Functionality and Circuitry Explanation

Pacemaker Microcontroller Shield

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1 Introduction

1.1 Product Overview

The Pacemaker shield is designed to simulate the bioelectrical interface of the heart with a real-time microcontroller.

1.2 Pacemaker Overview

A pacemaker is responsible for monitoring the operation heart and providing quick electrical pulses at specific time slots which force the heart to contract and preform its natural function. If the heart is pacing correctly without electrical assistance the pacemaker must then continue monitoring its activity until a malfunction is detected. Otherwise, the pacemaker will continually pace the heart to maintain proper functionality.

For this application, a two-lead connection is made, one to the ventricle (lower chamber of the heart) and one to the atrium (higher chamber of the heart) which apply pulses at offset time instances to allow blood to flow throughout the heart and into the body.

Data is collected through bipolar electrode which provide an analog signal thats indicitive of each chamber's activity. An electrode is found in each chamber and is responsible for both the sensing and the pacing.

1.3 Purpose

The purpose of the shield is to allow for the microcontroller to send and receive pacing information as well as collect data signals to and from the heart through the standard lead connections. The shield allows for collection of analog signals along with PWM output that charge capacitors that determine voltage settings in various locations in the shield.

1.4 Interfaces

This section will list and describe the various interfaces that occur in this system.

1.4.1 Bioelectrical Interface

The leads that enter the heart are standard ring-tip electrodes that attach to the atrial and ventricular chambers.

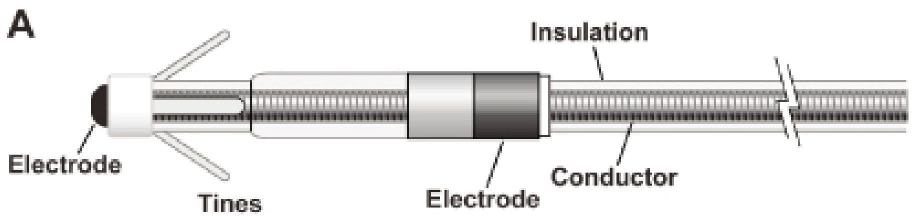

Figure 1: Ring-to-Tip Electrodes Used to Connect to the Heart

By applying a voltage potential between the ring and tip of the electrode then sufficient current will cause the heart to contract and preform the proper pacing functionality. When monitoring the heart internally and observing the action potential (natural signal) produced by both the atrium and the ventircle, it looks approximately as follows:

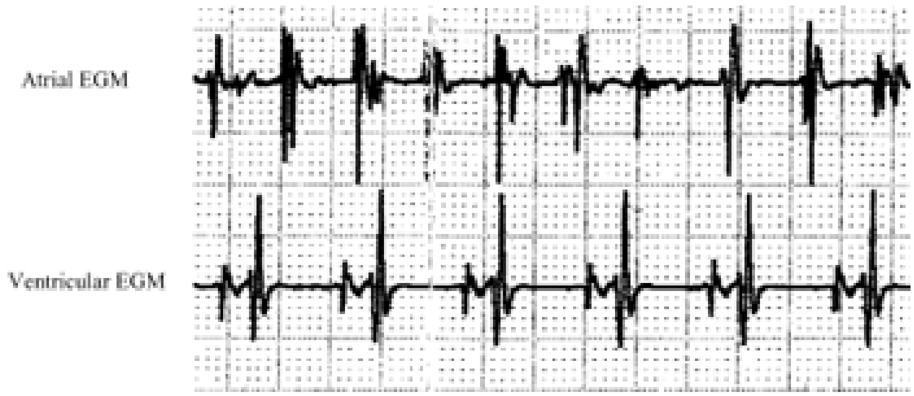

Figure 2: Intracadiac Electrogram Signals produced by the heart internally

It is a common mistake to think that an ECG is the signal that is collected by the pacemaker. Since the pacemaker is internal then it must collect internal signals. Intracardiac Electrograms (EGM) is the name of the signal that is produced by both the atrial and the ventricle seperately.

1.4.2 Microcontroller Interface

The shield is designed to have the same pin layout as the FRDM K64F board. The microcontroller uses the circuitry in the board to apply the proper actions onto the heart. A detailed explanation of all pins is presented in this document.

