Some Considerations on Repolarization Process of Ventricular Muscle, Represented by the T Wave in the ECG.

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It is well known that the T wave in the ECG. appears synchronously with the slow repolarization phase in the action potential of cardiac muscle(1–3). Concerning its polarity, i.e. the direction of galvanometer deflection, many observations have been performed without confident results (4). This may mainly be due to the fact that the T wave is very unstable in the usual experimental procedure.

For the interpretation of concordant polarity of the R and T waves in the usual electrocardiographic records, the concept of ventricular gradient is introduced by WILSON et al. Some workers are likely of opinion that the difference in the duration of action potential between basal and apical teil of ventricular muscle is a determining factor (5). Others offer the difference of recovery process in the epicardial and endocardial surface, caused by the temperature gradient (6,11). The difference between basal and apical region, however, was not recognized in the tortoise heart (7), and also it is undecided that the temperature gradient above-mentioned may exist in the cold blooded animal. The concept of ventricular gradient seems valid, but to interpret T wave on the basis of electrophysiological observations, more experiments are necessary.

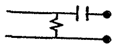
MATERIALS AND METHODS

An exposed heart of frog (*Rana nigromaculata*) or of toad was used *in situ*. The animal was pithed previously. Sometimes cats were lightly anaesthetized with pentobarbital, and the heart was punctured with needle electrode. The indifferent electrode was central terminal electrode of WILSON type, and the tip of which made of Ag-AgCl was placed in the subcutaneous tissue and fixed by the ligature. For an investigation of action potentials of ventricular muscle cell, the microelectrode of Ling and Gerard type was used as an exploring electrode. It was flexibly mounted on the preparation with micromanipulator after the method of WOODBURY et al. (8, 9). In the case of extracellular potential investigation, the monopolar needle electrode insulated to the tip was inserted into the preparation, or the cotton thread soaked with Ringer solution was in contact with heart surface.

The differential direct-coupled amplifier and double beam cathodray-oscilloscope were employed for recording.

EXPERIMENTAL RESULTS AND DISCUSSION

1. The configuration of the T wave.

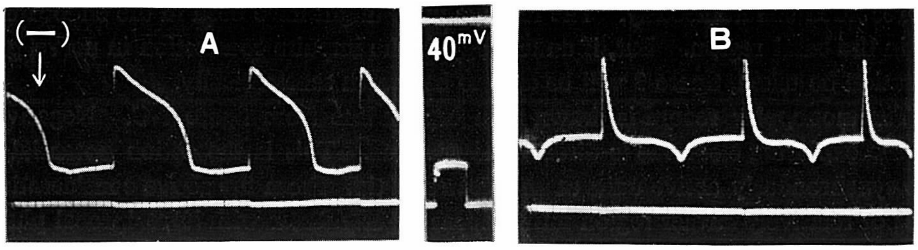
Fig. 1-A is a record obtained with the microelectrode. That the curve shows a time course of action potential of ventricular muscle cell is generally recognized (13). In this case, when the output/input potential is differentiated by a circuit as  , then the curve changes to fig. 1-B. Figure 1-C is an electrogram of the same preparation. Judging from the base line (resting potential could not be seen), the authors saw that the figure indicated that the electrode-tip was not intracellular but extracellular. In this case, it was also reasonable that the direction of the waves was inverted. The astonishing similarity of these two curves must be noted, and the action potential obtained by the extracellular lead, in the usual way, may be a differential form of the intracellular action potential.

The polarity of the waves was indicated in the figures. From the description in the textbook, one can consider that the potential change at the indifferent electrode is negligibly small and that electrograms taken by this method reflect the changes occurring at the exploring electrode. The initial deflection (corresponding R wave) in the figs. 1-B and 1-C may be passable, but the second one is not concordant with the first.

Figure 2 was obtained using the monopolar needle electrode. The tip of electrode was 0.2mm in diameter, and was thrusted into the ventricle at the anterior apical region, or placed on the surface. The muscle cells neighbouring the tip must be damaged by the insertion. In spite of this damage, action potentials resembling those obtained with microelectrode could be recorded for a short time after insertion (Fig. 2-A). With the time elapsed, the configuration changed gradually to that of fig. 2-A′. Those changes were also observed in the experiments of the cats (12). This is because of the fact, the authers think, that the muscle cells in the small region from which potential can be picked up, have a synchronous activity owing to their syncytial character. Those cell-group may be assumed as a functional unit.

