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Analysis of Conduction Path of Current Signal in the Cardiac Network of Human Heart

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Abstract: A theoretical analysis of current signal in the conduction network and hence the capacity of heart pump to drive blood in different parts of human body has been done. For this, an electrical analog of human heart network has been developed. Equivalents circuits have been drawn to find the trans-membrane potential at different stages of the complete cycle of heart's activities due to movements of K+, Na+, Ca2+ ions. A computer programming has been done to find the currents in different branches of heart and power required by the heart pump. Results have been shown graphically and discussed.

Key words: Cardiac network; current signal; electrical analog of conduction path; trans-membrane potential; power of the pump.

I. INTRODUCTION

Signal conduction path of human heart starts from SA node which acts as the source of current signal. It is similar to the electrical circuit or network through which current flows. Many scientists and researchers have explained the nature of the conduction of current signal generated by SA node to different parts of the heart to keep its activities in various conditions [1,2,3]. The action potential which is an electrical simulation created by a sequence of different ion fluxes in cardiac cell due to the movement of different types of ions, like- K^+, Na^+, Ca^{2+}, etc. The trans-membrane potential is the difference in electrical potential between the inside and outside of a cell. It is due to the movement of the above ions fluxes through specialized channels in the membrane of cardiomyocytes. It can be calculated using Nernst potential formula [4]. The action potential in typical cardiomyocytes has 5 phases – phase 0, phase 1, phase 2, phase 3 and phase 4. Any deviation in action potential signal will indicate the adverse condition of the heart. In this paper, an attempt has been made to obtain electrical analog of the signal conduction path of heart and the analysis of the same to study the action potential developed during five phases of complete cycle of heart beat. Analysis has also been done to find currents in different branches of the human heart and hence the power and maximum power of the pump to circulate blood in different parts of the body. The involment of pump includes the sarcolemmal Na^+-Ca^{2+} exchanger, Ca^{2+}- ATPase and Na^+- K^+-ATPase. Results have been shown graphically and discussed.

II. MATERIAL AND METHODS

2.1Conduction paths of heart network

Figure 1 shows the block diagram model of the signal conduction network of the human heart. The conduction starts from SA node which acts as the current signal generator. Current signal from SA node is transmitted through four paths. From SA node current signal reaches AV node through three different paths. Another route called Batchman's path transmit signal from SA node to right ventricle. AV node acts as a gate or switch for the passage of signal. AV node cannot transmit signal unless it is open. If it is opened, then signal can transmit to right bundle of His, left bundle of His and finally to Purkinjee fibres. The trans-membrane potential develops across each heart cell due to the movement of different types of ions, like- K^+, Na^+, Ca^{2+} etc. The heart pump circulates fresh blood to all cells after getting the current signal.

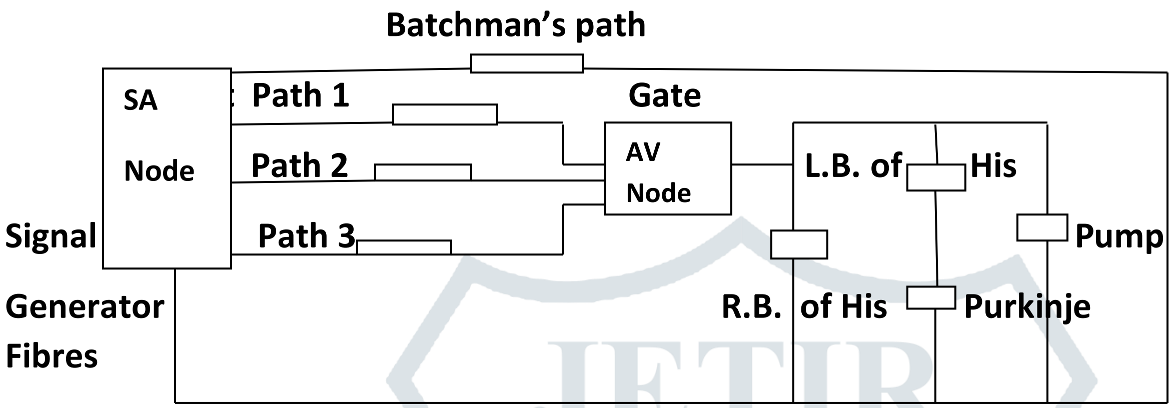

Fig.1: Physical Conduction Network of human heart

2.2 Electrical analog circuit of heart conduction path

Figure 2 shows the equivalent electrical analog circuit of human heart network. Here, SA node is denoted by a current generator having magnitude of current, I. AV node represents an electronic switch which causes the delay in conduction of current. Each conduction path is associated with its resistance and current. Heart pump is denoted by P which represents electrical load of the circuit. I_P is the current drawn by the load and V is the voltage across the heart pump.