2 Pin Explanation

2.1 Pin Layout

The pin descriptions follow the pin layout of the FRDM K64F microcontroller. The shield physically fits in most Arduinos and STM32 boards but is **not** pin-to-pin compatible with these controllers. Most notably due to the lack of PWM pins, specifically in the D2 and D4 locations. PWM is explained in .Section 3.3.4

Pin Name	Corresponding Name	Functionality
D0	ATR_CMP_DETECT	Used in the sensing circuitry of the atrium. Outputs ON (HIGH) when signal voltage is higher than threshold voltage and OFF (LOW) otherwise (includes 5mV hysteresis).
D1	VENT_CMP_DETECT	Same functionality as in ATR_CMP_DETECT but for the ventricle sensing signal (includes 5mV hysteresis).
D2	PACE_CHARGE_CTRL	Used to start and stop the charging of the primary capacitor (C22). If ON (HIGH) $\rightarrow$ PWM charges C22 If OFF (LOW) $\rightarrow$ PWM disconnected from circuit NEVER allow this signal to be set to HIGH if either ATR_PACE_CTRL and/or VENT_PACE_CTRL are HIGH because then the patient may be directly connected to the PWM signal!
D3	VENT_CMP_REF_PWM	In order to establish a threshold for when the ventricular action potential should be sensed, this pin uses PWM to charge a capacitor that will sustain a constant voltage for comparison. <u>Note</u> that the capacitor voltage is linearly proportional to the Duty Cycle of the PWM input. Use 500 Hz PWM frequency.
D4	Z_ATR_CTRL	This control allows the impedance circuit to be connected to the ring electrode of the atrium. It is used to analyze the impedance of the atrial electrode and the electrical connection between the atrial electrodes and the atrium itself. The output of this circuit is found at the Z_SIGNAL pin. More information regarding lead impedances is mentioned in Section 4 of this document.
D5	PACING_REF_PWM	Used to charge the primary capacitor (C22) of the pacing circuit. The PWM voltage output by this pin saturates to 0-5V and will charge C22 is PACE_CHARGE_CTRL is HIGH. <u>Note</u> that the capacitor voltage is linearly proportional to the Duty Cycle of the PWM input. Use 500 Hz PWM frequency.

D6	ATR_CMP_REF_PWM	Same functionality as in VENT_CMP_REF_PWM but for the atrial action potential. Note that the capacitor voltage is linearly proportional to the Duty Cycle of the PWM input. Use 500 Hz PWM frequency.
D7	Z_VENT_CTRL	This control allows the impedance circuit to be connected to the ring electrode of the ventricle. It is use is identical to Z_ATR_CTRL but for the ventricle. More information regarding lead impedances is mentioned in Section 4 of this document.
D8	ATR_PACE_CTRL	Used to discharge the primary capacitor through the atrium. Current flows through the switch if set to HIGH. If LOW there is no current flow. Pay attention to the direction at which current flows through the electrode. NEVER allow this output signal to be set to HIGH if PACE_CHARGE_CTRL is HIGH because then the patient's atrium may be directly connected to the PWM signal!
D9	VENT_PACE_CTRL	Same functionality as in ATR_PACE_CTRL but for the ventricle. NEVER allow this output signal to be set to HIGH if PACE_CHARGE_CTRL is HIGH because then the patient's ventricle may be directly connected to the PWM signal!
D10	PACE_GND_CTRL	To allow current to flow from the ring to the tip in either the atrium or the ventricle this pin must be HIGH since it controls the switch directly following the tip. Note: Once this pin is activated along with either ..._PACE_CTRL pins, the charge will flow through the switch and accumulate in the blocking capacitor (C21).
D11	ATR_GND_CTRL	Used to connect the ATR_RING_OUT to GND. This functionality is used when discharging the blocking capacitor through the atrium to allow no charge buildup.
D12	VENT_GND_CTRL	Same functionality as in ATR_RING_OUT but for the ventricle.
D13	FRONTEND_CTRL	Used to activate the sensing circuitry. If ON (HIGH) → Sensing circuitry will output heart signal. If OFF (LOW) → Sensing circuitry is disconnected from patient (Green Connectors) and will output nothing. Note: This switch controls both the atrial and ventrical circuits. It is up to the programmer to only record the data they desire since both will be activated.
GND	GND	References electronic GND. It is good practice to test that all grounds are connected with low resistance prior to the initial startup of the device. Once the device is in use or in the body this process is no longer necessary.