Figure 2-B′ is a so-called surface electrogram obtained with the needle electrode. If the thrusted tip of electrode in the experiment of fig. 2-A′ were supposed to be in the electrically inactive intercellular tissue, the situation might be the same as the surface lead. In other words, the tip is in an inactive region and many active units are in its neighbourhood. Therefore, the similarity of the two figures is reasonable.

In those figures, the repolarization process is indicated as a biphasic wave. Here again, it must be considered that the electrode tip was surrounded by many electrically active units. The action potentials of those units situated near the neighbourhood of the tip could be picked up synchronously. The recorded potentials,



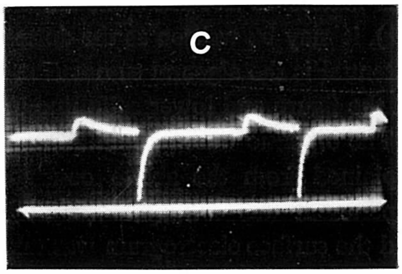
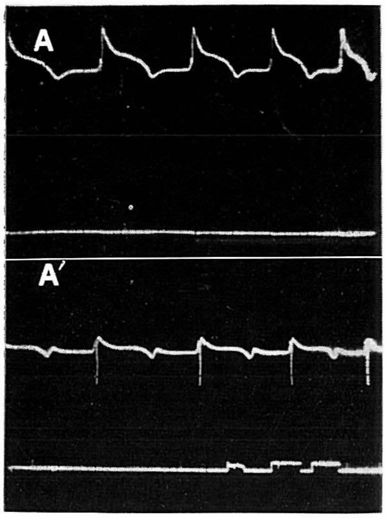


Fig. 1 Electrograms of frog's heart in situ. Downward deflection shows negativity of exploring electrode. A: obtained with microelectrode. B: differenciation of A. C: when the electrode was likely to be outside of the cell.
Marked amplitude, 40mV. Time was not marked on the baseline.



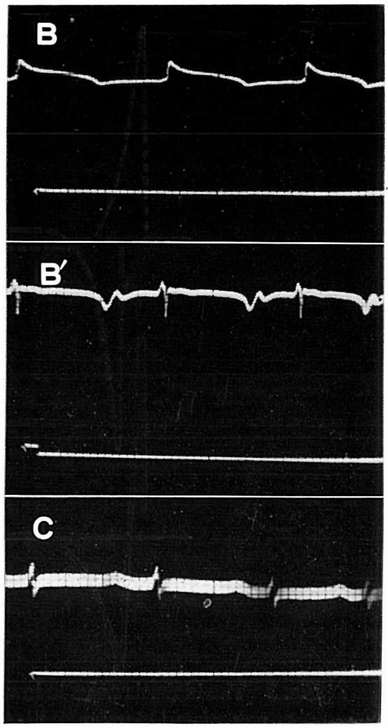


Fig. 2 Electrograms obtained with needle electrode. (see in the text) Arbitral amplification, and 1 second time marks.
A & B: immediately after heart punction.
A′ : 5 minutes later.
B′ : surface electrogram.
C. : from neighbouring tissue, may be considered as chest lead V_5.

however, are not these ones, but those resulted from relatively farther units might be recorded simultaneously. The relative units might have been in the endocardial or in the basal region. But, if an analogy to the impulse conduction in nerve preparation be taken, figure 3 will be able to be drawn schematically.

The monopolar record is drawn as a broken line from figure 1-C. Negativity of the exploring electrode is directed downwards. This is the action potential of the synchronously active units at the electrode tip. From the above consideration, that of relatively farther region must appear slightly faster with its reciprocal phase. The writers do not know the amplitude of the latter, but assuming the same value (11), it may be written as the dotted line in the figure. The practical record of the potential is the algebral summation of these two. This procedure can be performed on the figure and lower solid line in fig. 3 is obtained.