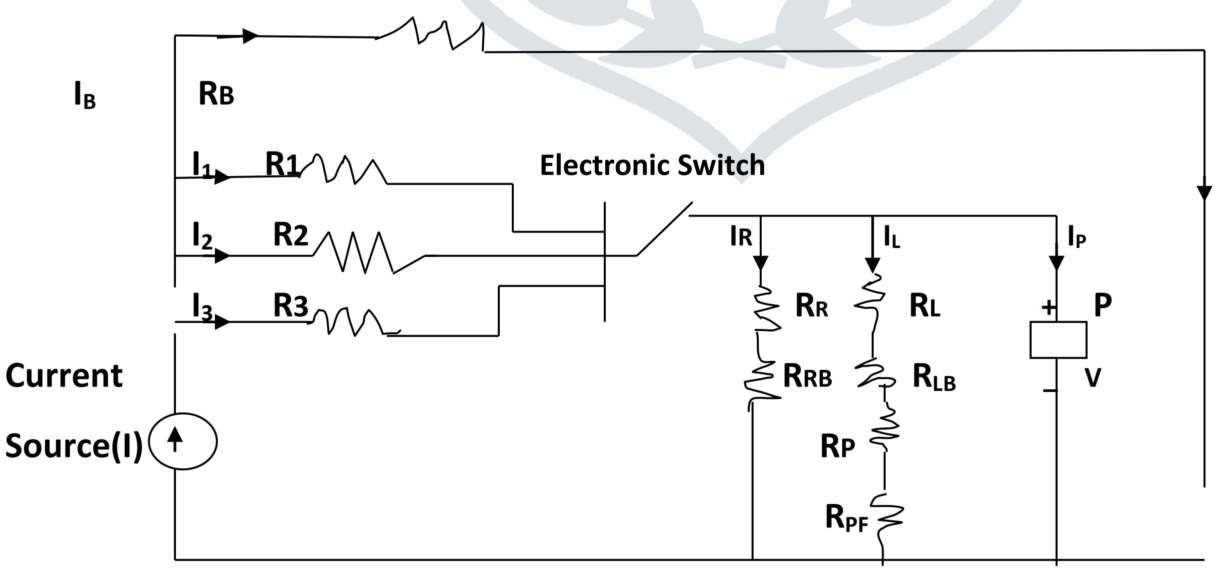

Fig. 2: Electrical analog of heart conduction path

III. ANALYSIS

For analysis following assumptions have been made:

a) SA node acts as a source of current signal,

b) AV node acts the receiver and distributor of current signal,

c) Heart is acting as a pump to circulate blood.

Analysis has been done to find

i) Equivalent circuit parameters and capacity of the heart pump, and ii) trans-membrane potentials due to the movement of different types of ions.

3.1 Determination of equivalent circuit parameters and the capacity of heart pump

Let, I = Current generated by SA node.

V = Potential across the pump

I_B = Current drawn by Batchman's path.

I_1 = Current in path 1.

I_2 = Current in path 2.

I_3 = Current in path 3.

I_R = Current in right bundle of his

I_L = Current in right bundle of his

I_P = Current in right bundle of his

R_B = Resistance of Batchman's path.

R_1, R_2, R_3 = Resistances of 3 paths respectively from SA node to AV node.

R_R = Path resistance of the right bundle of His.

R_{RB} = Total resistance of right bundle of His.

R_L = Path resistance of left bundle of His.

R_{LB} = Total resistance of left bundle of His.

R_P = Path resistance of Purkinjee fibre.

R_{PF} = Total resistance of Prukinjee fibres.

R = Resistance of the pump

P = Power of heart pump.

P_{max} = Maximum power of heart pump.

Applying KCL we get, $I = I_1 + I_2 + I_3 + I_B$ ……….(1)

$P = V. I_P$

……….(2)

$I_B = I – (I_1 + I_2 + I_3)$ ………….(3)

$I_R = V/(R_R + R_{RB})$ ………….(4)

$I_L = V/(R_L + R_{LB})$ …….. . ..(5)

$P_{max} = V^2 / 4 R$ ---------(6)

3.2 Calculation of action potential due to movement of ions at different phases:

The action potential can be calculated using Nernst formula given by

$E = (RT/nF)\log_e (C_1 / C_2)$

………….(6)

Where, C_1 = External ion concentration,

C_2 = Internal ion concentration, n = Charge of ions.