AREF	-	- Disconnected by design -
SDA	-	- Disconnected by design -
SCL	-	- Disconnected by design -
A5/SCL	-	- Disconnected by design -
A4/SDA	VENT_RECT_SIGNAL	This pin connects to the sensing circuitry and is used to output the rectified analog waveform of the ventricle. This waveform is used in the comparator amplifier to detect ventiruclar action potentials.
A3	ATR_RECT_SIGNAL	Same output functionality as in VENT_RECT_SIGNAL but for the atrium.
A2	Z_SIGNAL	Used to analyze the impedance of either the atrium or the ventricle if necessary. More information regarding lead impedances is mentioned in Section 4 of this document.
A1	VENT_SIGNAL	This pin outputs the analog waveform of the ventricle prior to full-wave rectification. This signal best represents what is actually happening in the heart in real-time. Use this analog output as data for any electrocardiogram outputs.
A0	ATR_SIGNAL	Same functionality as in VENT_SIGNAL but for the atrium.
VIN	-	- Disconnected by design -
GND1	GND	Same functionality as GND mentioned above.
GND2	GND	Same functionality as GND mentioned above.
5V	5V	Connected to the Arduino 5V output. Used to power the electronics of the shield. It is good practice to test that this is roughly 5V prior to usage.
3V3	3V3	Arduino uses 3.3V to output an HIGH voltage from the Arduino pins. It is good practice to test that this is roughly 3.3V prior to usage.
/RESET	-	- Disconnected by design -
IOREF	-	- Disconnected by design -
RESERVED	-	- Disconnected by design -

3 Circuitry Flowchart and Details

3.1 AV Sensing Circuit Flowchart

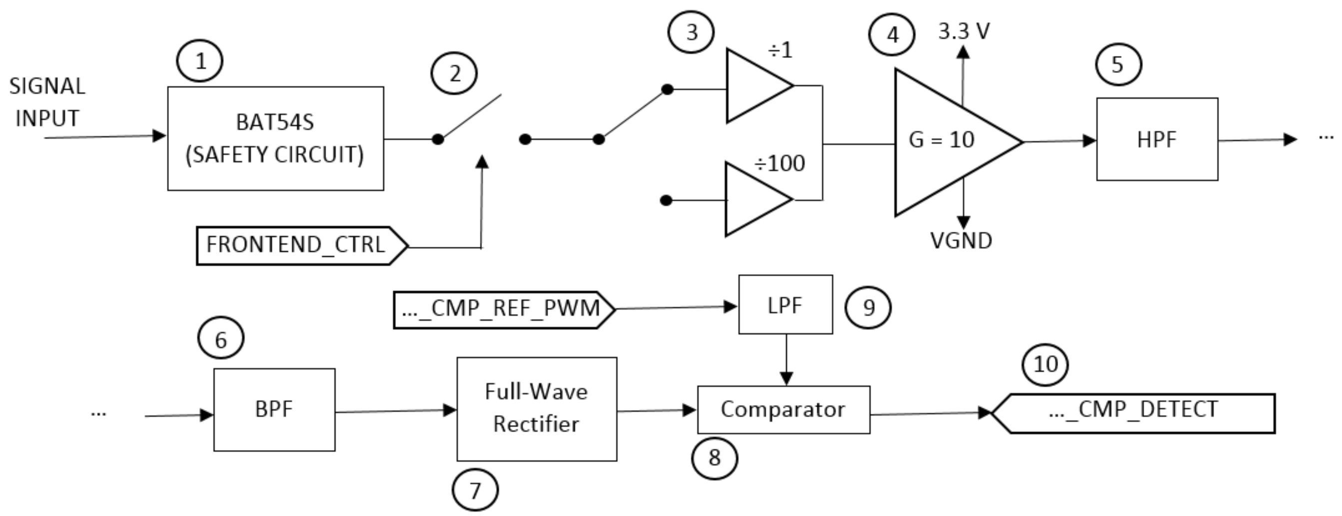

Figure 3: Sensing Flowchart Overview

1. BAT54S Schottky diode pair used to protect from over or under voltage
   → if voltage is too high relative to GND (other electrode lead) ⇒ diode ON ⇒ will drain to 3.3 or GND.

2. HP4066 Analog Switch used to allow electrical flow upon activation
   → if, C ⇒ ON (HIGH) → flow ⇒ ON
   C ⇒ OFF (LOW) → flow ⇒ OFF (pull high to 3.3V)

3. Voltage attenuation through switch and voltage division over resistor pair.
   → If, x1 attenuation ⇒ short between input and output.
   x100 attenuation ⇒ switch through resistor setup (shown below).

