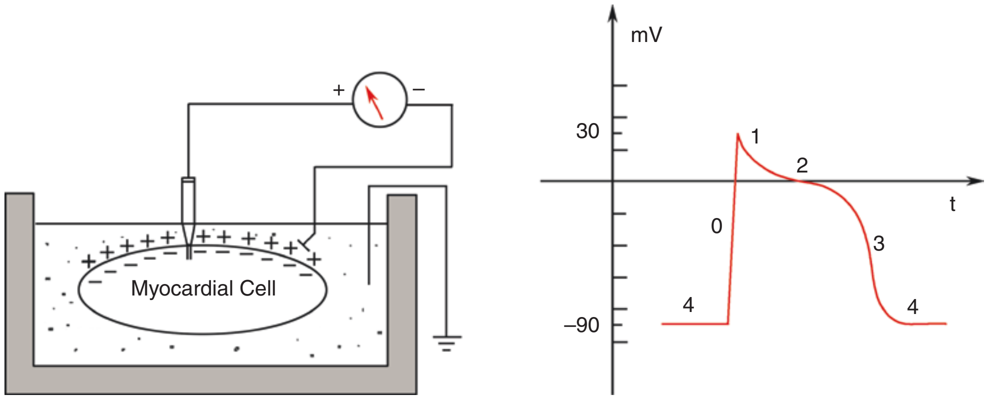


Fig. 51.7 Action potential of cardiac muscle cells

depolarized state. This process is the phase 0 of action potential. Na^+ channel is fast channel, activation and inactivation both happen in very short time, and when the cell depolarization reaches a peak, the potential inside will decline with the closing and inactivation of Na^+ channel, that is, the repolarization process of cardiac muscle. The repolarization process is rather slow, including Phase 1, Phase 2, and Phase 3. At phase 1, the cause for action potential waveform is the outflow of K^+; The waveform at phase 2 is relatively flattened so it is called the plateau phase or the slow recovery state, the mechanism of this plateau is mainly the relatively balanced state of outflow (K^+) and inflow (Ca^{2+}) of ions; The action waveform of phase 3 is rather steep. With the inactivation of Ca^{2+} channel and massive opening of K^+ channel, the process of repolarization accelerates apparently (the rapid recovery phase), and eventually recover to the previous negative inside and positive outside state, otherwise, the resting state.

51.1.2.4 Conduction of Action Potential

The action potential could travel around the cell without attenuation, which is a very important feature. When a spot of cell is stimulated and produces impulse, this part of the cell membrane presents a depolarization state that is "positive inside and negative outside," whereas the adjacent cell membrane presents a polarized state that is "negative inside and positive outside," and the potential difference occurs between them (Fig. 51.8). The potential difference renders "local current" between the two parts. When the local current begins to move, it results in the elevation of membrane potential in the adjacent cell membrane (the potential difference between the inside and outside of the membrane decreased). When the membrane potential reaches the threshold potential, it will excite the adjacent part to form action potential. In such case, one part of excitation in the membrane can travel through the whole cell membrane by the local current, producing new action potential successively until the whole cardiac cell is excited.

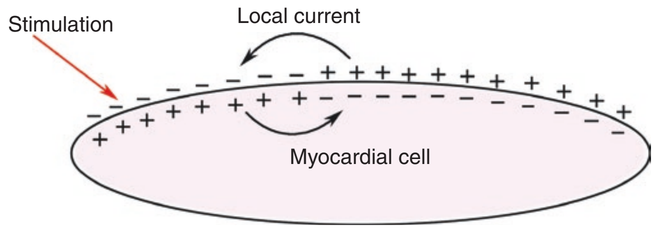


Fig. 51.8 Conduction of action potentials

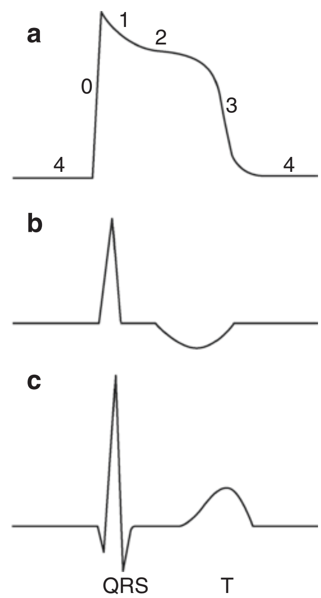


Fig. 51.9 Action potential of cardiac muscle cell and corresponding waveform. (**a**) Inner cell potential changes in one single cell, (**b**) Outer cell potential changes in one single cell, (**c**) The waveform of ECG is the potential changes of all cardiac muscle cells

51.1.2.5 Relationships of Depolarization, Repolarization and Waveforms on ECG

The recording of action potential is actually the recording of inner cell potential changes during the process of depolarization and repolarization in one single cell (Fig. 51.9a); What is recorded in the Fig. 51.9b is the outer cell potential changes of one single cell during the process of depolarization and repolarization; The waveform of ECG is the potential changes of the whole heart (all cardiac muscle cells) during the process of depolarization and repolarization.

