Pacemakers & Defibrillators

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Introduction

- Major use of medical electronics is as a diagnostic tool
  - Most instruments sense, record and display a physiological signal
  - Therapeutic and prosthetic devices are used as a means of treating human ailments
    - Electric stimulators, ventilators, heart-lung machines, artificial organs, prosthetic devices, implantable devices, drug delivery pumps (e.g. insulin pump), etc.
- Two common and important electric stimulator devices used to detect and correct arrhythmias
  - Cardiac Pacemakers
  - Cardiac Defibrillators

Arrhythmias: SA Block

Figure 4.9 The sinus node activation does not appear on the ECG. The vertical lines indicate sinus node activation instants. During 1˚ SA block there is a delay between sinus node activation and atrial activation. During 2:1 SA block the abnormality cannot be distinguished from sinus bradycardia. In third degree block only the ventricular escape rhythm is recorded. From Chou, T. C. 1986. *Electrocardiography in clinical practice*. 2nd Ed. Grune & Stratton.

Arrhythmias: Atrial Flutter

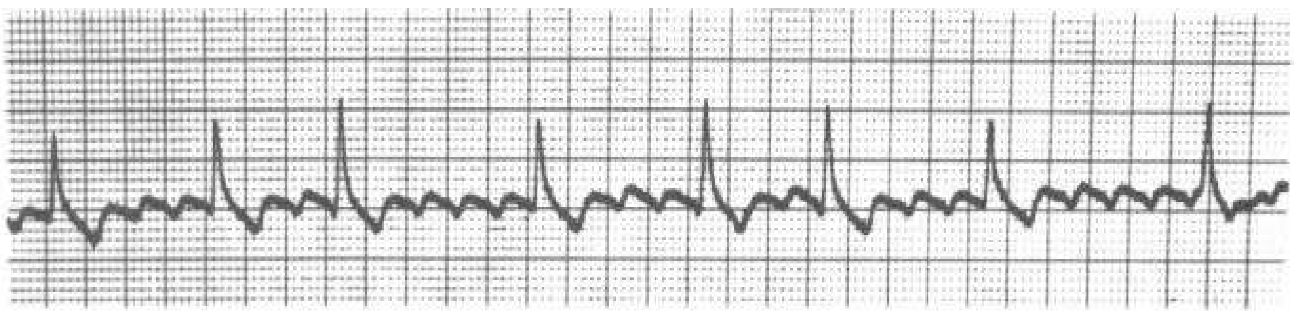
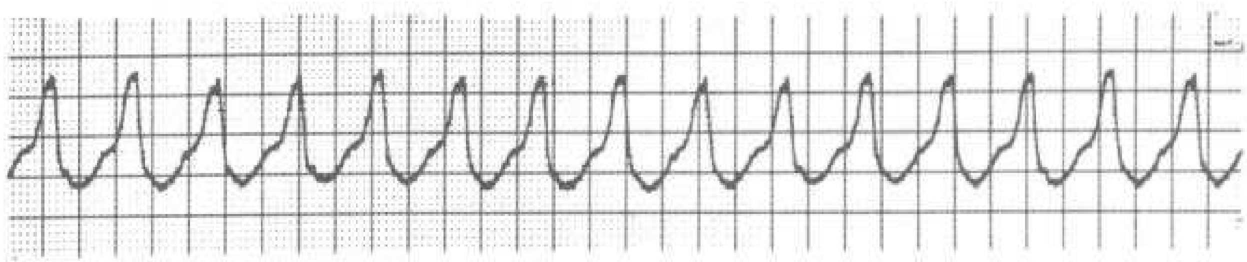


Figure 4.20 Atrial flutter is manifested by F waves between QRS complexes. Some P waves are blocked in order to protect the ventricles from a high depolarization rate. From Chou, T. C. 1986. *Electrocardiography in clinical practice.* 2nd Ed. Grune & Stratton.

Ventricular Tachycardia and Fibrillation

(*a*)



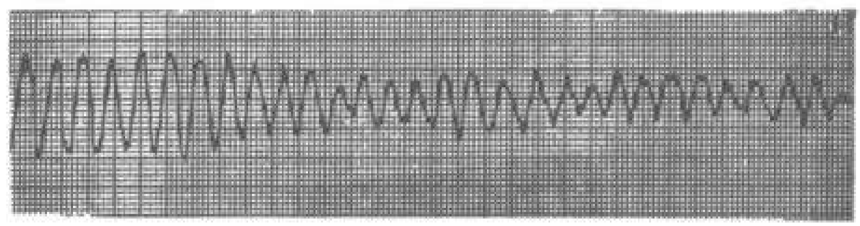
Needs a Cardioverter (essentially a small shock to ventricles)

Requires a CARDIOVERTER

small shock needed

Low blood pressure

(*b*)



Needs a Defibrillator (essentially a large shock to ventricles)

Requires a DEFIBRILLATOR

large shock needed

No blood pressure

Figure 4.23 (*a*) Ventricular tachycardia, which is different from ventricular flutter, (*b*), in that the ventricular complex has a sharp angular morphology. From Chou, T. C. 1986. *Electrocardiography in clinical practice*. 2nd Ed. Grune & Stratton.

Arrhythmias: Ventricular Fibrillation

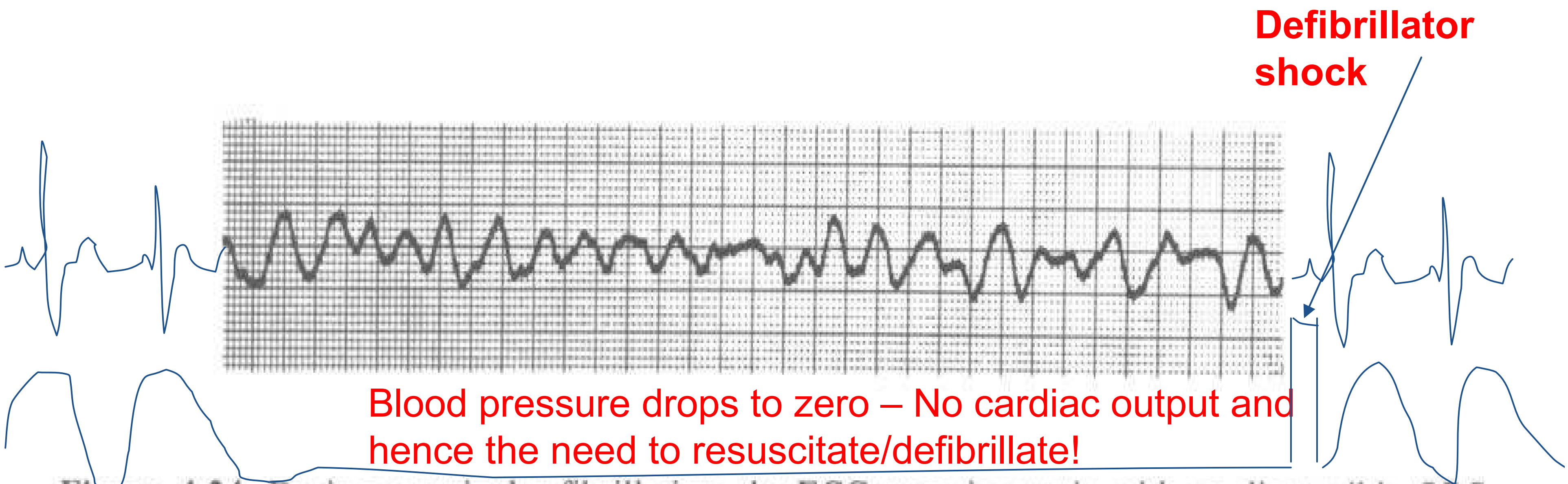


Figure 4.24 During ventricular fibrillation, the ECG trace is erratic with no discernible QRS complexes. From Chou, T. C. 1986. *Electrocardiography in clinical practice.* 2nd Ed. Grune & Stratton.

Uncoordinated beating of heart cells, resulting in no blood pressure.
Needs an electrical shock urgently…else brain damage in 4+ minutes.

External or implantable defibrillator. In the mean time do CPR!

Cardiac Pacemakers

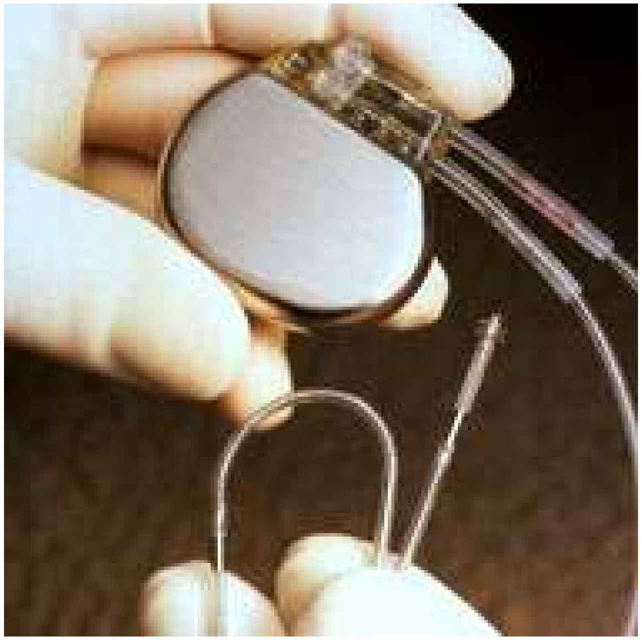
- An electric stimulator for inducing contraction of the heart
  - Very low-current, low-duty-cycle stimulator
- Electrical pulses are conducted to the various locations
  - On the surface (Epicardium)
  - Within the muscle (myocardium)
  - **Within the cavity of the heart (endocardium)**
- Needed when heart is not stimulating properly on its own (i.e. arrhythmias)

Pacemaker Circuit

- **Very** basic pacemaker circuit
  - No feedback control
  - Sends pacing signal no matter what heart might be doing on its own
  - Make sure understand how circuit works

Pacemakers

- Pacemakers work as follows:
  - Insulated wires are threaded through a patient's veins to the heart.

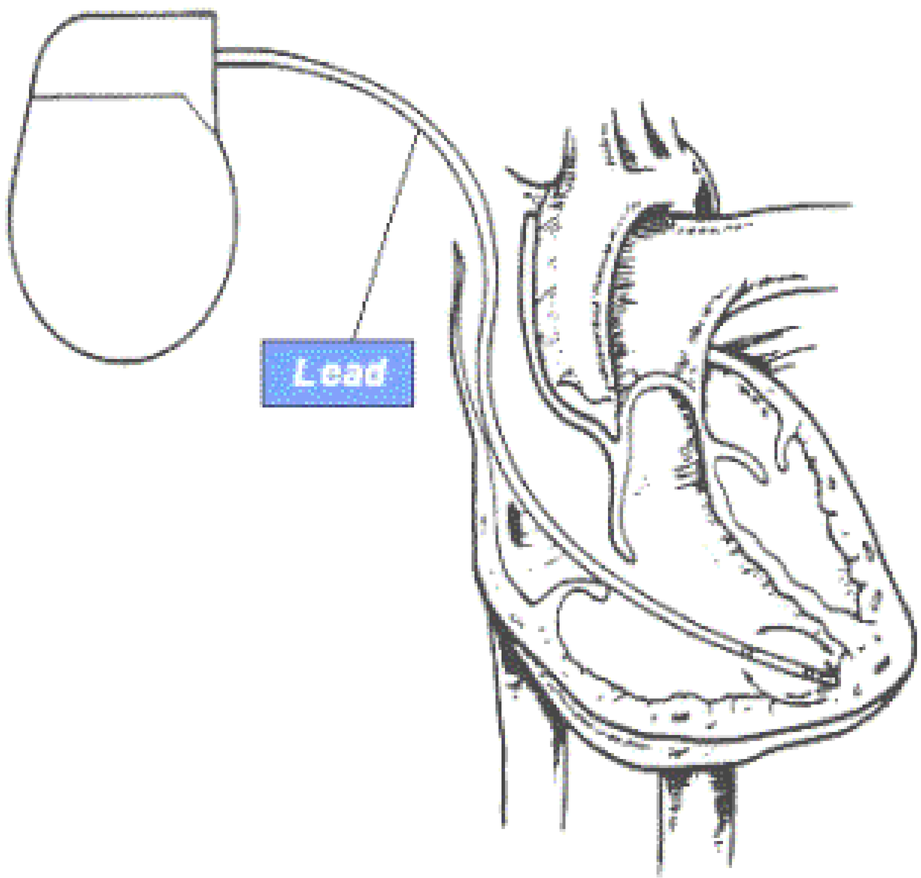


Short History of Pacemakers

- The basic approach to cardiac pacing is to supply an electrical shock to the heart, resulting in a ventricular contraction.
- Early pacemakers utilized skin electrodes with large surface areas or subcutaneous needle electrodes (1950's).
- Electrodes placed on the surface of the heart were then introduced via an opening in the chest wall (thoracotomy).
- Modern pacemakers use catheter electrodes introduced into the right ventricle via the cephalic or sub-clavian vein.