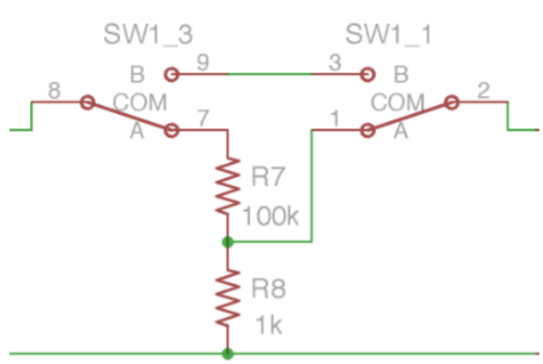

Figure 4: x1/x100 Attenuation Switch Circuitry

4. AD 623 Instrumentational Amplifier with Gain = 10 and CMRR @ 60 Hz of typically 100 dB.

$$100dB = 20\log_{10}\frac{A_{differential}}{|A_{common\_mode}|}$$

$$A_{common\_mode} = 10^{-4}$$

   Note: 60 Hz is attenuated by roughly four orders of magnitude less than signal! Also the output signal is very clean and DC offset is filtered out.

5. RC Passive High Pass Filter

   Capacitor = 10μF
   Resistor = 330 KΩ

   Resulting in Cutoff Freq $\approx$ 0.05Hz (used to filter out DC w.r.t VGND)

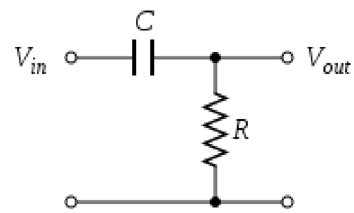

Figure 5: Circuit Diagram of Passive High Pass Filter

6. 2nd Order Band-Pass Filter

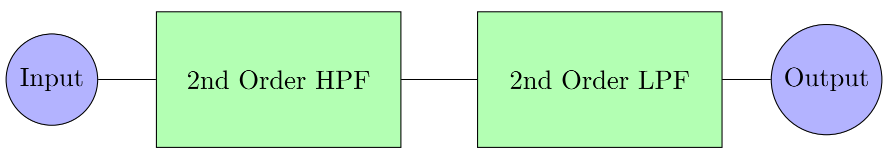

Figure 6: Sensing Circuit Band-Pass Filter Breakdown

   Note: Standard HPF and LPF circuitry used to design the BPF (Op Amp with 2 caps and 2 resistors)

   Bandwidth ranges:
   Ventricle sensing circuit → 0.1 to 40 Hz
   Atrium sensing circuit → 0.1 to 70 Hz

7. Full-Wave Rectification is achieved by using x2 LMV344 Op Amps along with Schottky diodes to maintain rectified direction (+ve).
   → For more look up "precision full-wave rectifier"

   TODO: recitification occurs using VGND which improperly recitifies signals → check how to change this in circuit

8. MCP6546 Comparator used to compare between rectified signal and PWM threshold input.
   → If, threshold > signal ⇒ Output LOW
   threshold < signal ⇒ Output HIGH

9. μController outputs PWM signal with duty cycle thats proportional to the threshold levels with linear proportionality
   → Duty cycle = 0% ⇒ 0 Vref
   100% ⇒ 3.3 Vref

10. Once the comparator triggers to the ON/OFF levels it will output a rising or falling edge to the μC through the ATR_CMP_DETECT pin
    → use this signal to analyze when either the ventricle or atrium trigger a pulse