51.1.3 Roman Numerals and the Meaning of Combinations of Characters and Numerals

51.1.3.1 The Conventional 12-Leads

The Roman numerals (I, II and III) in ECG, and several combinations of characters and numerals (aVR, aVL, aVF, V_1, V_2, V_3, V_4, V_5, V_6) represent the leads on ECG. It consists of three standard leads (I, II and III), three augmented leads (aVR, aVL, aVF) and six chest leads (V_1, V_2, V_3, V_4, V_5, V_6).

Standard leads, or bipolar limb leads (Fig. 51.10):

- First standard lead, or Lead I, in which left upper limb is connected to positive electrode and right upper limb connected to negative electrode.
- Second standard lead, or Lead II, in which left lower limb is connected to positive electrode and right upper limb connected to negative electrode.
- Third standard lead, or Lead III, in which left lower limb is connected to positive electrode and left upper limb connected to negative electrode.

Augmented unipolar limb leads (Fig. 51.11):

- Augmented right upper limb lead, or Lead aVR, in which electrodes are placed on right upper limb.
- Augmented left upper limb lead, or Lead aVL, in which electrodes are placed on left upper limb.
- Augmented left lower limb lead, or Lead aVF, in which electrodes are placed on left lower limb.

Chest leads: As known as V leads, are also unipolar leads. (Fig. 51.12):

- Lead V_1: Electrode is placed in the fourth intercostal space to the right of the sternum.
- Lead V_2: Electrode is placed in the fourth intercostal space to the left of the sternum.

