Project Report

Aim of the Project

Study and analyse the stimulation of the cardiac tissue through anode and cathode electrodes.

Theoretical Modeling

During the electrical stimulation of cardiac tissue, a pulse of current is sent to the stimulating electrode. An electrode that is collecting positive charge from a medium is called a cathode and an electrode that is transferring positive charge to the medium is called an anode.

(i) Stimulation of cardiac tissue through anode:

If the stimulating electrode is inside the cell, current from the electrode flows out through the membrane and thus, the inside of the membrane will be made more positive than the outside i.e., positive charge within the cell would increase and cause depolarization.
An anodic electrode just outside the cell will send positive current in through the membrane near the electrode and would thus lower the potential inside. This hyperpolarizes the membrane near the electrode.

Also, further away from the stimulation point will be a region where current flows out through the membrane, thus depolarizing the cell. This is the virtual cathode. In anode excitation, a strong anodal stimulus is applied that hyperpolarizes the tissue directly below the electrode but depolarizes the tissue at two virtual cathodes at some millimeters distance from the anode along the fiber direction.
However, the outward current is spread out over more membranes, so the current density and hence the depolarization is less than the hyperpolarization near the anode. A strong stimulus is necessary to produce enough depolarization at the virtual cathodes to excite propagating wave fronts.

Therefore, anode make excitation has a higher threshold than cathode make excitation, discussed later.
Thus, during stimulation of cardiac tissue through a small anode, the tissue under the electrode and in the direction perpendicular to the myocardial fibers is hyperpolarized, and adjacent tissue on each side of the anode parallel to the fiber direction is depolarized (Figs. 1 and 2).

If the tissue is refractory just before this stimulus pulse is turned on, the hyperpolarization during the stimulus causes the tissue to become excitable. Following the end of the stimulus pulse, the depolarization along the fiber direction interacts electrotonically with the excitable tissue, initiating an action potential (break excitation).

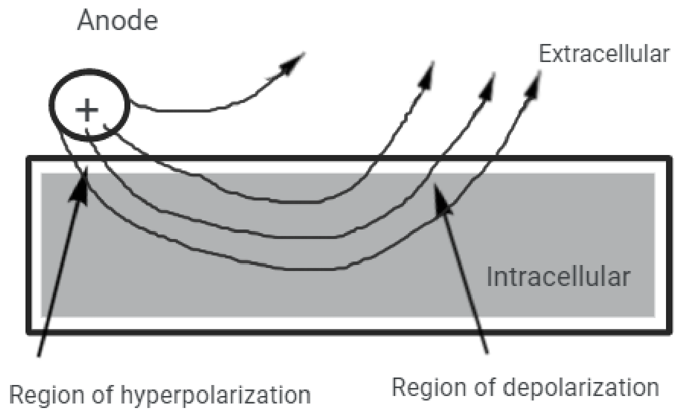

Figure 1. A schematic showing the fact that a region of hyperpolarization is located near a stimulating anode and a region of weaker depolarization further away.

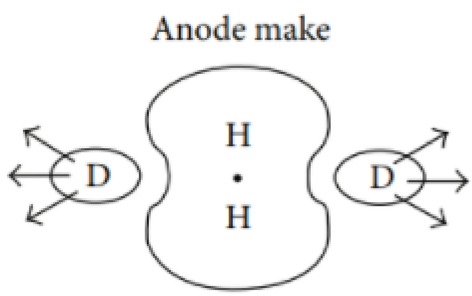

Figure 2. A schematic illustration of the anode make excitation.
Fiber direction is along the horizontal and the anode electrode is indicated by the dot.
D represents the region that is depolarized and H represents the region that is hyperpolarized.
Arrows denote the direction of propagation of the resulting action potential

Break excitation occurs after the stimulus is turned off and plays an important role in stimulating refractory tissue. There are two types of break excitation: cathode break and anode break.

Anode break excitation:

In anode break excitation, a strong anodal stimulus is applied when the tissue is refractory from the previous action potential. As soon as the stimulus is applied, the tissue under the anode is strongly hyperpolarized and made excitable, but the tissue at the virtual cathodes is depolarized and remains unexcitable. After the stimulus is turned off, depolarization at the virtual cathodes diffuses into the hyperpolarized tissue under the anode, exciting wave fronts that propagate perpendicular to the fiber direction.