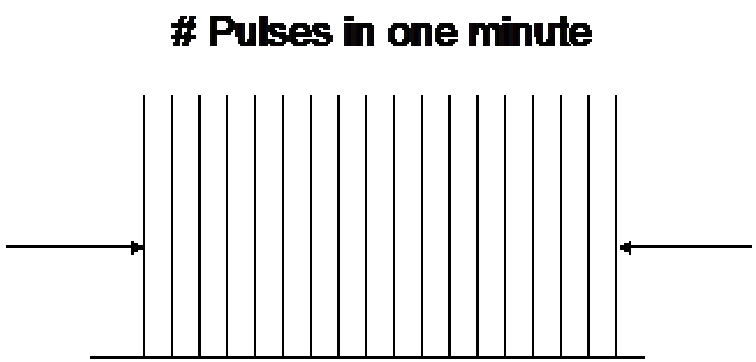
Pacemakers

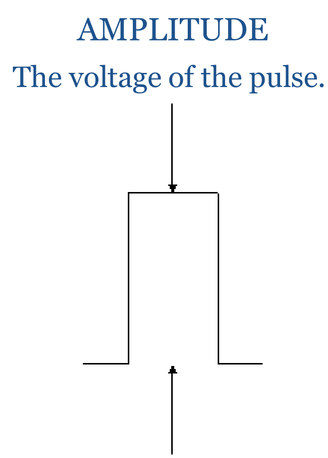
- Pacemakers generate electrical pulses that reach the heart through the leads.

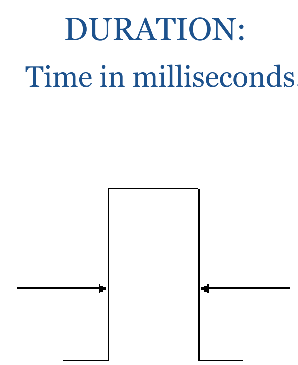


Key Concepts

- <u>Threshold</u> is the point at which the stimulus is sufficient to produce a heart beat
- Sending more energy than necessary to the heart has no benefit in terms of the resulting heart beat -- since the heart either contracts or it doesn't.
- Sending a pulse stronger than "threshold" uses more battery energy than needed.
- A series of pulses may be characterized or described by three criteria:
- <u>Rate</u>: the number of pulses or beats per minute





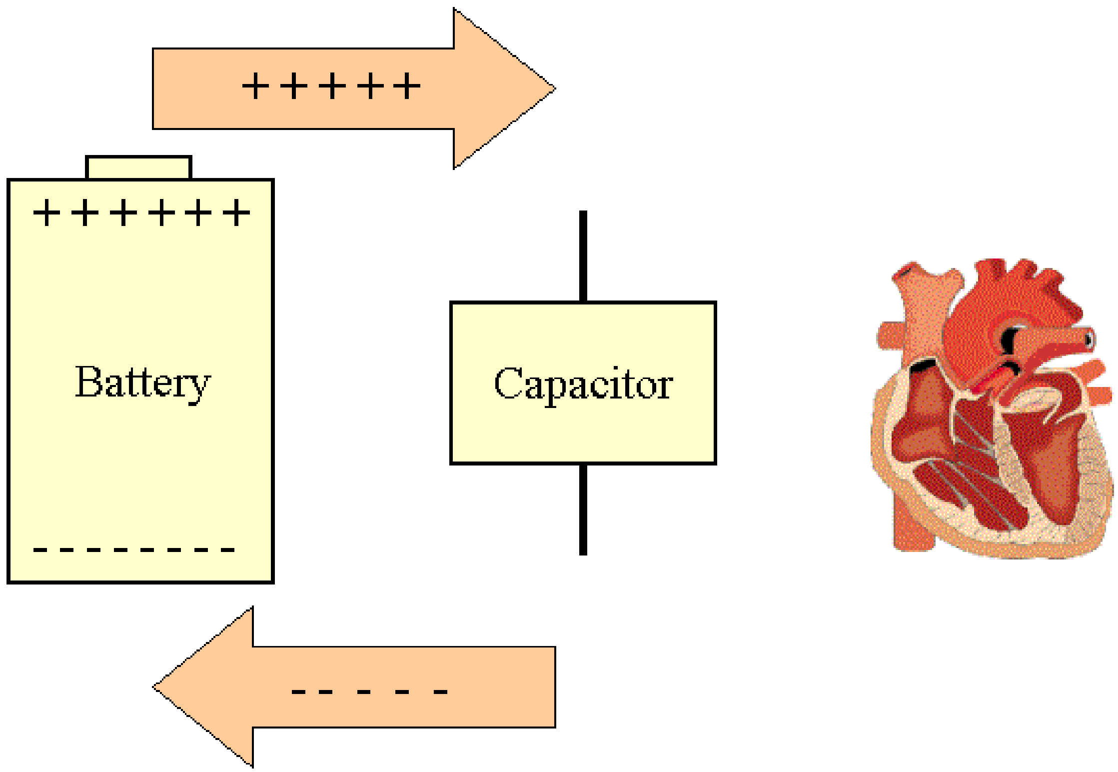


Key Concepts

- Strength-duration: Heart muscle responds to the amplitude and duration of each pulse
  - A strong pulse of short duration may cause the heart to beat, but so may a weak pulse of greater duration
- Pacing:
  - Stimulation of the heart using electrical pulses is called pacing
  - Knowing how much electricity to release and at what time intervals is of paramount importance to patient safety

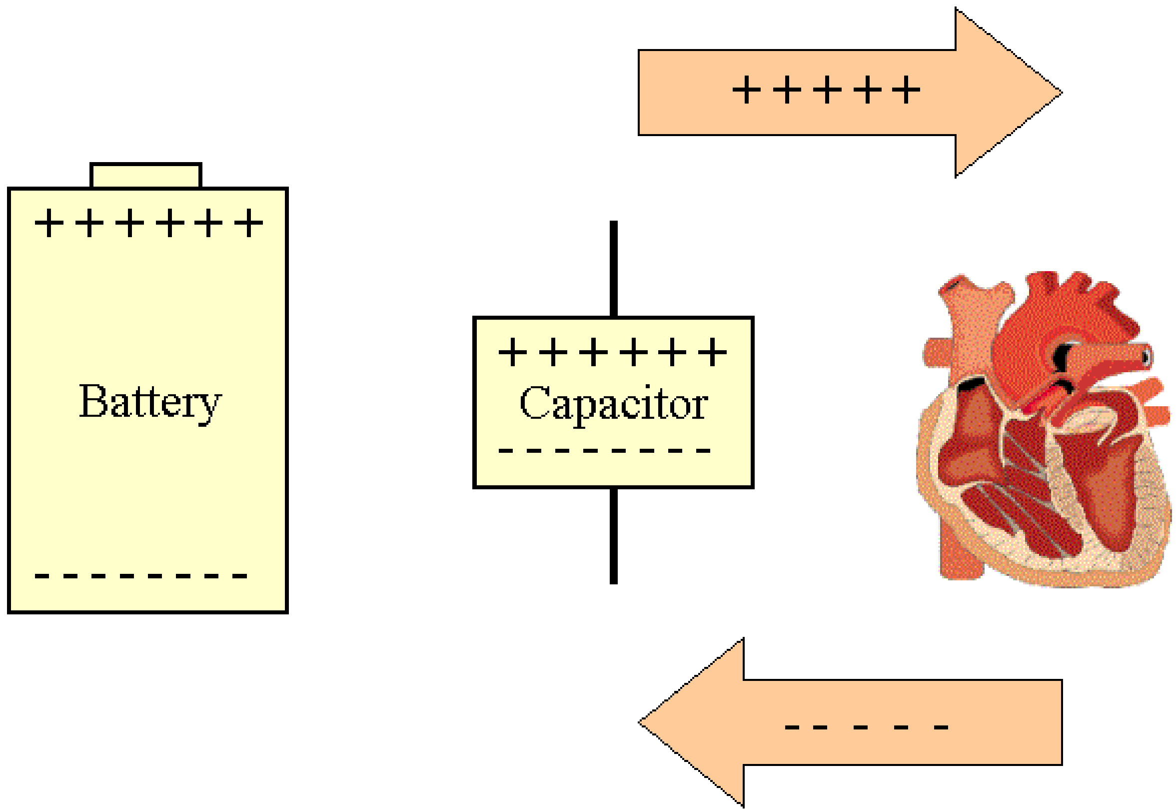
Pacemakers

Pacemakers charge a capacitor from a battery



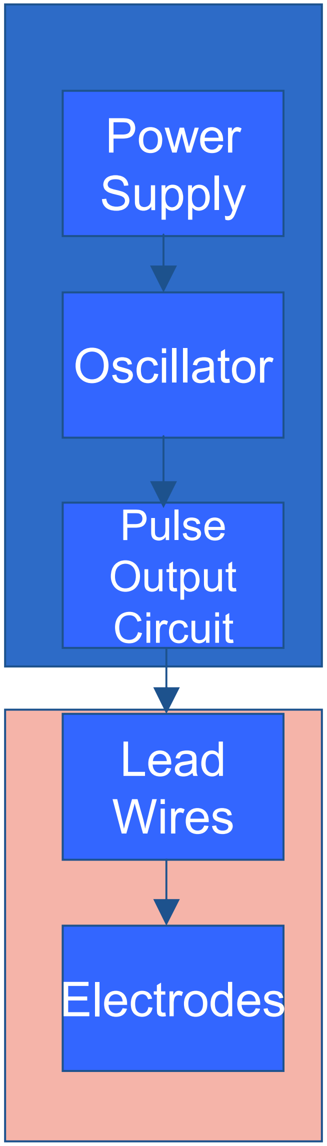
Pacemakers

Then, periodically discharge the capacitor into the heart



Cardiac Pacemakers

- Asynchronous device is free-running
  - Produces uniform stimulation regardless of cardiac activity (i.e. fixed heart-rate)
  - Block diagram (right) shows components of asynchronous pacemaker
    - Power supply – provides energy
    - Oscillator – controls pulse rate
    - Pulse output – produces stimuli
    - Lead wires – conduct stimuli
    - Electrodes – transmit stimuli to the tissue
  - The simplest form of the pacemaker; not common any longer