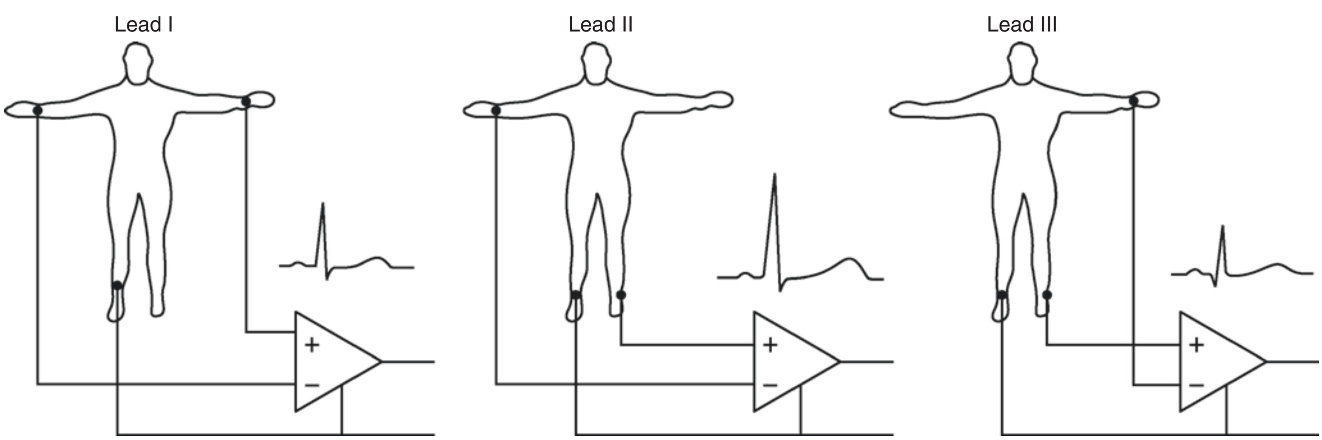


Fig. 51.10 Electrode placement of standard limb leads

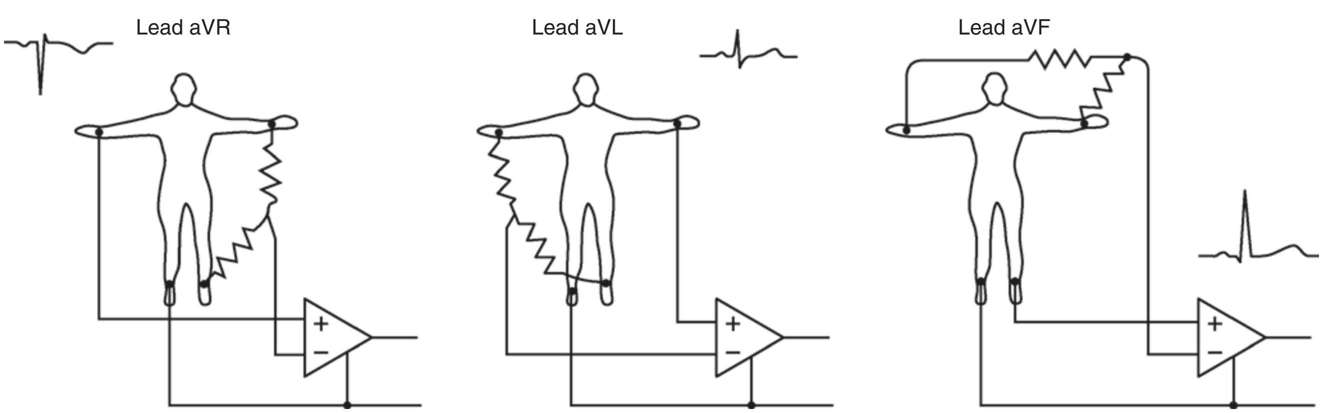


Fig. 51.11 Electrode placement of augmented unipolar limb leads

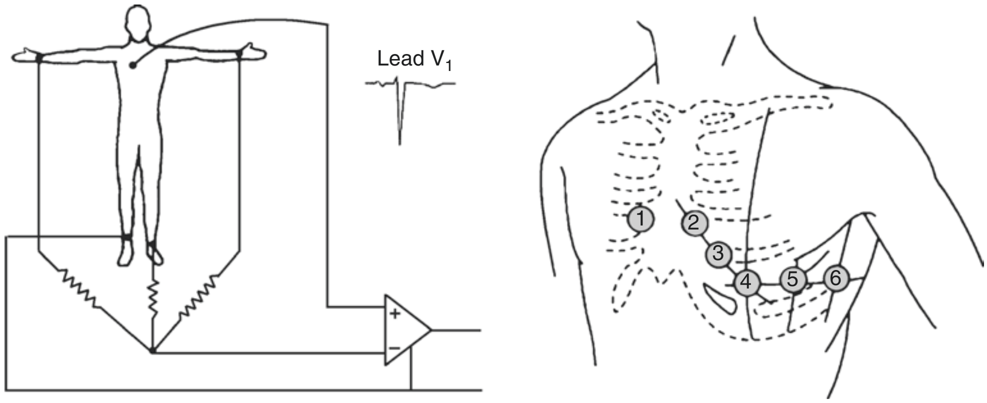


Fig. 51.12 Electrode placement of chest leads

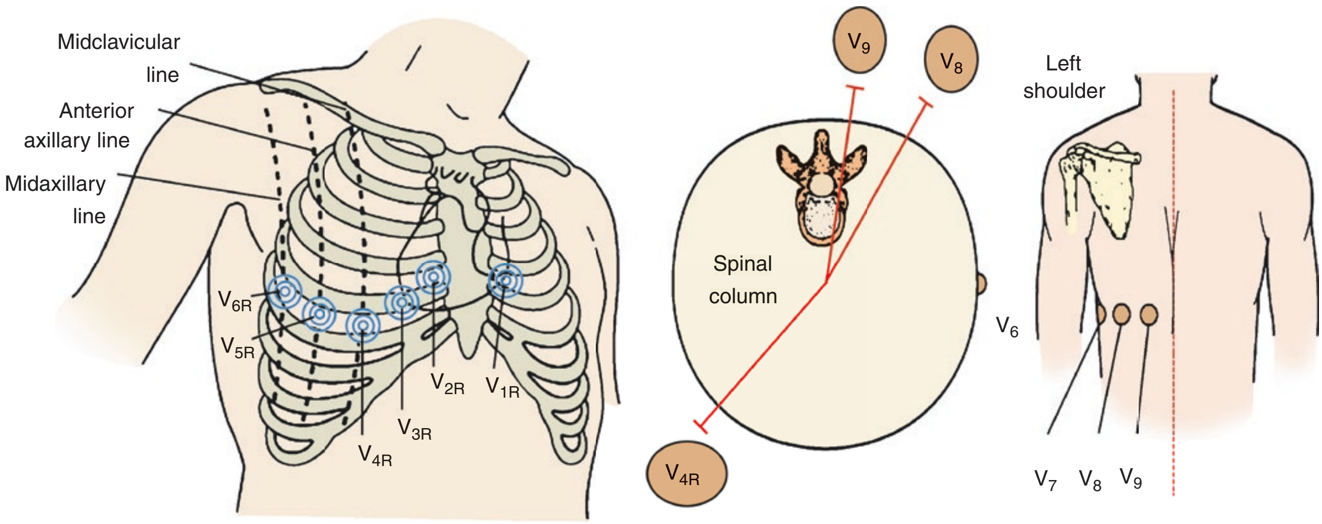


Fig. 51.13 Electrode placement of right-sided chest leads and posterior leads

- Lead V_3: Electrode is placed in the midpoint between V_2 and V_4.
- Lead V_4: Electrode is placed in the fifth intercostal space in the midclavicular line.
- Lead V_5: Electrode is placed at the intersection of left anterior axillary line and V_4 electrode level.
- Lead V_6: Electrode is placed at the intersection of left middle axillary line and V_4 electrode level.

51.1.3.2 Other Special Leads

Right-Sided Chest Leads (Fig. 51.13)

Chest Leads V_1 to V_6 are placed at the same position on the right chest, and thus labeled as V_{1R} to V_{6R}. Right-sided chest leads are mainly used to make clinical diagnosis of right ventricular hypertrophy, dextrocardia and right ventricular infarction.

Posterior Leads (Fig. 51.13)