The biphasic waves at the repolarization period in figs. 2-A′ and 2-B′ can be well explained from the above considerations. To make this point surer, another experiment was attempted (Fig. 4). The exploring electrode was Ringer-thread and the surface electrogram was taken in the usual way described (Fig. 4-A). Then, the small amount of 1 molar KCl solution was given to the thread from a syringe. The electrogram changed in its configuration remarkedly (Fig. 4-B). This change,

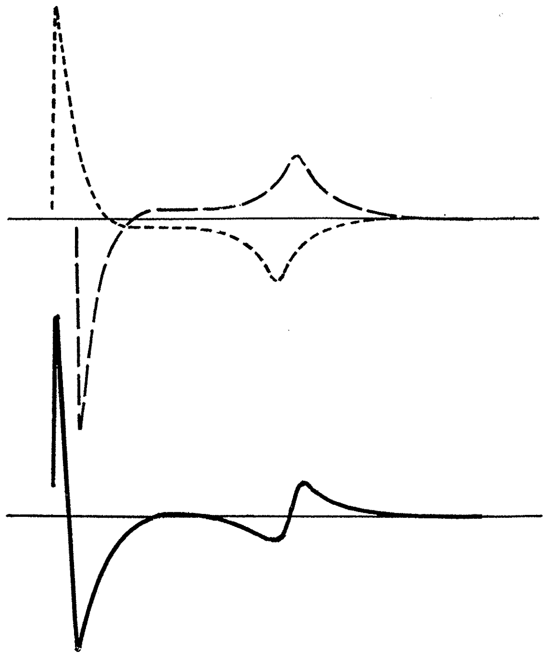


Fig. 3 The biphasic wave in lower curve can be assumed as algebraic sum of two potentials. One of which is that of synchronously active unit surrounding the exploring electrode (broken line), and the others of relative region are supposed as dotted line.

A

B

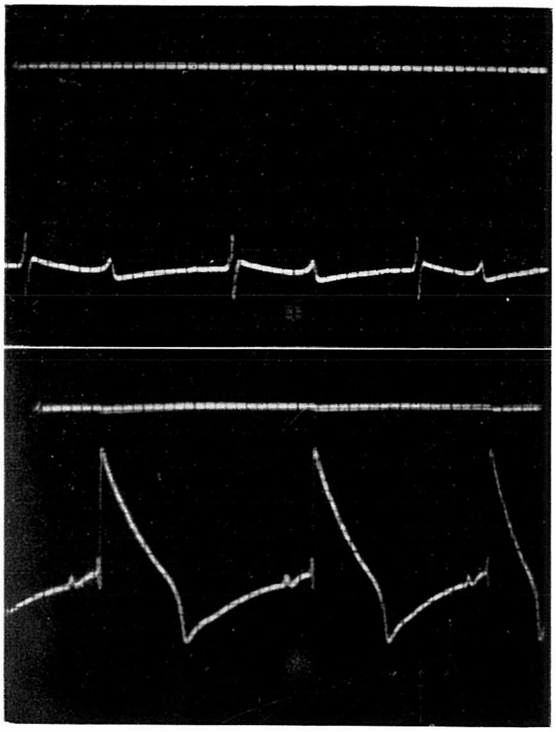


Fig. 4 Augmentation of the potential at the relative region. The unit near the exploring electrode was inactivated by the application of KCl.
A: the ECG. before the treatment, with the same amplification.

although observed tempolarily, may be attributable to the depolarizing action of the KCl; e.g. the previously active small region touching the thread was inactivated and did not contribute to the production of the electrogram. Schematically in this case, the dotted line in the figure 3 must be exaggerated, and the authors confine their interpretation comparing the figures. It was also recognized that the small deflection preceding the main one in figure 4-B has a positive polarity and/so reflects the potential change not occurring at the exploring electrode region. This is perhaps the P wave.

2. The upright T waves in the electrocardiogram. (ECG.)

In the clinical lead of ECG., the experimental condition is not so simple. (The conduction of electricity in the volume conductor is discussed in elsewhere). If the potential at the ventricular surface spreads electrotonically the T wave might have biphasic form from the above consideration, decreasing its amplitude according to the distance of the exploring electrode from the heart. But practically, this is not the case in the clinical lead.

It seems very reasonable, on the other hand, that the majority of the unit of the heart muscle cell must undergo repolarization during the same period of time, as they form the syncytium. In the near region of the heart, although decreased somewhat by the inversely directed potential, the summated potential resulted from this synchronous repolarization can be picked-up by the electrode. This potential may correspond the broken line in the figure 3; i.e. the potential change in the near region is augmented and the positive deflection for the production of T wave can be recorded. Why, however, the initial deflection can not be augmented likely? The conjecture may be possible that the slow wave is more distorted than the fast one in the volume conductor. But this explanation is unnecessary, because the initial deflection above-mentioned is not R wave but S one. And in the textbook or in many papers, distinct S wave can be seen accompanying the "upright" T wave in so-called chest lead, V_5.