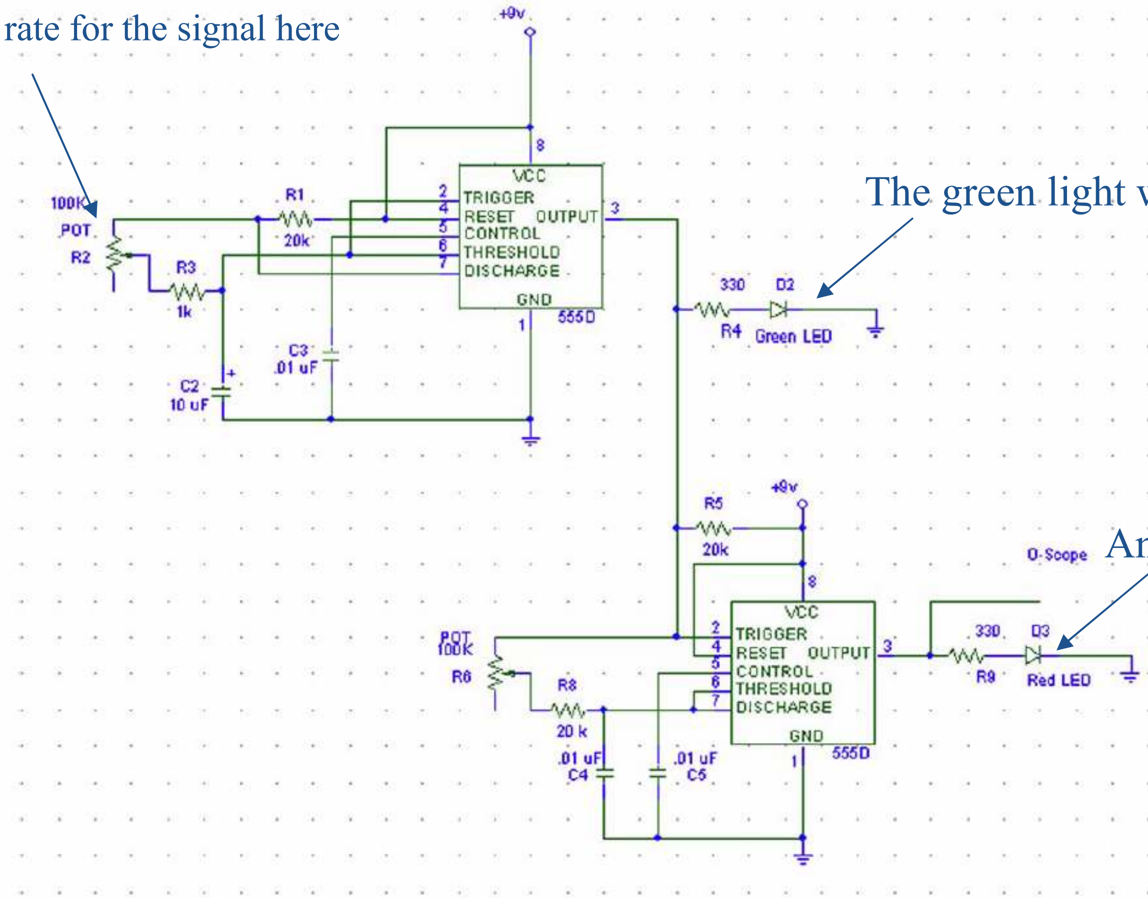


Building a Circuit

Set the rate for the signal here

The green light will then flash

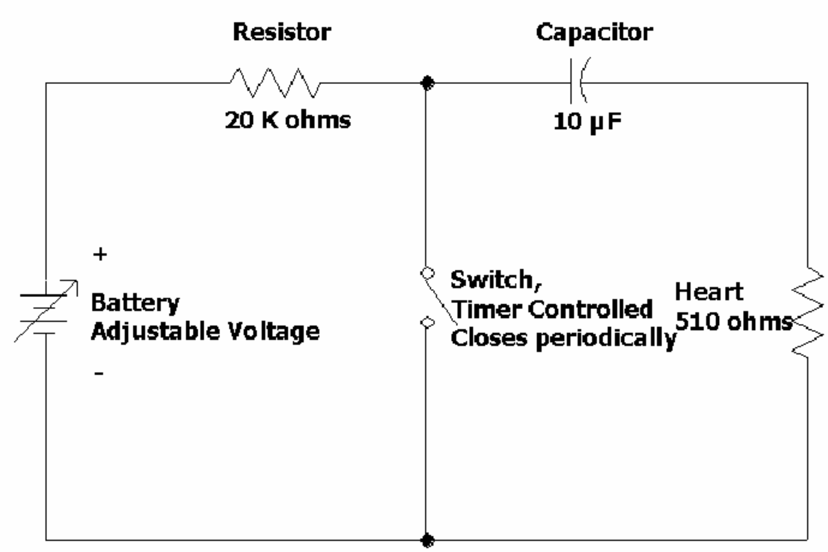
And so will the red



The Pacing Circuit - Model

The 510 ohm resistor on the right hand side of the circuit mimics the electrical load the heart places on the pacemaker.

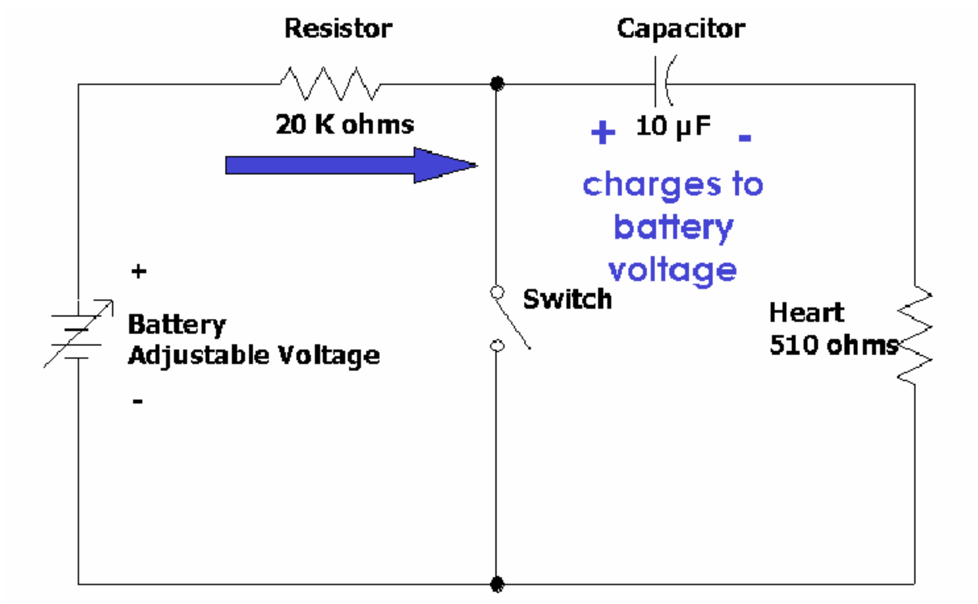
The rest of the circuit--battery, resistor and switch--complete this simple pacemaker circuit.



As the switch alternately opens and closes, the capacitor is charged and then discharged into the wires connected to the heart.

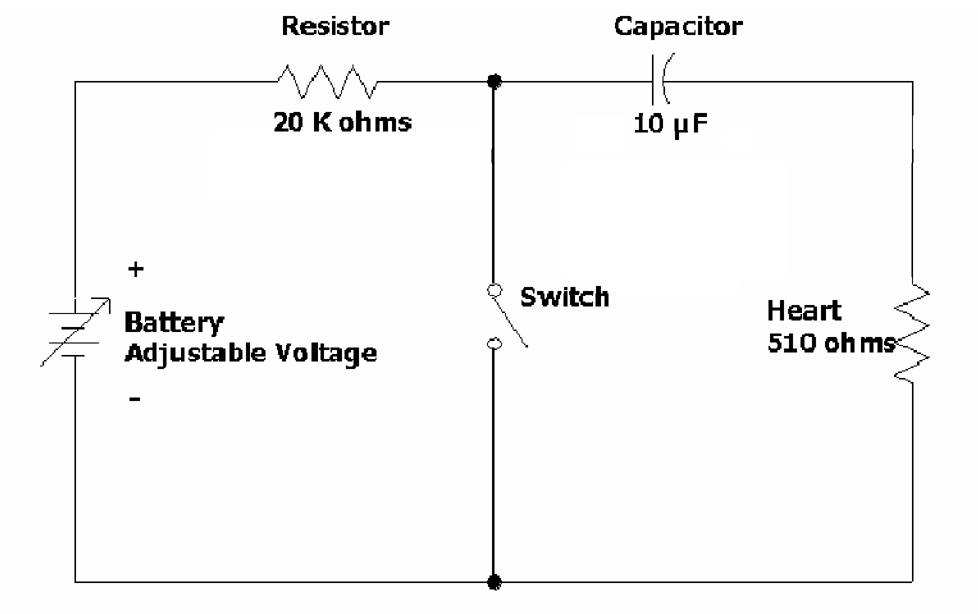
The Pacing Circuit - Model

- Let us assume that the circuit has been assembled.
- At the time of assembly, the capacitor is presumed to be completely discharged.
- There is zero voltage on the capacitor.
- Let us further assume that the switch has not yet been closed.



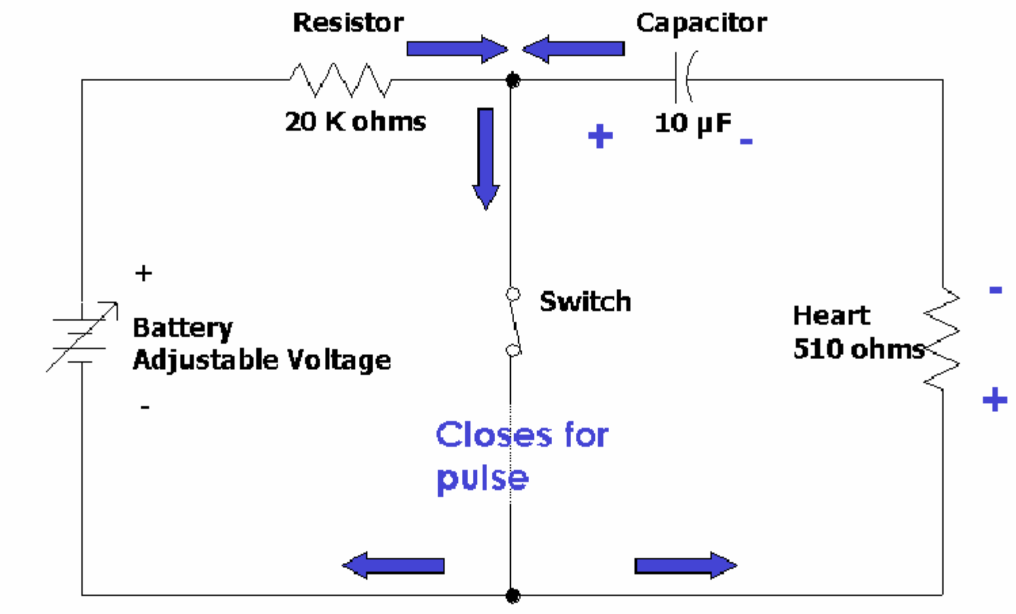
The Pacing Circuit - Model

- Current flows from the battery to charge the capacitor.
- When the circuit has reached steady state, the capacitor and battery will have equal voltage.