Electrodes are placed at intersections of V_4 level and posterior axillary line, left scapular line and left of spinal column, with each labeled as posterior leads V_7, V_8 and V_9, respectively.

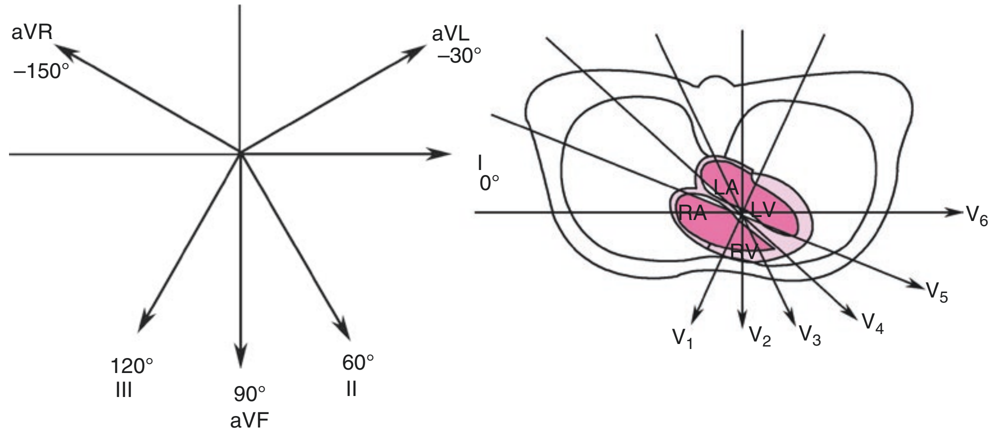
An 18-Leads ECG

In certain clinical situation, an 18-leads ECG will be adopted, including three right-sided chest leads (V_{3R}, V_{4R} and V_{5R}) and three posterior leads (V_7, V_8 and V_9) besides the conventional 12 leads.

51.1.3.3 The Axis

The axis of a certain lead is defined as an imaginary line extending from negative electrode to positive electrode of the lead. Usually, an arrowhead is used to represent the positive electrode. Axes are mainly categorized as limb leads (Fig. 51.14) and chest leads (Fig. 51.14). For example, in lead I, positive electrode is placed on left upper limb and negative electrode on right upper limb. Therefore, the axis for Lead I starts from right upper limb to left upper limb (from negative to positive), and the direction is shown in Fig. 51.14. In lead II, positive electrode is placed on left lower limb and negative electrode on right upper limb. Therefore, the axis for Lead II starts from right upper limb to left lower limb (from negative to positive), and the direction is shown in Fig. 51.14. Following the method discussed