3.2 AV Pacing Circuit Flowchart

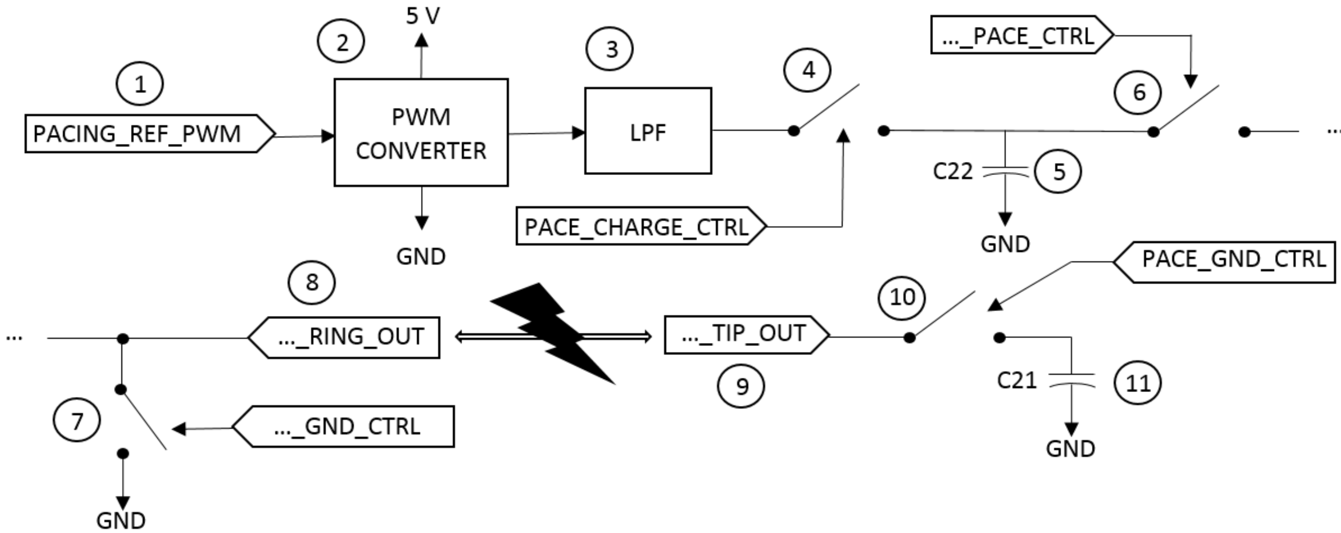

Figure 7: Pacing Flowchart Overview

1. PACING_REF_PWM is a PWM output from the μC with ranges of 0 to 3.3 V. Its purpose is to charge the capacitor based on the duty cycle. For more info reference the Pin Assignment Table above
   → The duty cycle of the PWM signal is linearly proportional to the maintained capacitor voltage.

2. Since only 3.3 V can be output from the μC then a step-up converter is used to set the charged voltage up to 5V.
   → Input PWM from 0-3.3V
   → Output PWM from 0-5V

   Note: The conversion does not distort the PWM waveform, it simply amplifies it.

3. LPF used to diminish high frequency noise, instrumentation noise and 60 Hz

$$f_c \approx 48.2Hz$$

4. Controlled by PACE_CHARGE_CTRL
   → If, CLOSED ⇒ C22 Charges
   → If, OPEN ⇒ No Current Flow

5. C22 - Electrolytic Capacitor charged by PWM input signal. As mentioned above, charged voltage is linearly proportional to the duty cycle of the PWM signal. Higher/Lower frequencies will also alter the charging characteristics of the capacitor.

6. To discharge C22, certain switches may be opened to direct current to the Atrium or the Ventricle.

ATR_PACE_CTRL	VENT_PACE_CTRL	Result
OFF	OFF	No Pacing
ON	OFF	Atrial Pacing
OFF	ON	Ventricular Pacing
ON	ON	Parallel Connection (Not Useful)

Note: If PACE_CHARGE_CTRL is ON while ..._PACE_CTRL signals are on then the patient will be pulsed with PWM signal (avoid this due to high voltage and high frequency directly to the patient).

7. In order to ground other components of the heart to disallow unwanted pacing (pacing ventricle and atrium is floating may cause current flow) the ..._GND_CTRL must be activated as a pull-down for the electrode.

8. ..._RING_OUT is connected to the ring on the electrode positioned on the heart

9. ..._TIP_OUT connects to the heart through the electrode and is responsible for the return path of the circuit.

10. This switch is controlled by PACE_GND_CTRL and will ground both the ventricular and atrial electrode tips when set to ON (closed position).

11. Blocking Capacitor (C21) will receive the charge flow from C22 while pacing occurs. After the initial pacing occurs it is necessary to discharge the blocking capacitor back through the heart to produce a net zero current flow in the heart. Pacing pulses must be AC with no DC component to discourage long-term electromigration effects in the leads and the cells of the heart.