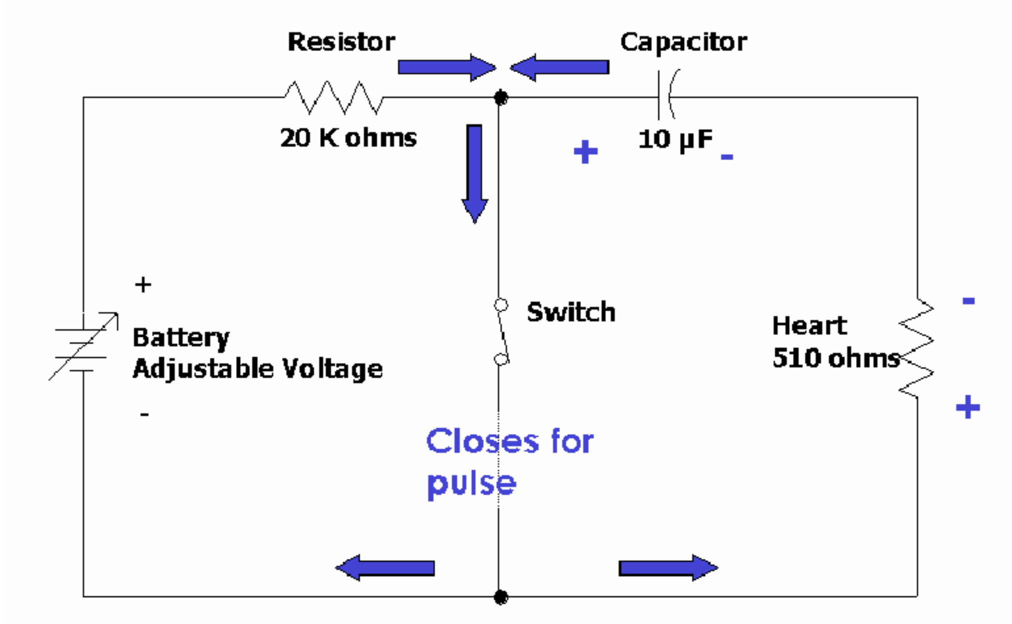
The Pacing Circuit - Model

- To generate a pulse from the circuit, the switch closes.
- When the switch closes, current flows in two loops as indicated by the blue arrows.
- In the left hand side of the circuit, current flows from the battery through the 20K ohm resistor, through the switch, and back to the battery.
- This is wasted current since it has no effect on charging or discharging the capacitor. Nor does it contribute to the current delivered to stimulate the heart.



The Pacing Circuit - Model

- In the right hand side of the circuit, current flow is caused by the discharge of the 10 µF capacitor through wires in the patient's veins to the heart.
- This is the current that stimulates the heart to contract or beat.
- Note the polarity of the pacing pulse as shown in the diagram.



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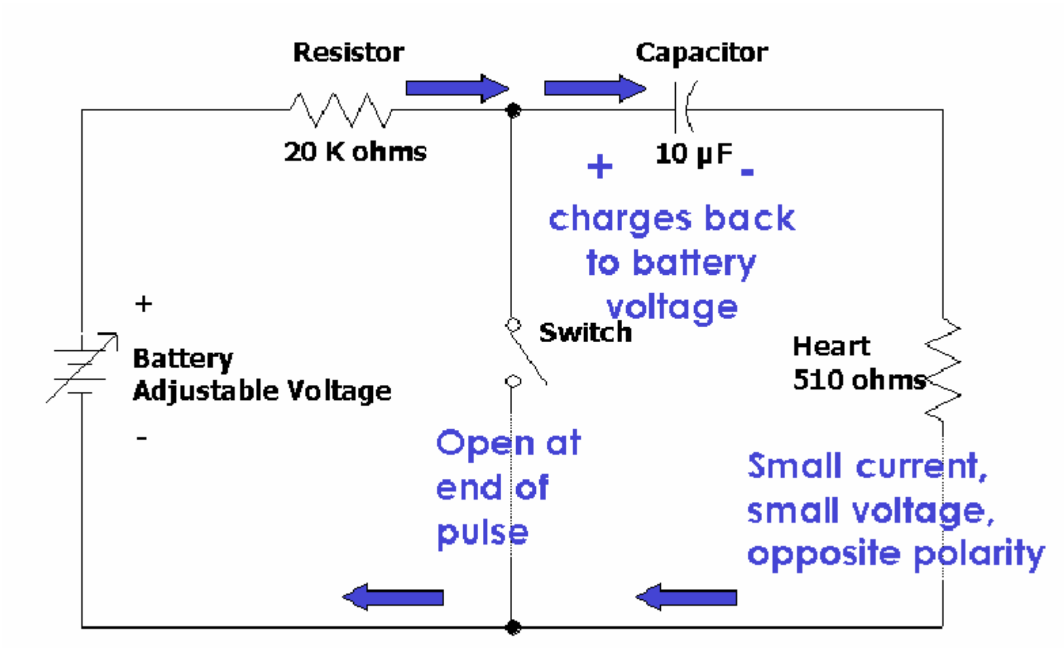
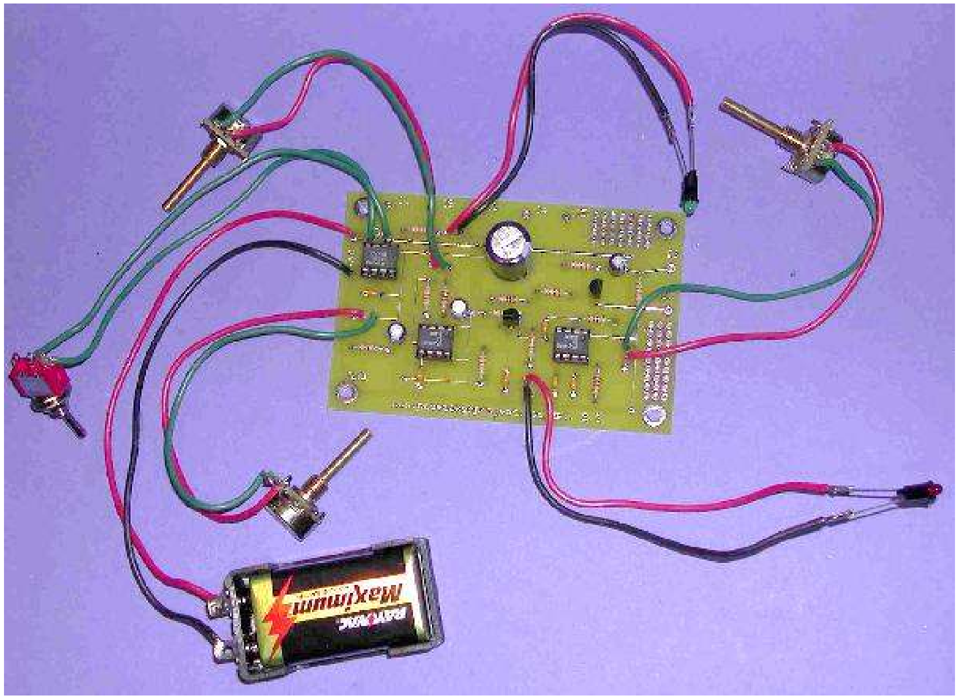
The Pacing Circuit - Model

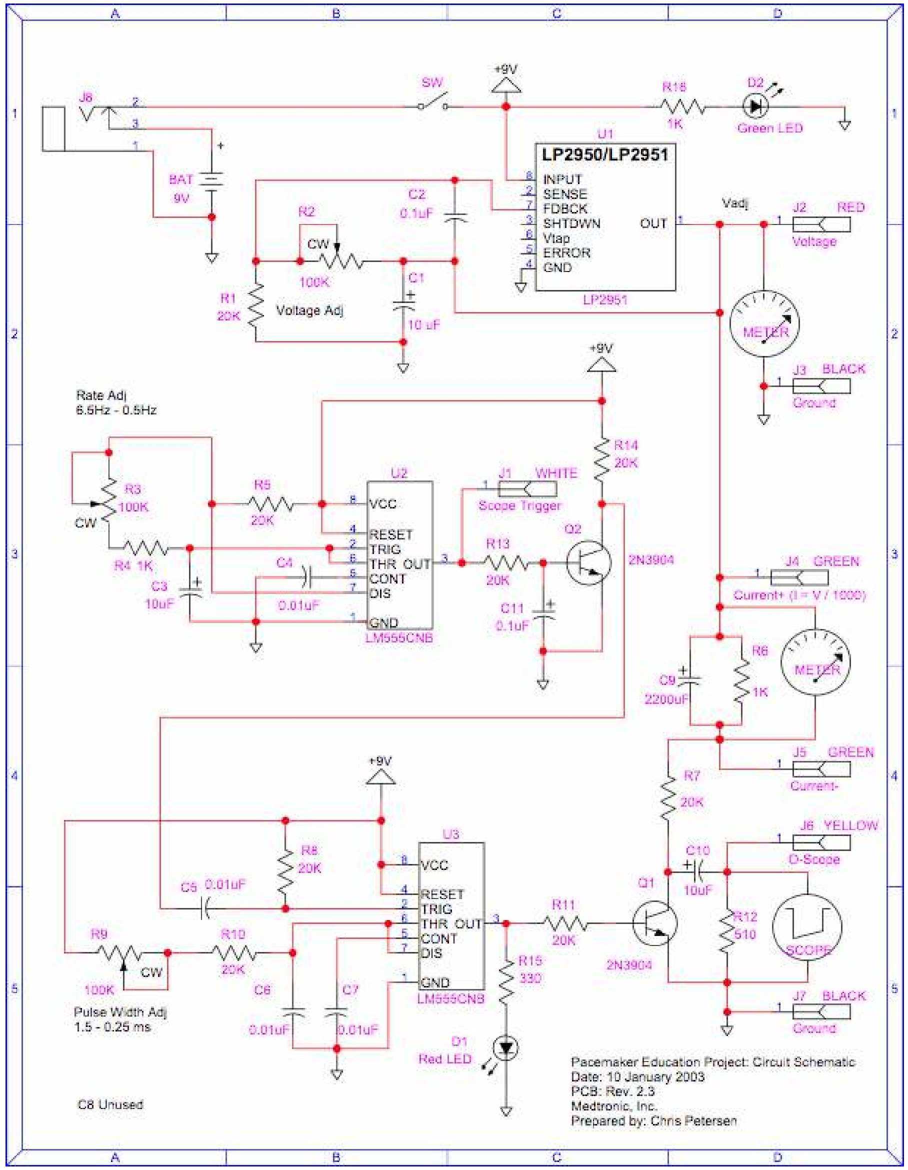
- Given sufficient time, the capacitor will receive and store a charge equal to the battery voltage.
- Periodically, the switch closes and the charged capacitor delivers an electrical pulse to the heart.
- When the switch opens, the battery recharges the capacitor.



If we were to build this…



If we were to build this…



Analyzing the Circuit

Charge and Sample period

A capacitor can be visualized as two metal plates separated by a distance.

Applying a current to one plate will drive electrons away from the other plate. This creates an electric charge between the plates.