Fig. 51.14 Hexaxial reference system and cardiac axes in horizontal plane



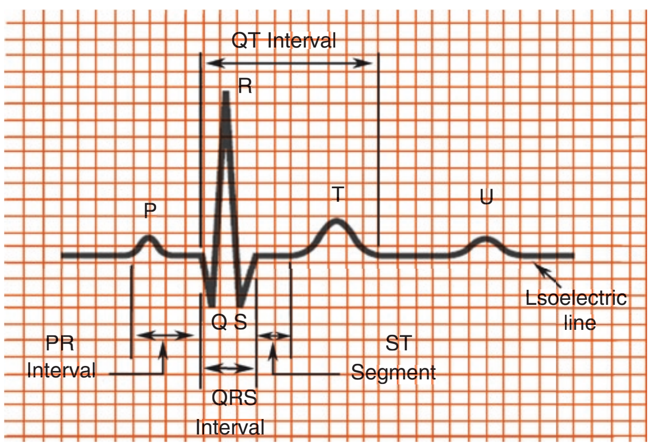


Fig. 51.15 Waves and segments in ECG

above, you could try to work out directions of the rest of axes by yourself.

Axes for limb leads are in cardiac frontal plane, indicating distribution of vectors in the frontal plane and is called hexaxial reference system. Axes of chest leads are in cardiac horizontal plane, indicating distribution of vectors in the horizontal plane.

51.2 Section 2: Configuration and Representation of Waves and Segments in ECG

Electrical impulse discharged from sinoatrial node activates atria and ventricle and sequentially causes depolarization and repolarization, producing a series of potential differences on the body surface, which are recorded as ECG (Fig. 51.15). Waves in ECG are labeled as P, Q, R, S, T and U, all of which were defined during early ECG development. Among all the waves, P, T and U waves are single deflection, while Q, R and S are grouped together to form QRS complex.

51.2.1 P Wave

P wave is the first deflection in a group of waves. It represents left and right atrial depolarization. P wave is upright (including rounded, notched, double-peaked, tall-peaked), or may have biphasic and inverted morphology (Fig. 51.16).

51.2.2 PR Interval

PR Interval refers to the interval from the beginning of P wave to the beginning of QRS Complex, and measures the time during which depolarization begins in atrium and travels through internodal pathways, atrioventricular junction, bundle of His, left and right bundle branch and their fascicles and Purkinje fibers to depolarize ventricles.

51.2.3 QRS Complex

QRS complex is a group of deflections that has greater amplitude and consists of Q, R and S waves. It represents depolarization in left and right ventricles. A typical QRS complex includes three consecutive deflections. The first negative deflection is called Q wave, the first positive deflection is called R wave and the negative deflection after R wave is called S wave, altogether comprise the QRS complex.

Occasionally, a positive deflection follows S wave and thus is called R′ wave (R-prime). If R′ wave occurs, then a negative deflection follows, and it's called S′ wave. If its amplitude is less than 0.5mv, then the wave is represented by lowercase letters q, r and s. If its amplitude is greater than or equal to 0.5mv, then the wave is represented by capital letters Q, R and S. Common configurations of the QRS complex are in Fig. 51.17.