An oversimplified explanation of the discharging sequence can be represented by this image:

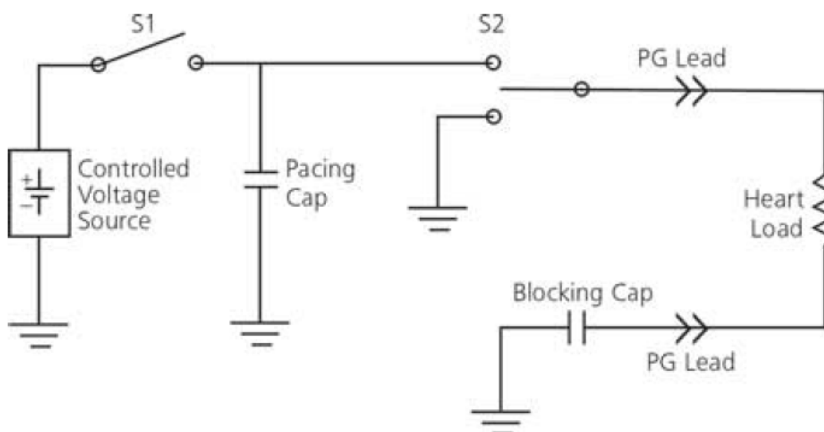

Figure 8: Simplified Pacing Schematic

Quick Explanation: Switch S1 is controlled by PACE_CHARGE_CTRL. Switch S2 is toggled between ..._PACE_CTRL and ..._GND_CTRL. The Pacing Cap is responsible for actual pacing while the Blocking Cap will slowly discharge over the heart to produce a net zero current flow.

3.3 Mandatory Pin Arrangements for Pacing

This section will describe the mandatory pin settings in order to successfully pace. These are set as such in order to avoid critical errors that may occur otherwise (i.e. unwanted pacing, risking patient, false charging...).

The pacing process is composed of three major cyclic states:

1. Charging primary capacitor (C22)

2. Pacing either Atrium or Ventricle

3. Discharging blocking capacitor (C21)

Note: Steps 1 and 3 can (and should) be done at the same time since they are not electrically dependent.

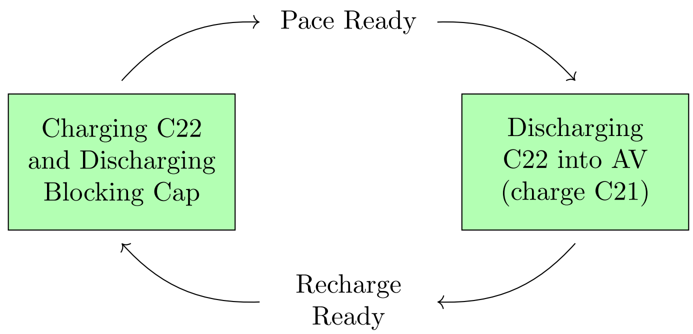

Figure 9: Dual State Pacing Flowchart

3.3.1 Charging C22

In order to charge C22 a threshold must be set that is proportional to PWM duty cycle. The PWM signal ranges from 0 to 3.3 V but the converter (mentioned in section 3.2) ranges the signal from 0 to 5 V.

Mandatory Pin Arrangement:

> Note: Listed in proper chronological order. The order at which the pins are set is crucial for the safety of the patient (always protect the patient from being directly connected to the PWM input charging signal).

Pin	Setting
ATR_PACE_CTRL	LOW
VENT_PACE_CTRL	LOW
PACING_REF_PWM	500 Hz with Desired Duty Cycle
PACE_CHARGE_CTRL	HIGH

3.3.2 AV Pacing

Once the Pacing Capacitor (C22) is charged, the system may require that a pace be applied to either in the atrium or the ventricle.

Mandatory Pin Arrangement:

> Note: Listed in proper chronological order. The order at which the pins are set is crucial for the safety of the patient (always protect the patient from being directly connected to the PWM input charging signal).
>
> This pin arrangement is an example of **pacing** the ventricle. For atrial pacing simply activate ATR_PACE_CTRL instead of VENT_PACE_CTRL.

Pin	Setting
PACE_CHARGE_CTRL	LOW
PACE_GND_CTRL	HIGH
ATR_PACE_CTRL	LOW
ATR_GND_CTRL	LOW
Z_ATR_CTRL	LOW
Z_VENT_CTRL	LOW
VENT_GND_CTRL	LOW
VENT_PACE_CTRL	HIGH

3.3.3 Discharging Blocking Capacitor (may be combined with state 1)

After pacing occurs, the Blocking Capacitor is charged with the current that passed through the heart (state 2). The Blocking Capacitor is discharged by grounding the ring of the recently paced chamber (state 2 paced the ventricle). The Blocking Capacitor is used to balanced out the charge build-up that is caused by the pacing current. A net zero current must be established in order to protect the patient.