Current is the change in charge, Q, over a period of time, t:

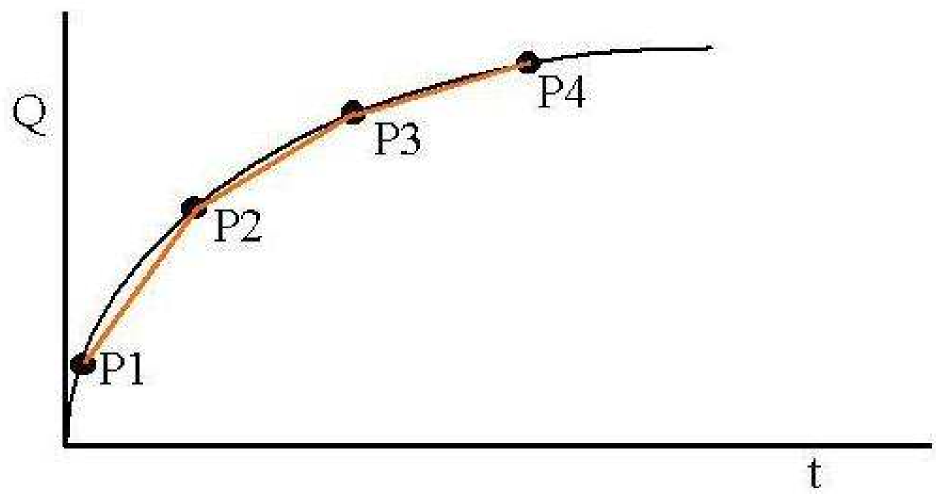
$$\frac{Q_2 - Q}{t_2 - t_1} = I \qquad \text{(eq. 1)}$$

If current varies as a function of time, care must be taken to select the time or sample period of the model.

Analyzing the Circuit

As shown in the graph, below, of a capacitor charging to a voltage, average current is calculated between points P1 and P2.

This creates a straight line approximation of the actual waveform. When a waveform varies slowly such as between P3 and P4 the approximation more closely follows the actual waveform.



Analyzing the Circuit

As the sample period shortens the points move closer together.
This limits the amount the waveform can change between points.
Thus, the accuracy of the calculation improves.
As a result, the most accurate representation is when the time between samples approaches zero:

$$\lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} = I$$

When modeling such a calculation in a computer a tradeoff must be made between accuracy and processing time.
If highly accurate results are desired of the model, the time between samples must be very small.
Thus, a very large number of calculations will have to be performed.

Analyzing the Circuit

Capacitance

The measure of capacitance, C, defines how much charge the capacitor plates can hold and how difficult it is to create that charge.

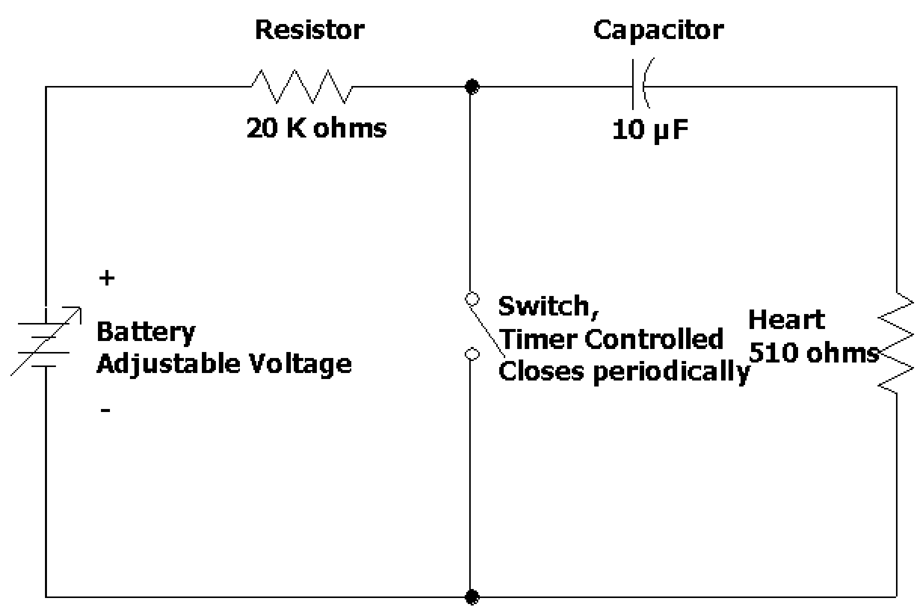
When there is a voltage difference across a capacitor the capacitance value determines how much charge is required to represent that voltage between the capacitor plates.

This can be represented as: $$V \times C = Q \qquad \text{(eq. 2)}$$

Analyzing the Circuit

The pacing circuit can take two forms depending on the switch being open or closed.

To accurately model the operation of the circuit both forms must be considered.

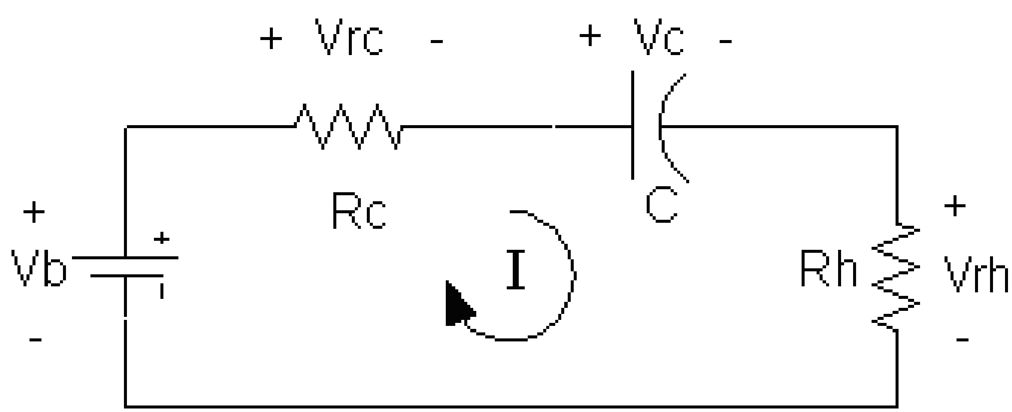


Analyzing the Circuit

Switch open, charging

When the switch is open there is one path for the flow of current from the battery, through each circuit element.

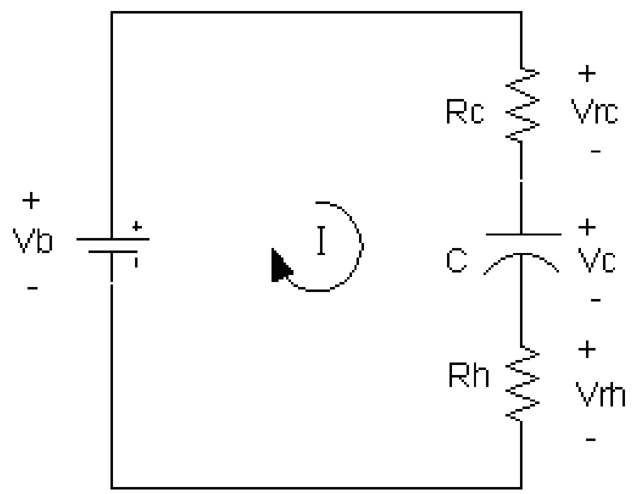
Flow of current is denoted I in the diagram below. The arrow shows the direction of positive current flow for the simulation.



Analyzing the Circuit

Current through each circuit element is identical. Current flowing from the battery positive terminal is equal to the current flowing back into the battery negative terminal.

We now analyze voltage at each point in the circuit. Redrawing the circuit helps visualize the analysis.



Analyzing the Circuit

The battery voltage is equal to the sum of the voltage drops across each circuit element, so: $V_b = V_{rc} + V_c + V_{rh}$ (eq. 3)

Ohm's Law associates voltage, current and resistance.

$V = I \times R$ (eq. 4)

By combining these equations the voltage and current at each circuit element can be determined. We now solve for current and use equation 1 to determine the change in capacitor charge as a function of time. Substituting equation 4 for voltage across the resistors, equation 3 is rewritten:

$V_b = IR_c + V_c + IR_h$ (eq. 5)

and,

$V_b = I(R_c + R_h) + V_c$ (eq. 6)

Analyzing the Circuit

Solving for current, I, yields: $$I = \frac{V_b - V_c}{R_c + R_h} \qquad \text{(eq. 7)}$$

As long as V_b and V_c are unequal current will flow.

Restating equation 1 in terms of charge:

$$\Delta Q = I \times \Delta t \qquad \text{(eq. 8)}$$

From equation 2, a changing charge implies capacitor voltage will also be changing:

$$\Delta V_c = \frac{\Delta Q}{C} \qquad \text{(eq. 9)}$$

Analyzing the Circuit

Equations 7, 8 and 9 are used to model the circuit. A three step process is used for each small time period and repeated for the entire duration of the simulation. We calculate:

1. Current - From equation 7, and the previous calculated capacitor voltage, V_c, circuit current at this instant in time is calculated.

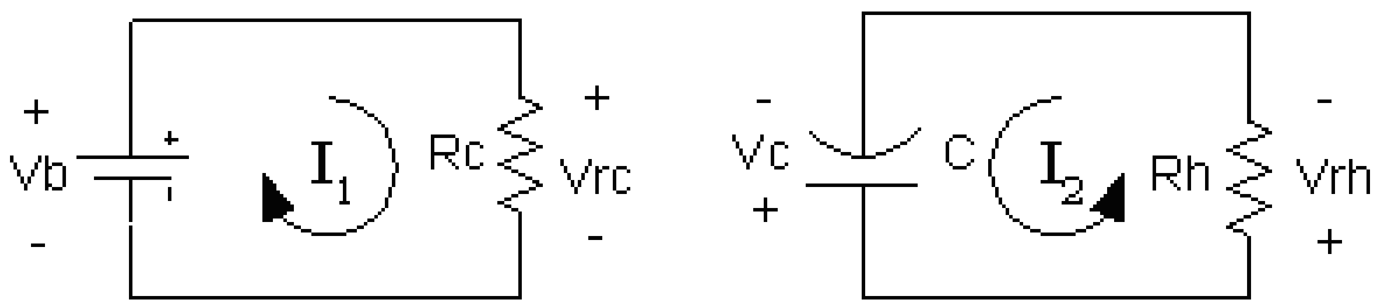
2. Change in capacitor charge - From equation 8 and the assumption that current is constant during the sample period, change in capacitor charge is calculated.

3. Change in capacitor voltage - From equation 9, V_c is updated.

Analyzing the Circuit

Switch closed, discharging

When the switch is closed two circuits are created. One consists of the battery and 20K resistor. The other is composed of the capacitor and heart, $R_{h.}$



Analyzing the Circuit

The capacitor circuit becomes simple with only the capacitor and heart resistor, so:

$$V_c = V_{rh} \qquad \text{(eq. 10)}$$

solving for current using equation 4:

$$V_c = I \times R_h \qquad \text{(eq. 11)}$$

rearranging:

$$I = \frac{V_c}{R_h} \qquad \text{(eq. 12)}$$

Analyzing the Circuit

Because the capacitor is now releasing its stored energy or discharging, current I_2 in the diagram now flows in the opposite direction as when the switch was open. The current value is now negative:

$$-I = \frac{V_c}{R_h} \quad \text{(eq. 13)}$$

When the switch is closed, equation 13 is used for the capacitor and heart resistor, R_h.