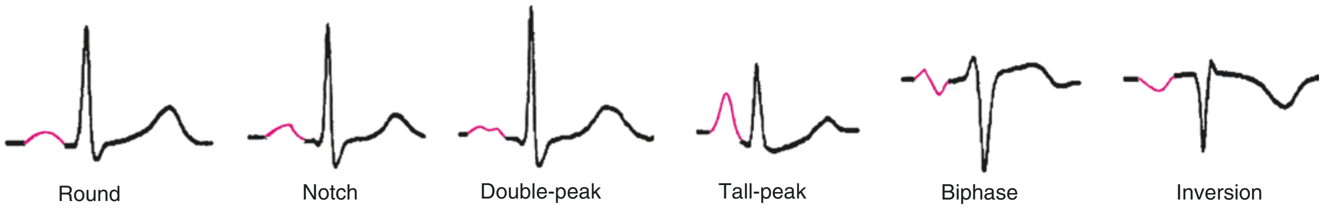


Fig. 51.16 Common configuration of P wave

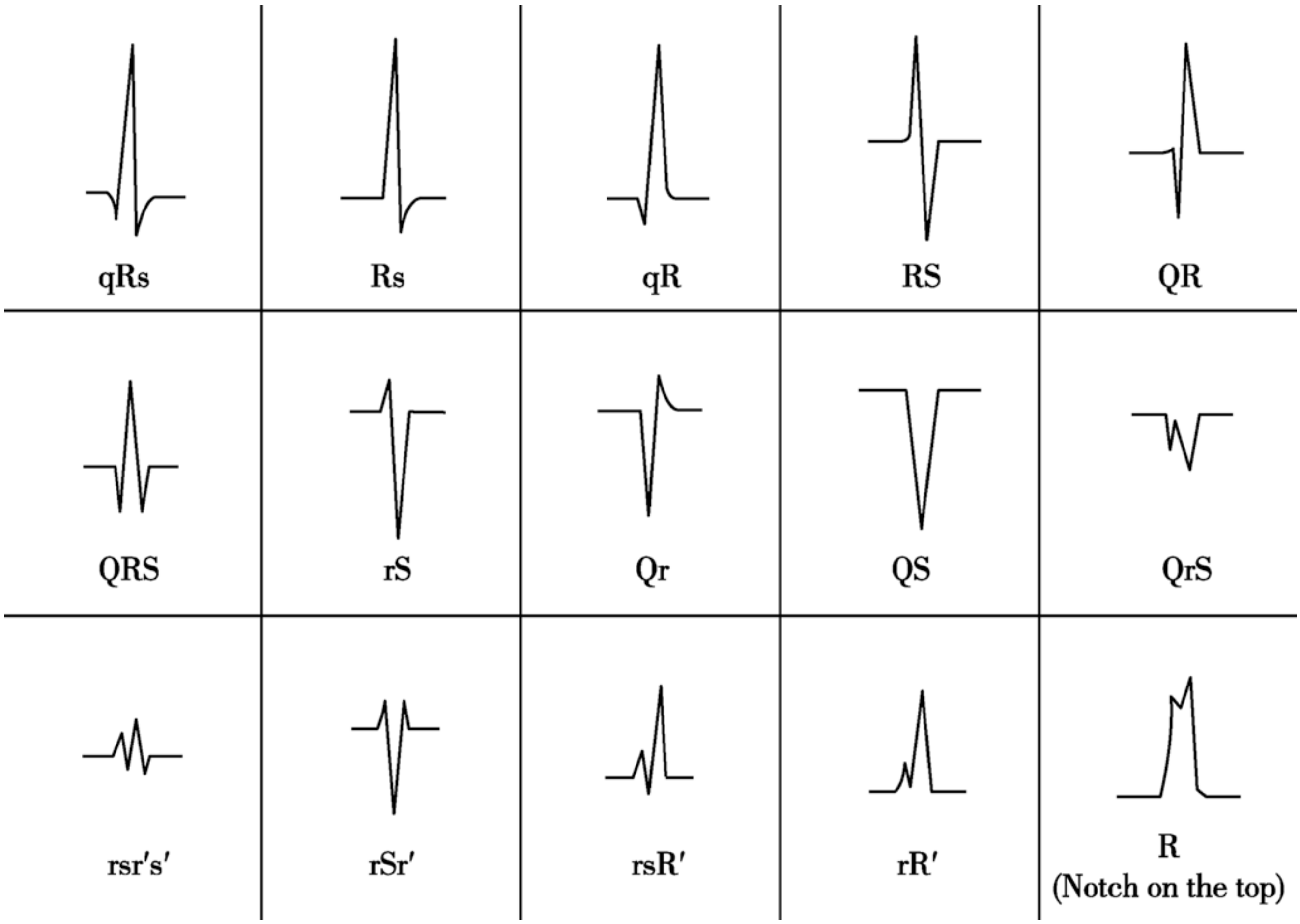


Fig. 51.17 Common configurations of the QRS complex

51.2.4 ST Segment

ST segment is the line that connects the end of QRS complex and the beginning of T wave, representing the slow process of ventricular depolarization. See Fig. 51.18 for the common variants of ST segment.

51.2.5 T Wave

T wave is a deflection that follows ST segment and represents rapid repolarization across the ventricle. Like P wave, T wave has multiple variants: upright, notched, flattening, positive-negative biphasic, negative-positive biphasic and inverted. See Fig. 51.19.