RT/F = 61.5 = Constant.

Using equation 6, calculated action potentials for different types of ions are given in Table-I.

Table –I : Action potential of different ions.

Types of ion	External concentration	Internal concentration	Value of n	Action potential(mv)
K^+	5	155	+ 1	- 91.7
Na^+	144	12	+1	+66.4
Ca^{2+}	210	37	+2	+ 105
Cl^-	120	4	-1	- 90.8

Phase 4: It is **Resting phase**. In this case, the potential is -90mV due to a constant outward leakage of K^+ through inward rectifier channels. At resting trans-membrane potential Na^+ and Ca^{2+} channels are closed. **Phase 0:** This is called **Depolarization phase**. Here, TMP rises to above -90mV due to the triggering of action potential in a neighbouring in cardiomyocyte or pacemaker cell. Then first Na^+ channels start to open one by one and Na^+ leaks into the cell, thus raising further TMP. At the threshold potential of -70 mV , enough fast Na^+ channels are opened and a self –sustaining inward Na^+ current is generated. Further, the large Na^+ current rapidly depolarizes the TMP to 0 mV and slightly above 0 mV for a transient period time called overshoot and finally fast Na^+ channels close themselves. The long opening Ca^+ Channels open when TMP is greater than -40 mV and cause a small but steady influx of Ca^+ down its concentration gradient.

Fig.3 shows the schematic graph for 5 phases of conduction of different ions for one complete cycle of heat beat.