Analyzing the Circuit

Average Current

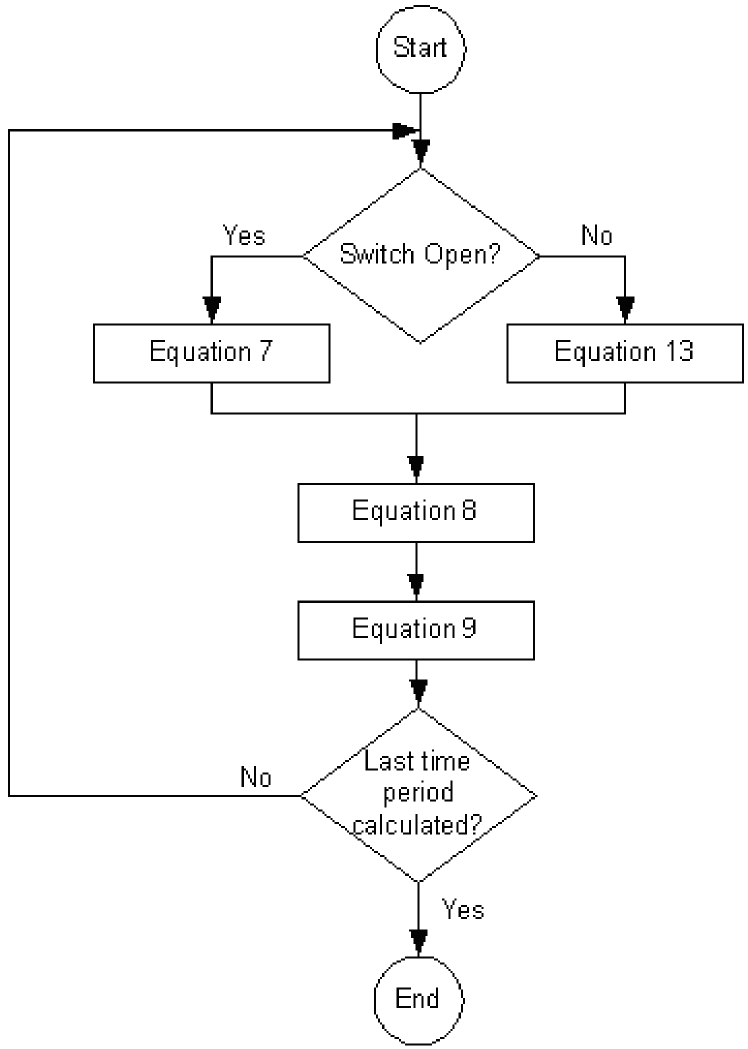
Current is the measure of the flow of charge per unit of time.

To figure expected battery life of the pacemaker circuit, one needs battery capacity and current drawn by the circuit.

Current drawn by the circuit varies as a function of time.

Average current can be computed as total charge consumed by the circuit divided by time.

Overall Flowchart



Pacemaker: Power Supply

- Lithium iodide cell used as energy source
- Open-circuit voltage of 2.8V
- Lithium iodide cell provides a long-term battery life
- High source impedance

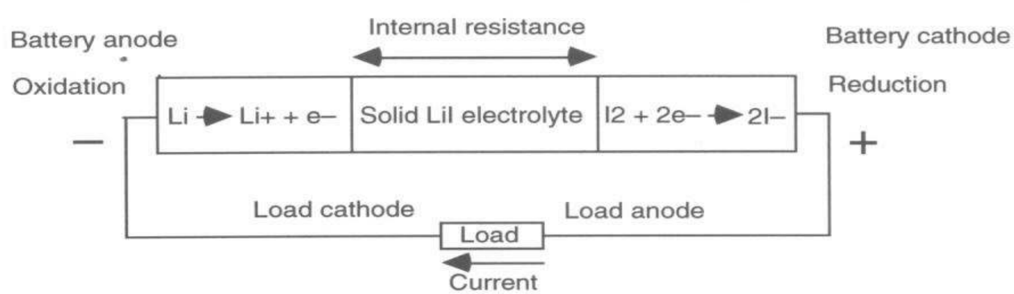


Figure 7.1 Conventional current flows from anode to cathode. The lithium reacts with the iodine to form lithium-iodide, which grows in volume and increases the resistance.

Pacemaker: Power Supply

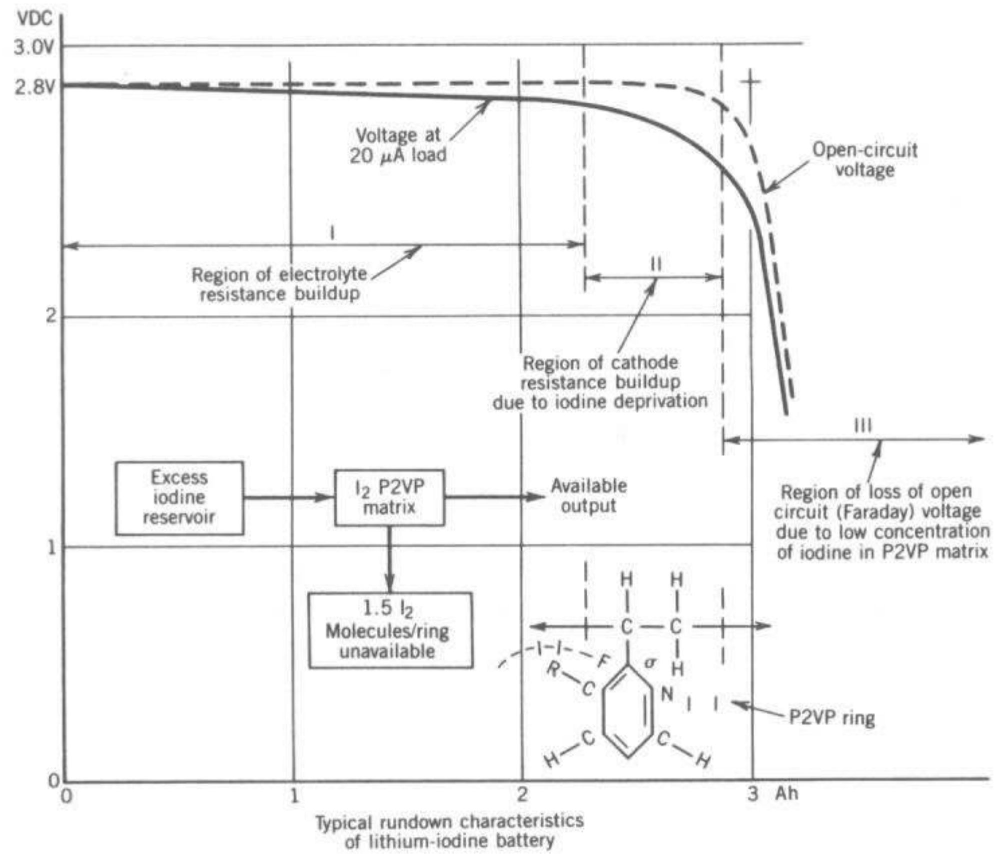


Figure 7.3 Typical low-rate, triple-phase rundown pattern of lithium–iodine battery for phase I, phase II, and phase III. From Greatbatch, W., and Seligman, L. J. 1988. Pacemakers. In J. G. Webster (ed.) *Encyclopedia of medical devices and instrumentation.* John Wiley & Sons.

Pacemaker: Output Circuit

- Output circuit produces the electrical stimuli to be applied to the heart
- Stimulus generation is triggered by the timing circuit
- Constant-voltage pulses
  - Typically rated at 5.0 to 5.5V for 500 to 600μs
- Constant-current pulses
  - Typically rated at 8 to 10mA for 1.0 to 1.2ms
- Asynchronous pacing rates of 70 to 90 beats per min; non-fixed ranges from 60 to 150bpm
- With an average power drain of 30μW, a 2 A-h battery would last more than 20 years

Pacemaker: Output Circuit

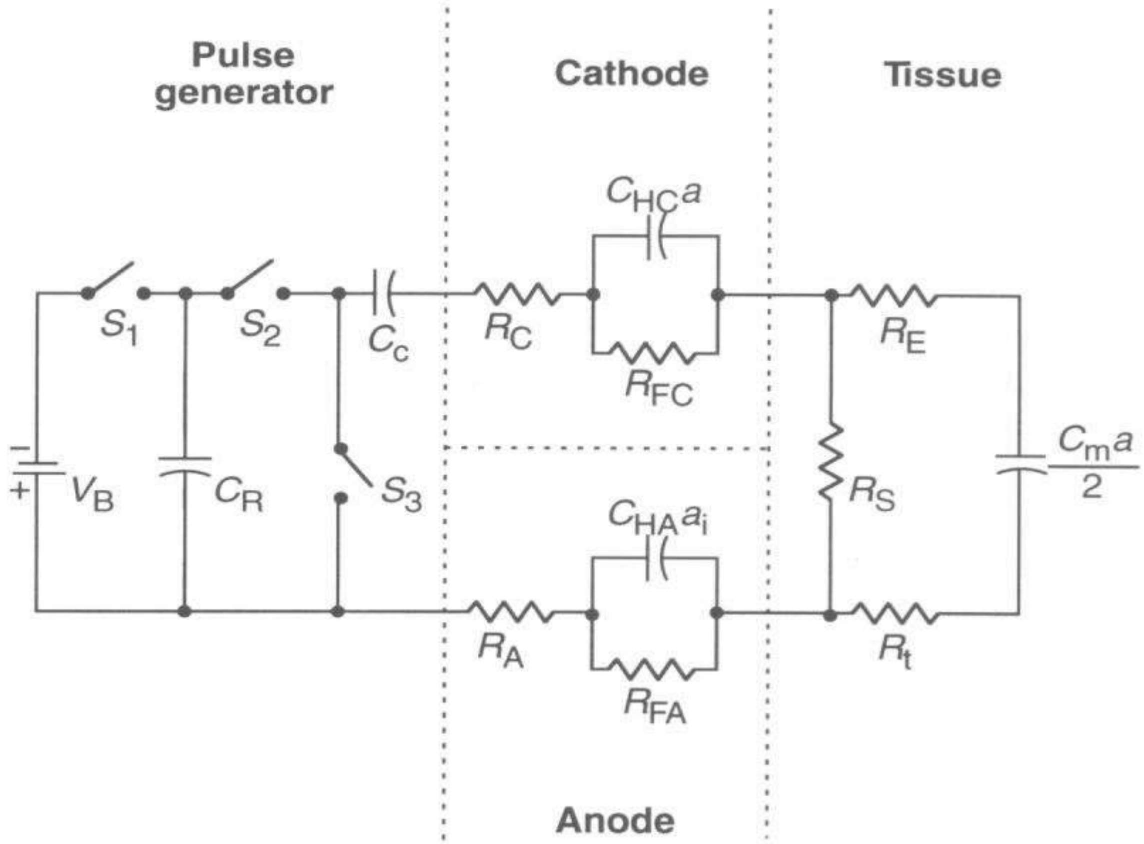


Figure 6.4 Simple pacing system electrical model as correlated with exhibited physical characteristics of: device, materials, tissue, and electrochemical components. This model is based only upon measurable system components and excludes empirical assumptions. Components include: the pulse generator, stimulating cathode, anode, and tissue. From Bolz, A., Fröhlich, R., and Schaldach, M. 1993. Elektrochemische aspekte der elektrostimulation–ein beitrag zur senkung des energiebedarfs. In M. Hubmann and R. Hardt (eds.) *Schrittmachertherapie und hämodynamik*. München: MMVverlag.