51.2.6 QT Interval

QT interval measures the time from the beginning of QRS complex to the end of T wave, representing the whole process of ventricular depolarization and repolarization. QT interval is frequently affected by heart rate. When heart rate is between 60 and 100 bpm, duration of QT interval is

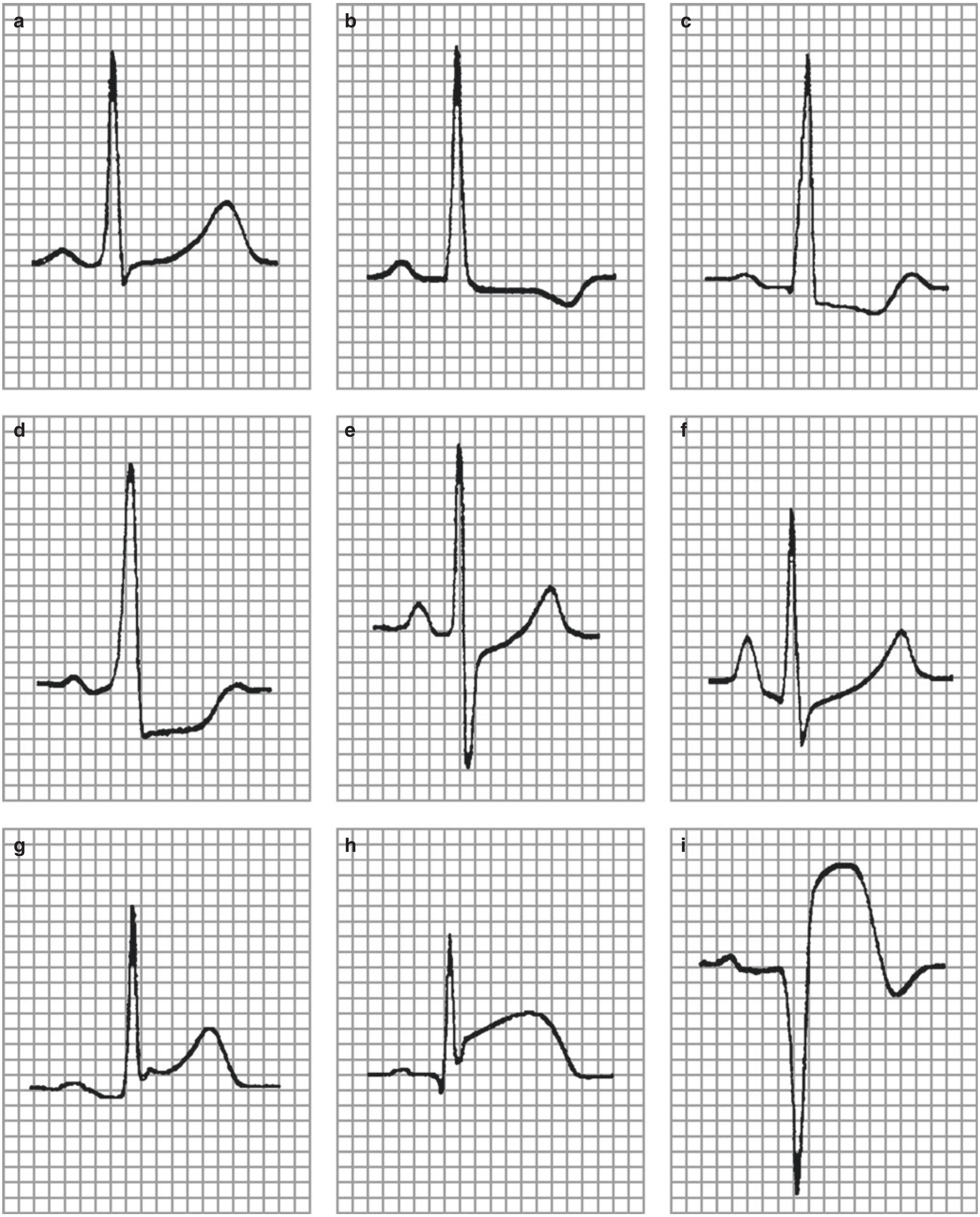


Fig. 51.18 Common deviations of ST Segment. (**a**) Normal ST segment, (**b**) Horizontal ST depression, (**c**) Down-sloping ST depression, (**d**) Horizontal ST depression, (**e**) J Point depression (J point is the point between the end of QRS complex and the beginning of ST segment), (**f**) Up-sloping ST depression, (**g**) Concave ST elevation, (**h**) Convex ST elevation, (**i**) Convex ST elevation