Mandatory Pin Arrangement:

Note: Listed in proper chronological order. The order at which the pins are set is crucial for the safety of the patient (always protect the patient from being directly connected to the PWM input charging signal).

This pin arrangement is an example of reducing the **net charge build-up** to zero in the ventricle. For atrial pacing simply activate ATR_GND_CTRL instead of VENT_GND_CTRL.

Pin	Setting
PACE_GND_CTRL	HIGH
VENT_PACE_CTRL	LOW
Z_ATR_CTRL	LOW
Z_VENT_CTRL	LOW
ATR_PACE_CTRL	LOW
ATR_GND_CTRL	LOW
VENT_GND_CTRL	HIGH

3.3.4 PWM

In the context of capacitors, Pulse Width Modulation (PWM) is a helpful method to mimic analog signals with the use of digital outputs. By toggling a digital signal at high frequency with variable duration it is possible to output an average value of voltage ranging from digital HIGH and LOW.

For example, consider a PWM frequency of 1 kHz where the period is 1 ms and a HIGH voltage of 5V. If the Duty Cycle (percentage of the period where the signal is HIGH) is set to 20% then the average voltage would be,
(0.2 * 5V) = 1V

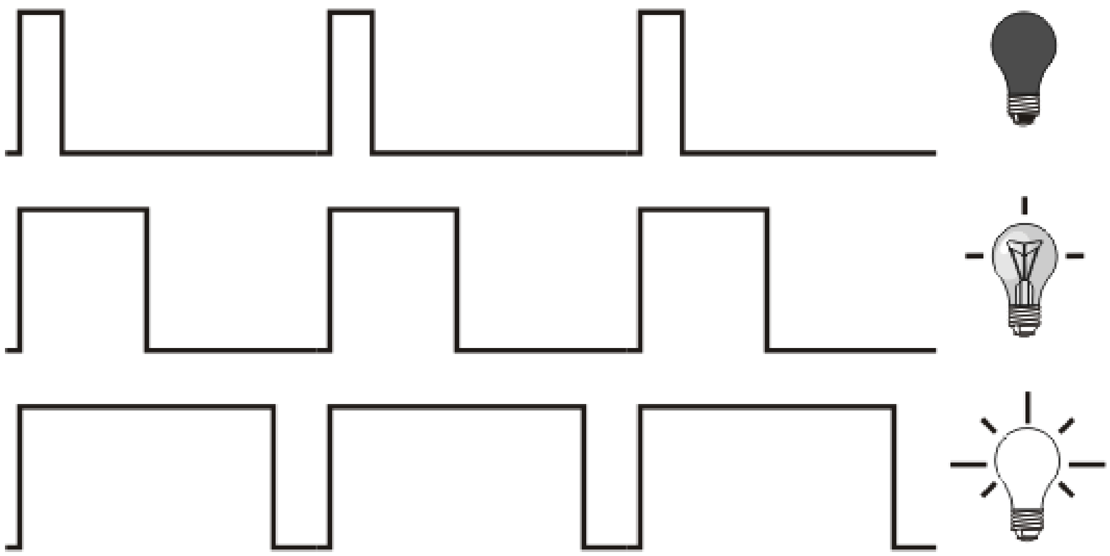

Figure 10: Example of PWM with resulting output average voltages

As shown in *Figure 10* the first PWM signal is outputing a low Duty Cycle, resulting in little output voltage to power the light bulb. As Duty Cycles increase, the average voltage goes up and more power is transferred to the bulb. The same functionailty is used in the pacemaker to charge up capacitors used to pace the heart and set reference voltages since a binary output is inadequate.

3.4 Strength-Duration Curve

In order to apply a proper pace the pacemaker must consider two factors; the voltage and the time length. The heart will only fibrillate if it receives sufficient charge flow for a long enough time. The Strength-Duration Curve (SDC) displays the necessary voltages required for a corresponding pulsing period. Any combination of voltage and duration that is located below the curve will not be captured by the heart and will not properly pace either the ventricle or the atrium.