Another important factor which affects the amplitude or polarity of T wave must be mentioned here. When the extracellular potential is a derivative of the intracellular, the rate of change in the latter determines the amplitude in the former. In other words, the faster the rate of repolarization of the cell is, i.e. the sharper the slope of descending curve in figure 1-A is, the more remarkable is the deflection

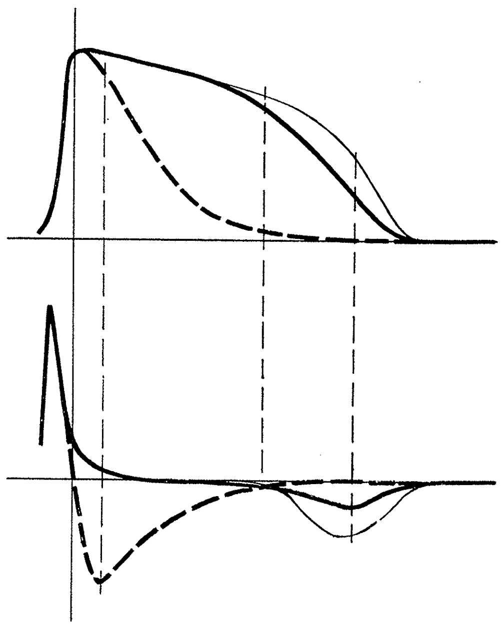


Fig. 5 Relationship between the change of repolarization process and recorded potential.
Upper curves: intracellular action potential.
Lower ones : assumed derivative form of the former, may be the practical record of extracellular lead.
Note the configuration of the latter.

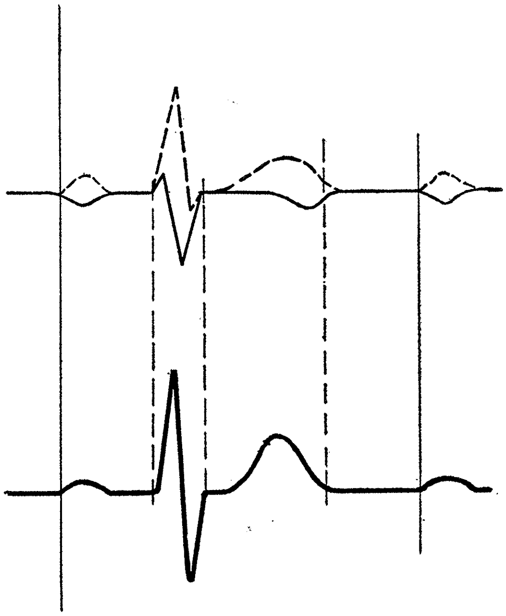


Fig. 6 Graphic interpretation of standard limb-lead. Upper curves were cited from the textbook, and lower one is the algebraic sum of the two. VR and VL are potential change at right and left arm respectively, and relative negativity of the left is directed downwards as described.

representing the T wave.

Many circumstances where the rate of repolarization of the cell membrane changes are known (13, 14). For example it becomes faster when the pulse rate increases. These relationship is indicated in the figure 5 diagrammaticaly, where the S-T displacement in the ECG. may be interpreted in the same way.

Lastly a few word is necessary for the interpretation of the standard limb-lead. The upper curves in figure 6 were cited from the textbook (15). The ordinate indicates the potential at the exploring electrode and its negativity is directed downwards as described. As for the polarity, let us assume that the VL is a standard. Then the VR must be directed oppositely, as drawn with broken line. The difference of these two is the practical electrocardiogram in lead I. This procedure can be done graphically, and the lower curve are obtained. Note the similarity of the curve to the well-known ECG., and the upright T wave is reasonable, because it is a common practice in the clinical lead (I) that the relative negativity at the left arm will cause the downward deflection.

3. Addendum.

In our experiments the amplifier was coupled directly, but the A. C. (or C-R) amplifier is mostly used in the clinical medicine. The established potentials may be distorted in its decreasing phase by the condenser discharge. This must not be forgotten for the interpretation of the minute changes of the recorded waves.

SUMMARY

The electrogram of the frog's ventricle was recorded with various methods, and the relationship between the repolarization process in the muscle cell and the "upright" T wave in the usual electrocardiogram was discussed.

1). The extracellulary recorded potential has a derivative form of the intracellular action potential, and the positively directed potential is the result for the repolarization phase.
2). The concept of ventricular gradient seems valid for the explanation of the upright T wave. But the relative region in this concept need not be so far as described by others.
3). The rate of repolarization was also one of the important factor in the discussion.

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