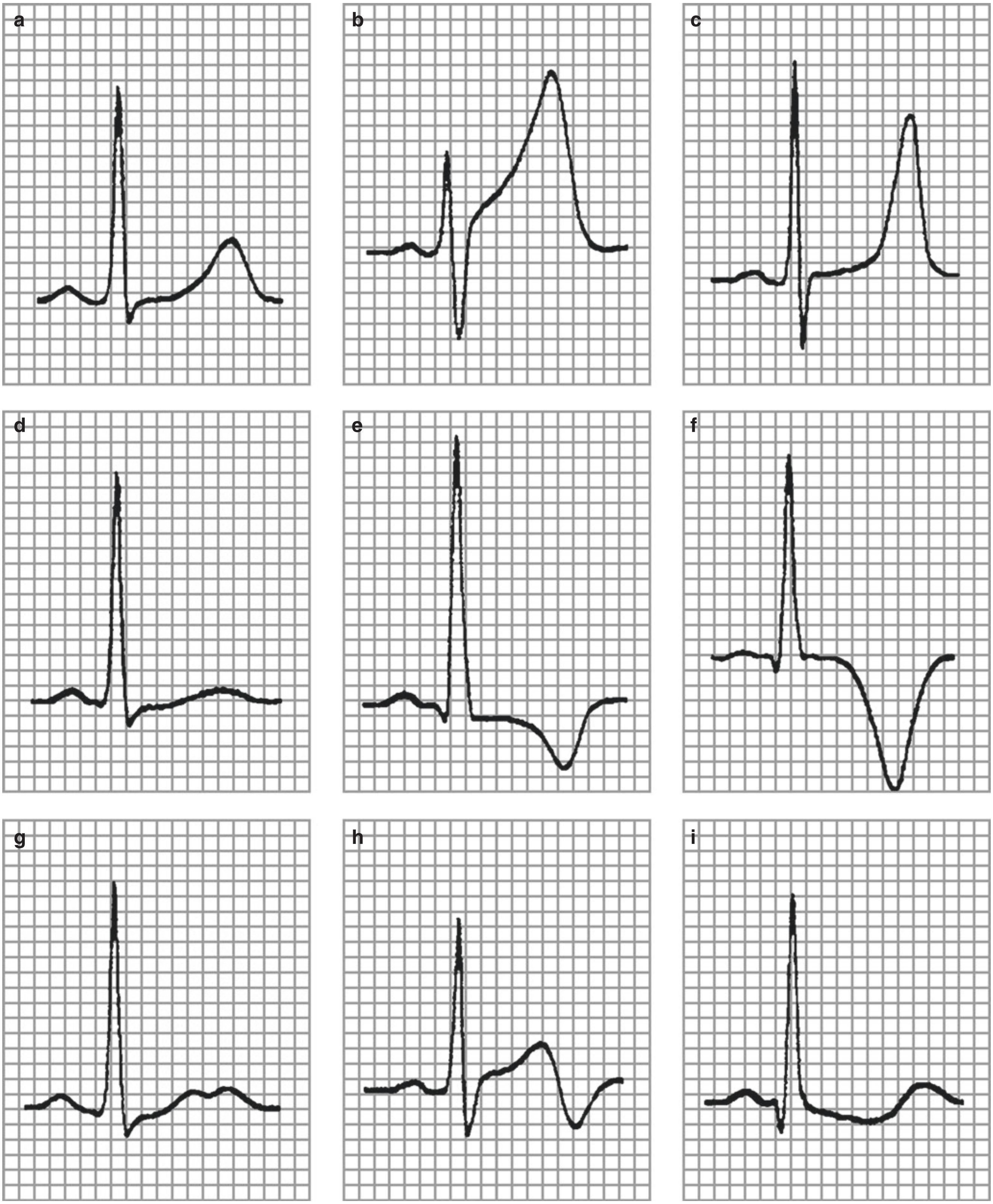


Fig. 51.19 Common deviations of T WAVE. (**a**) Normal T wave, (**b**) Peaked T wave, (**c**) Tall peaked T wave, (**d**) Flattening T wave, (**e**) Asymmetrically inverted T wave, (**f**) Symmetrically inverted T wave, (**g**) "Camel Hump" T wave, (**h**) Positive-negative biphasic T wave, (**i**) Negative-positive biphasic T wave

0.32–0.44 s. To eliminate its effect on QT interval, we can calculate a corrected value of QT interval (QTc) by the following equation: $QTc = QT/\sqrt{RR}$, which represents the QT interval at 60 bpm.

51.2.7 U Wave

U wave is a small deflection that follows T wave, and its generating mechanism remains unknown. More details will be discussed later.