Pacemaker: Output Signal

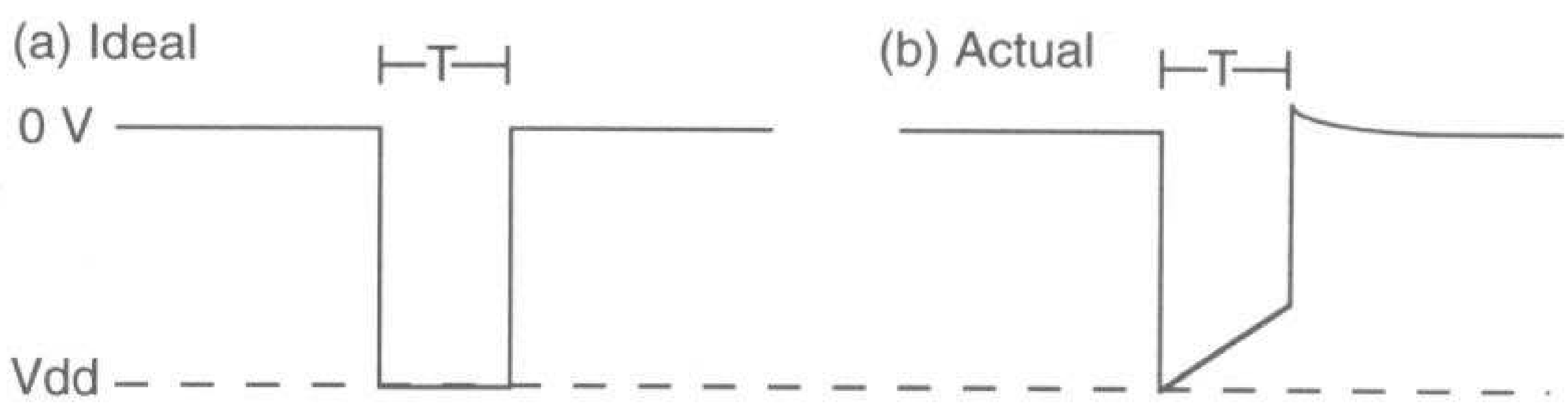
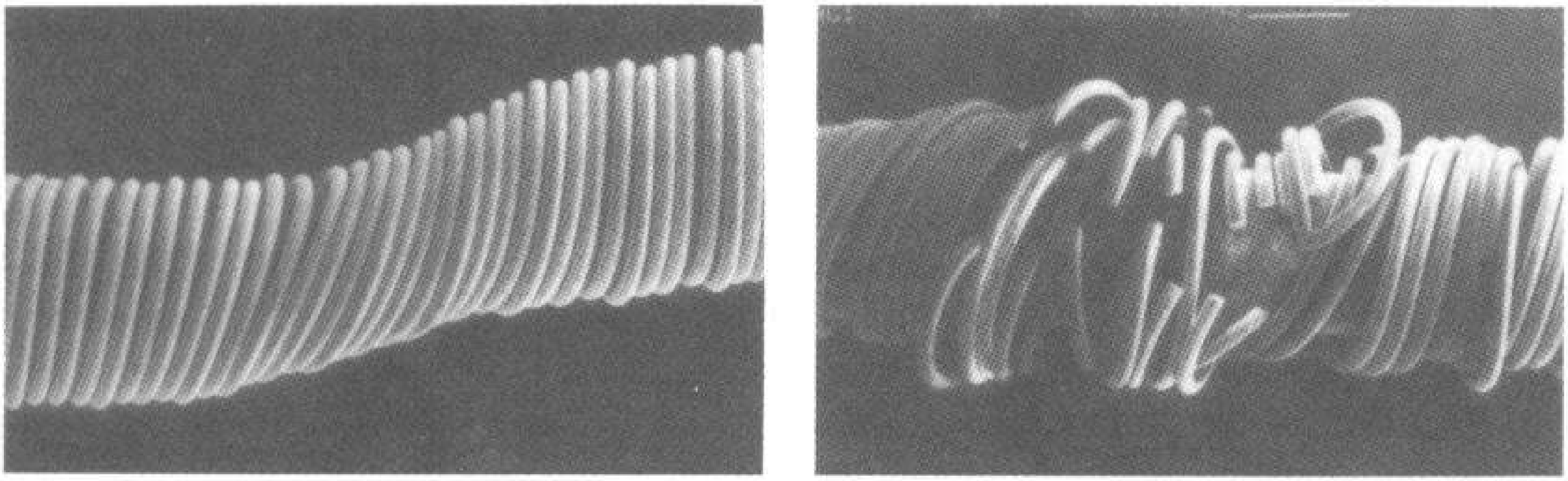


Figure 11.4 (*a*) A representation of an ideal stimulation pulse from a constant voltage stimulator. The voltage is measured from the stimulating tip to the reference (either the ring or the pacemaker can). V_{dd} can either be a fixed value, as in single voltage devices, or a programmable value, with variability dependent upon the pacemaker model. The period of stimulation T is variable in all devices. (*b*) A realistic depiction of a waveform appearing across the heart emitted from a capacitor discharge output circuit. Note that the drop in pulse voltage magnitude is dependent upon the size of the output capacitor. A larger capacitor will have a waveform which more closely resembles an ideal constant voltage. The small rise and exponential decay after the stimulus pulse is an afterpotential, which is discussed in section 11.3.

Pacemaker: Leads

- Important characteristics of the leads
  - Good conductor
  - Mechanically strong and reliable
    - Must withstand effects of motion due to beating of heart and movement of body
  - Good electrical insulation
- Current designs
  - Interwound helical coil of spring-wire alloy molded in a silicone-rubber or polyurethane cylinder
  - Coil minimizes mechanical stresses
  - Multiple strands prevent loss of stimulation in event of failure of one wire
  - Soft coating provides flexibility, electrical insulation and biological compatibility

Pacemaker: Leads



(*a*) (*b*)

Figure 6.14 Examples of compressed leads. (*a*) Compression damage to soft wire coil after a single application of compression in medial subclavian implantation. (*b*) Coil fracture morphology associated with repetitive and compressive scissoring between a patient's clavicle and first rib. From Jacobs, D. M., Fink, A. S., Miller, R. P., Anderson, W. R., McVenes, R. D., Lessar, J. F., Cobian, K. E., Staffanson, D. B., Upton, J. E., and Bubrick, M. P. 1993. Anatomical and morphological evaluation of pacemaker lead compression. *PACE*, **16**: 434–444.

Pacemaker: Electrodes

- Unipolar vs. Bipolar Pacemakers
  - Unipolar:
    - Single electrode in contact with the heart
    - Negative-going pulses are conducted
    - A large indifferent electrode is located elsewhere in the body to complete the circuit
  - Bipolar:
    - Two electrodes in contact with the heart
    - Stimuli are applied across these electrodes
- Stimulus parameters (i.e. voltage/current, duration) are consistent for both

Pacemaker: Electrodes

- Important characteristics of electrodes
  - Mechanically durable
  - Material cannot:
    - Dissolve in tissue
    - Irritate the tissue
    - Undergo electrolytic reaction due to stimulation
    - React biologically
  - Good Interface with leads
- Current designs
  - Platinum, platinum alloys, and other specialized alloys are used

Pacemaker: Electrodes

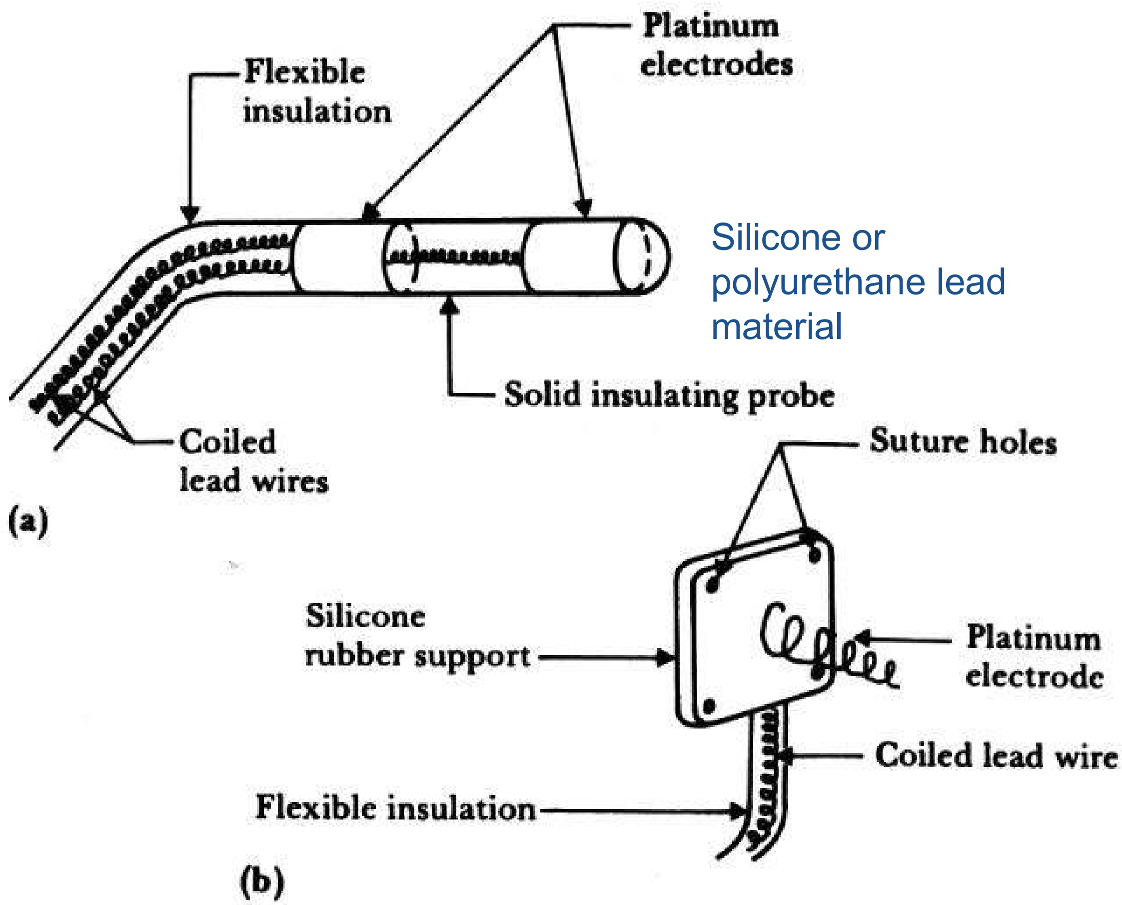


Figure 13.2 Two of the more commonly applied cardiac pacemaker electrodes (a) Bipolar intraluminal electrode. (b) Intramyocardial electrode.