The depolarization decays more slowly than the hyperpolarization. Anode break excitation thus has the highest threshold of the four mechanisms - anode make, cathode make, anode break and cathode break, because a strong stimulus is necessary to create enough depolarization to diffuse into excitable tissue and initiate a wave front (Fig. 3).

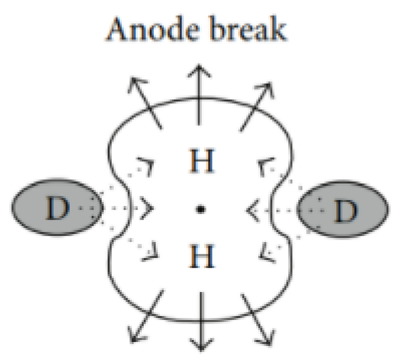

Figure 3. A schematic illustration of the anode break excitation.
Fiber direction is along the horizontal and the anode electrode is indicated by the dot.
D represents the region that is depolarized and H represents the region that is hyperpolarized.
Arrows denote the direction of propagation of the resulting action potential.

(ii) Stimulation of cardiac tissue through cathode:

The situation is reversed for a cathodic electrode. A cathodic electrode just outside the cell will collect the positive current coming from the membrane near the electrode. This depolarizes the tissue under the electrode. The depolarization under the cathode reaches a threshold, triggering a wavefront that propagates outward.

The excitation occurs soon after the start of the stimulus pulse. For weak stimuli, the wavefront originates from a point directly under the electrode, but for stronger stimuli it begins from a point farther from the electrode that depends on both the direction of propagation and the stimulus strength.

Because the depolarization under the electrode during cathodal stimulation is stronger than the depolarization at the virtual cathode during anodal stimulation, the threshold stimulus current is larger for anode make than cathode make stimulation.

Thus, during stimulation of cardiac tissue through a small cathode, the tissue under the electrode and in the direction perpendicular to the myocardial fibers is depolarized, and adjacent tissue on each side of the cathode parallel to the fiber direction is hyperpolarized (Fig. 4).

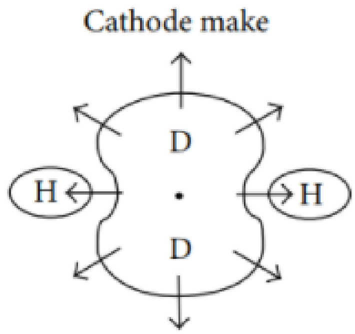

Figure 4. A schematic illustration of the cathode make excitation.
Fiber direction is along the horizontal and the anode electrode is indicated by the dot.
D represents the region that is depolarized and H represents the region that is hyperpolarized.
Arrows denote the direction of propagation of the resulting action potential

Cathode break excitation:

When the tissue is in refractory after the previous excitation, a strong cathodal stimulus is applied. This results in cathode break excitation.

The depolarization under the electrode is not capable enough to excite an action potential after the application of stimulus. This happens if the tissue is unexcited or refractory. Interestingly, at the virtual anode, the hyperpolarization causes the tissue to recover from refractoriness very quickly. When we turn off the stimulus, the depolarization under the cathode gets diffused in the adjacent hyperpolarization region. This excites the tissue and initiates a wavefront. This wavefront travels along the fiber direction (Fig. 5).

The threshold of this cathode break excitation is higher than the cathode make excitation. This is because of the fact that this mechanism is possible only when at virtual anode, the hyperpolarization on each side of the cathode is strong enough to make the tissue refractory.

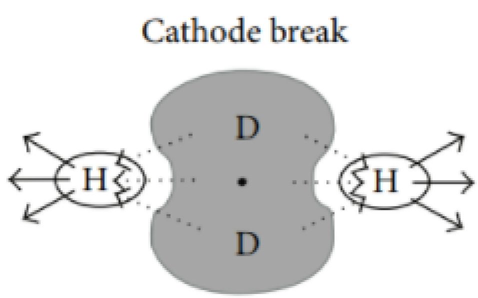

Figure 5. A schematic illustration of the cathode break excitation.
Fiber direction is along the horizontal and the anode electrode is indicated by the dot.
D represents the region that is depolarized and H represents the region that is hyperpolarized.
Arrows denote the direction of propagation of the resulting action potential