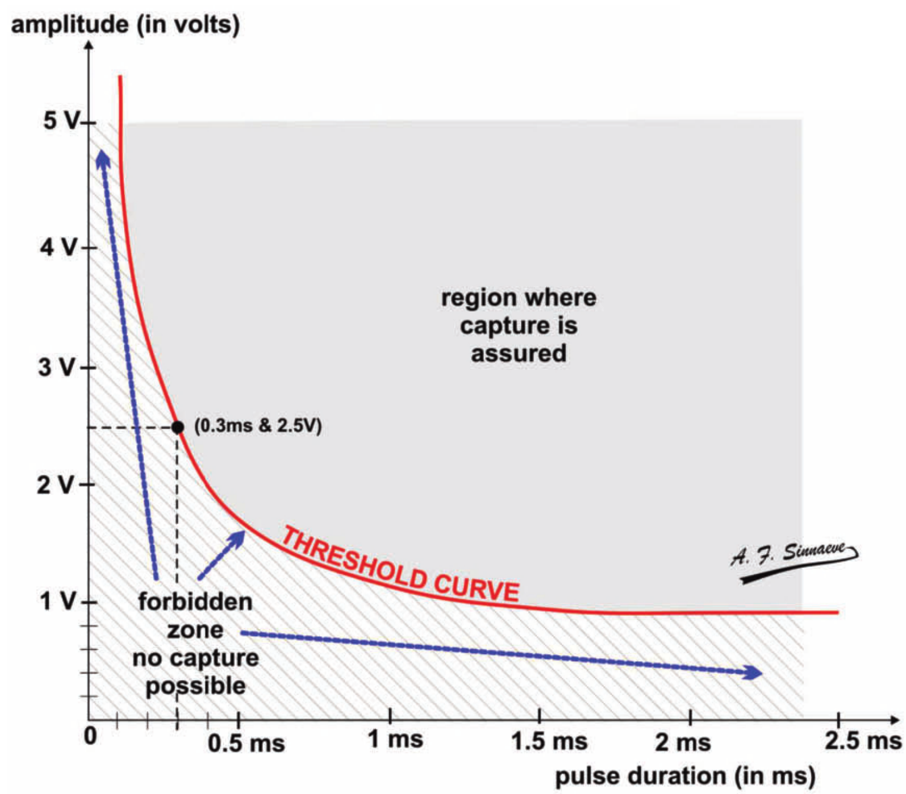

Figure 11: Strength-Duration Curve shows the relationship between voltage and pulse width

The figure above displays this relationship and shows how small enough durations require unnecessarily high voltages (stay away from this). Additionally, excessively long durations may require less voltage but may not be captured as well due to their in sufficient current density.

3.5 Proper Pace Capture

A pacemaker is not only responsible for providing timely paces to the heart but also to keep track of which paces were properly captured (a capture refers to the induced pacing of the heart due to an artificial stimuli). After artificial pacing is preformed it is the job of the on-board controller to confirm that the proper natural behaviour is detected as a response. If the heart does not properly respond to the pulse it must record this incident and may be required to try again (with adjusted pulse characteristics if necessary).

Remember, the primary responsibility of the pacemaker is to ensure that proper pacing occurs! If an error occurs such as non-captured stimulus it defeats the purpose of the pacemaker.

4 Lead Impedance

This section will discuss the importance of proper lead impedance, its effects on the device, how it can be detected and what to do.

4.1 What is Impedance?

Impedance is an electrical measure of how the flow of current is affected as it flows through the circuit. In the context of biomedical devices, impedance is important when analyzing the ability of a device to transmit sufficient energy (in the form of electrical charge/current) to a specific area in the body.

Impedance considers both the effects of resistance and capacitance but in the context of pacemakers we will focus on the resistive characteristics of the pacemaker electrodes.

4.2 Impedance in Pacemakers

In the case of pacemakers, the component that is most concerned with impedance are the electrodes which carry significant current flow over long distances relative to the rest of the circuit. If the device suffers from impedance that is too high it will reduce the flow of current which may be too low to transmit a sufficient pulse. But if the impedance is too low then the circuit will draw excess current from the battery which may either be harmful to the patient or reduce the lifetime of the battery.

Improper Impedance can occur due to many factors, for example in the case of high impedance the coiled leads may haved cracked or fractured resulting in very high impedance. Additionally, the lead may lose proper contact from the heart which will not only result in high impedance but may apply current to undesired locations in the heart.

Low impedance is common in cases where the leads fracture and create contact within the ring and the tip leads, this will cause excessive current to be drawn and will not reach the heart effectively.