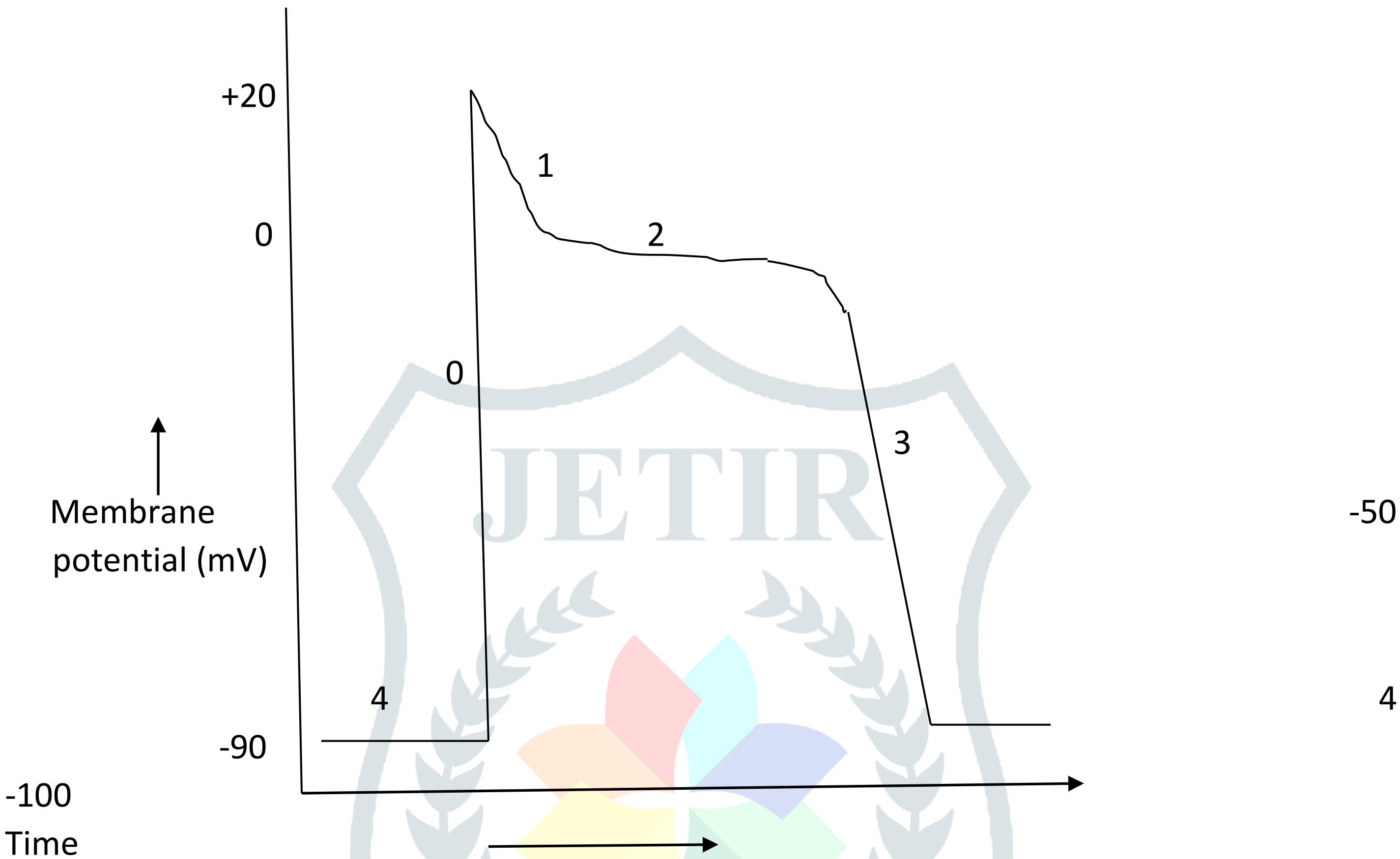

Fig.3. Schematic diagram for 5 phases of heart conduction

depolarizes the TMP to 0 mV and slightly above 0 mV for a transient period time called overshoot and finally fast Na^+ channels close themselves. The long opening Ca^+ Channels open when TMP is greater than -40 mV and cause a small but steady influx of Ca^+ down its concentration gradient.

Phase 1: This phase is called early **Repolarization**. In this case, TMP is slightly positive. K^+ channels open briefly and an outward K^+ returns the TMP to approximately 0 mV.

Phase 2 : It is called **Plateau phase.** In this phase, long opening Ca^+ channels are still open and there is a small, constant inward current of Ca^+. This becomes significant in the excitation-contraction coupling process. In this process, K^+ leaks out down its concentration gradient through delayed rectifier K^+ channels. These two counter currents are electrically balanced and the TMP is maintained at a plateau just below 0 mV through phase 2.

Phase 3 : This is called **Repolarization phase**. In this case, Ca^+ channels are gradually activated. Persistent outflow of K^+ ions now exceeds Ca^+ inflow and brings TMP back towards resting potential of -90 mV to prepare the cell a new cycle of depolarization. The normal trans-membrane ionic concentration gradients are restored by returning Na^+ and Ca^+ ions to the extracellular environment and K^+ ions to the cell interior.

3.3 Calculation of currents and maximum power required by the heart pump (Computer programming):

```
#include  <iostream>
#incude   <math.h>

using namespace std;

int main( ) {

int  V1t, R_L, R_E, I, I1,I2,I3,IB;

     cin >> V1t  >>  R_L  >> R_E;
      cout  << “Enter the values of voltage (V) = “ << V1t << “ , R_L  =  “ , R_L << “ , R_E  = “        << R_E <<  end1;

int I  = (float)(I = I1+I2+I3+IB);

     int P_max  = (float)( V1t  * V1t * R_L)/ pow((R_E + R_L),2);
     cout <<  “The Maximum Power consumption is “  << P_max   << end1;
                   cout   <<   “The   values   of   Currents   are    “   <<   I,I1,   I2,I3,IB     <<   end2;
    return  0;
}
```

IV. RESULTS AND DISCUSSION

From the analysis given in previous section(Section III), it can be seen that to run the heat pump, conduction of current is required in a systematic order. Any disturbance of current in conduction path can cause heart disorder and its deviation from normal conditions. Again, movements of K^+, Na^+, and Ca^{2+}, and hence their trans-membrane potentials have a great role for normal conduction of currents in the heart network. Any disorder in heart can be determined by the calculations of the currents in different branches of the equivalent circuits of the heart and also the actual shape of the graph (Fig.3) which is given for 5 phases of complete cycle of the heart. Using Fourier analysis of the ECG signals at normal and abnormal conditions, and making comparison of them, the defect in the conduction system can be found out. Table-II shows the various currents in different branches of network and maximum power that can be generated by heart pump. But, this is a theoretical analysis and actual results can be obtained from the required experiments to be conducted. However, it is a useful analysis to study the condition of the human heart. Heart conduction system is the network of signals that keeps our heart beating. These electrical signals make our heart contract or relax. Each contraction also controls blood flow through our heart. We can keep our heart conduction system and our entire heart healthy by making lifestyle changes such as managing stress and exercise regularly.

Table-II: Calculated values of currents and power

I_1 (μA)	I_2 (μA)	I_3 (μ A)	I_B (μ A)	I_R (μ A)	I_L (μ A)	I (μ A)	I_P (μ A)	P_{max} (μW)
20	10	20	2	13	12	52	27	250

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