Simulation results

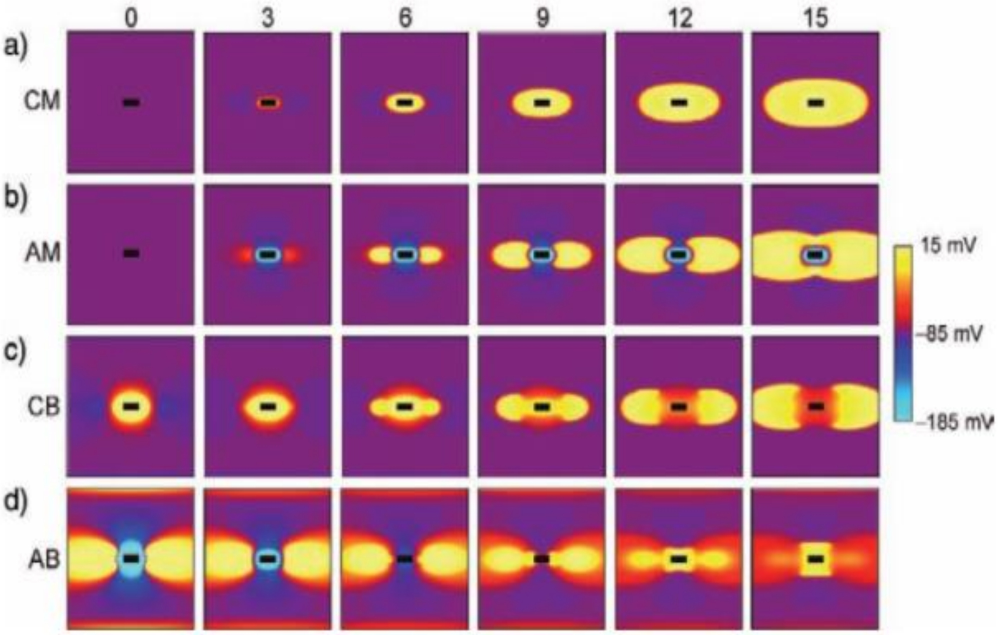

Figure 6: The transmembrane potential calculated during or following unipolar stimulation of cardiac tissue. The four rows correspond to cathode make (CM), anode make (AM), cathode break (CB), and anode break (AB) excitation. Each column corresponds to the time in milliseconds; in CM and AM the stimulus turns on at t = 0, and in CB and AB the stimulus turns off at t = 0

Inference

Before starting the simulation, we can infer that the hyperpolarization region should be just below (perpendicular) to the anode in the case of anode make and away from the cathode in the cathode make. This is because the hyperpolarization region is where the membrane potential becomes more negative than ordinary potential difference. Similarly inferences for anode break and cathode break can be made.

Conclusion

During the electrical stimulation of cardiac tissue, we may observe 4 different mechanisms depending on the type of electrode used.

An anode electrode gives rise to hyperpolarization of the tissue under the electrode and in the direction perpendicular to the myocardial fibers, and depolarization of the adjacent tissue on each side of the anode parallel to the fiber direction. On the other hand, a cathode electrode gives rise to depolarization of the tissue under the electrode and in the direction perpendicular to the myocardial fibers, and hyperpolarization of adjacent tissue on each side of the cathode parallel to the fiber direction.

The break excitation phenomena observed are also different for the two electrodes. The threshold of the cathode break excitation and anode make excitation is higher than the cathode make excitation and the threshold of anode break excitation is highest of the four mechanisms - anode make, cathode make, anode break and cathode break.

References

1. Sunil M. Kandel, Bradley J. Roth, "The Strength-Interval Curve in Cardiac Tissue", *Computational and Mathematical Methods in Medicine*, vol. 2013, Article ID 134163, 11 pages, 2013. https://doi.org/10.1155/2013/134163

2. Wikswo JP, Roth BJ (2009) Virtual electrode theory of pacing. In Efimov IR, Kroll MW, Tchou PJ (eds) Cardiac bioelectric therapy: mechanisms and practical implications. Springer, New York, pp 283-330

3. Russell K. Hobbie, Bradley J. Roth (2007) The Exterior Potential and the Electrocardiogram. In Intermediate Physics for Medicine and Biology Fourth Edition. Springer, New York, pp 192-196