Pacemaker: Electrodes

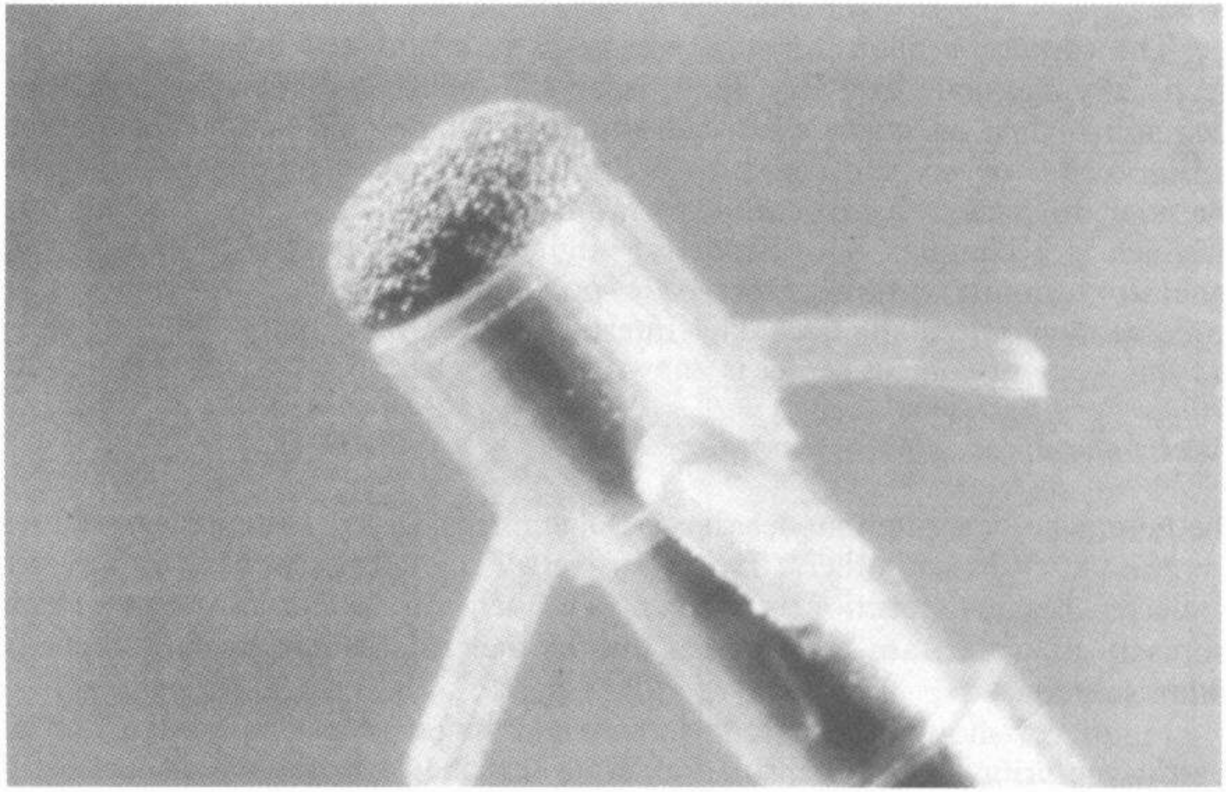


Figure 6.1 A modern pacemaker electrode. The Medtronic [Medtronic, Inc., Minneapolis, MN U.S.A.] model 4003 CapSure® unipolar tined porous electrode is an example of a porous steroid elution electrode. Behind the porous tip surface is a silicone rubber plug filled with an inflammation suppressing steroid. The secretion of this drug through the tip surface decreases inflammation and resulting encapsulation. This increases the electrode's pacing efficiency and efficacy and sensing sensitivity From Mond, H., Stokes, K. B., Helland, J., Grigg, L., Kertes, P., Pate, B., and Hunt, D. 1988. The porous titanium steroid eluting electrode: a double blind study assessing the stimulation threshold effects of steroid. *PACE*, **11**: 214–219.

Pacemaker: Electrodes

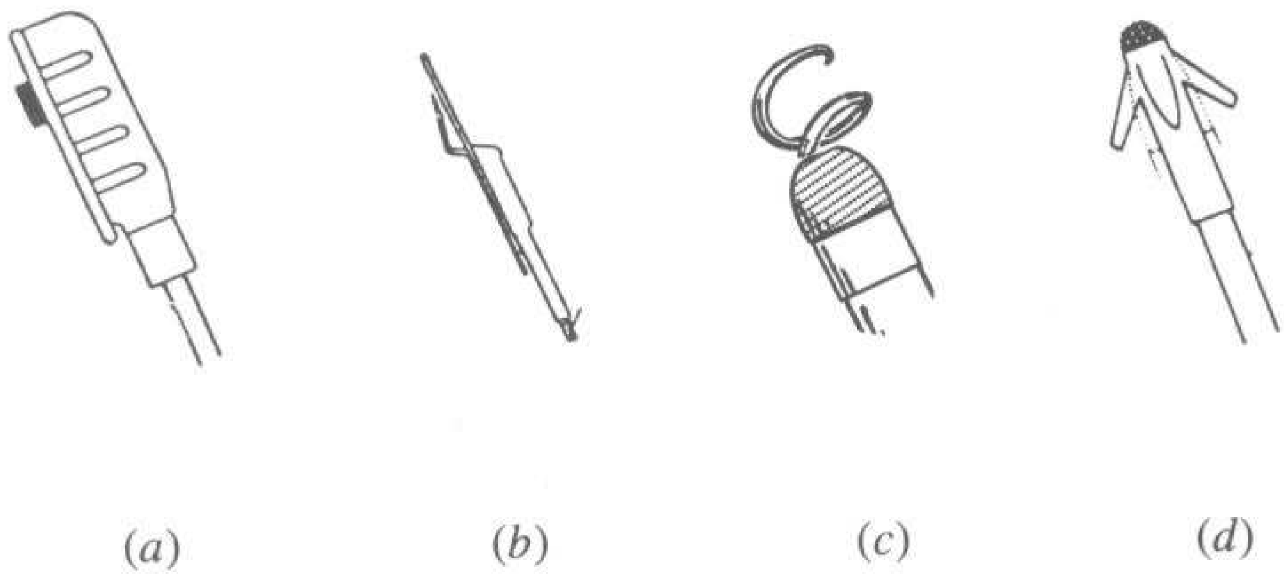


Figure 6.12 Examples of active and passive fixation electrodes. (*a*) Epicardial suture pad active fixation with disk-shaped, steroid eluting platinized porous platinum electrode in center (From Medtronic, Inc.); (*b*) Barbed epicardial polished platinum "fish–hook" electrode (Medtronic model 6917A, From Medtronic, Inc.); (*c*) Helical active fixation electrode; (*d*) Tined passive fixation electrode (BIOTRONIC, Inc. model DJP/JP, From BIOTRONIC, Inc.).

Pacemaker: Sensing Electrodes

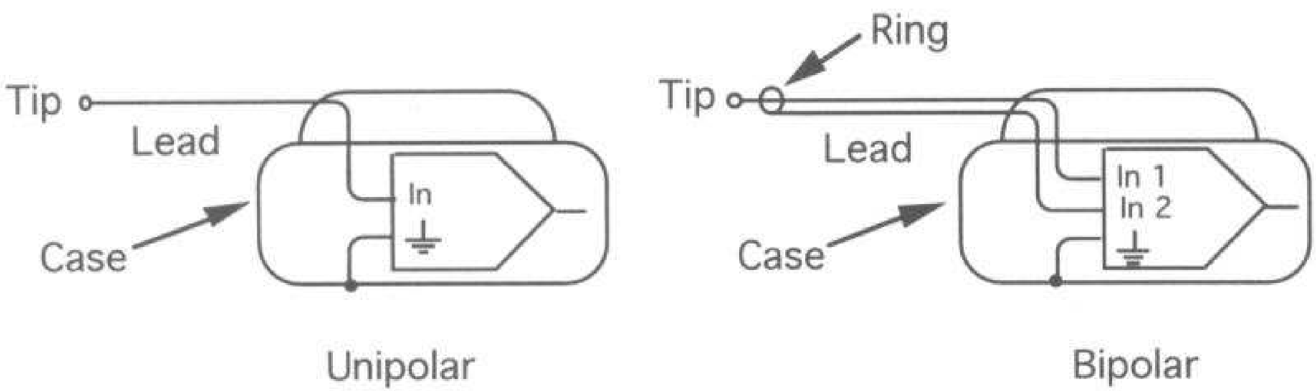


Figure 8.2 Illustration of unipolar and bipolar sensing.

- Unipolar and bipolar electrodes are also used as sensing electrodes
- Used in conjunction with advanced pacemaker technologies

Pacemaker: Packaging

- Housing for the components must be compatible and well tolerated by the body
- Needs to provide protection to circuit components to ensure reliable operation
- Size and weight must be considered
- Common designs consist of hermetically sealed titanium or stainless steel

Advanced Pacemakers

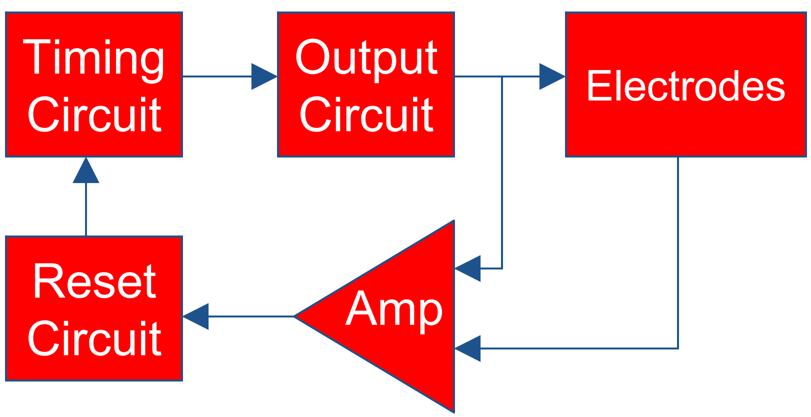
- Synchronous Pacemakers
  - Used for intermittent stimulation as opposed to continuous stimulation as in asynchronous pacemakers
- Rate-Responsive Pacemakers
  - Used for variable rates of pacing as needed based on changes in physiological demand

Synchronous Pacemakers

- Prevents possible deleterious outcomes of continuous pacing (i.e. tachycardia, fibrillation)
  - Minimizes competition between normal pacing
- Two general types of synchronous pacemakers
  - Demand pacemakers
  - Atrial-synchronous pacemakers

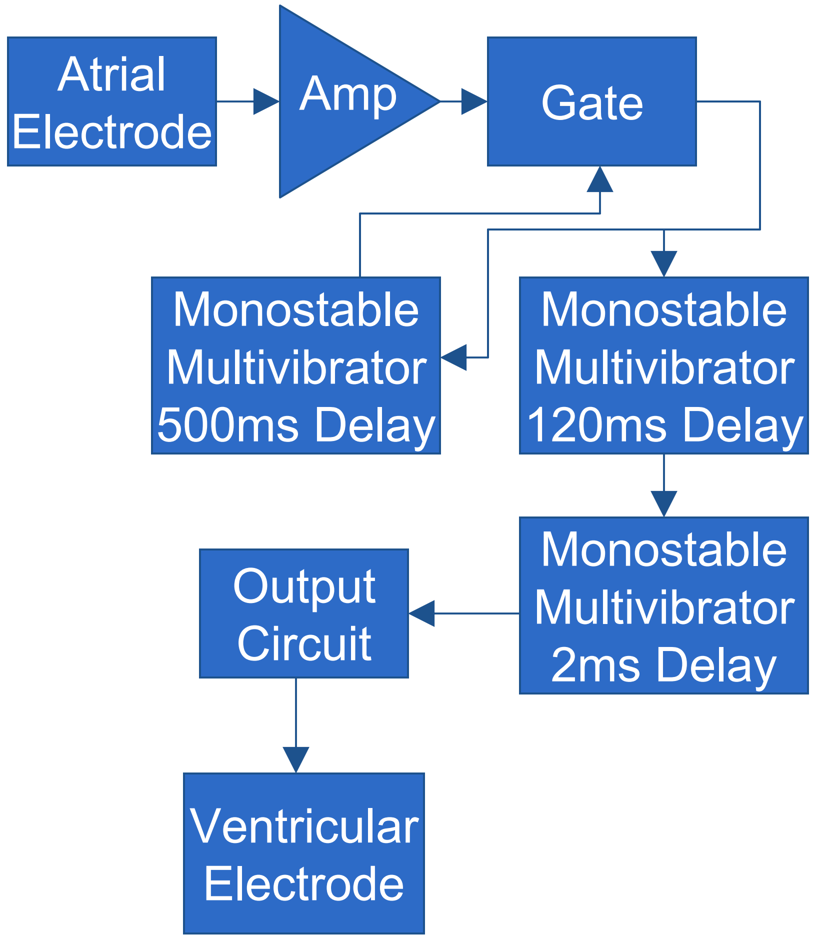
Demand Pacemakers

- Consists of asynchronous components and feedback loop
- Timing circuit runs at a fixed rate (60 to 80 bpm)
- After each stimulus, timing circuit is reset
- Normal cardiac rhythms prevent pacemaker stimulation



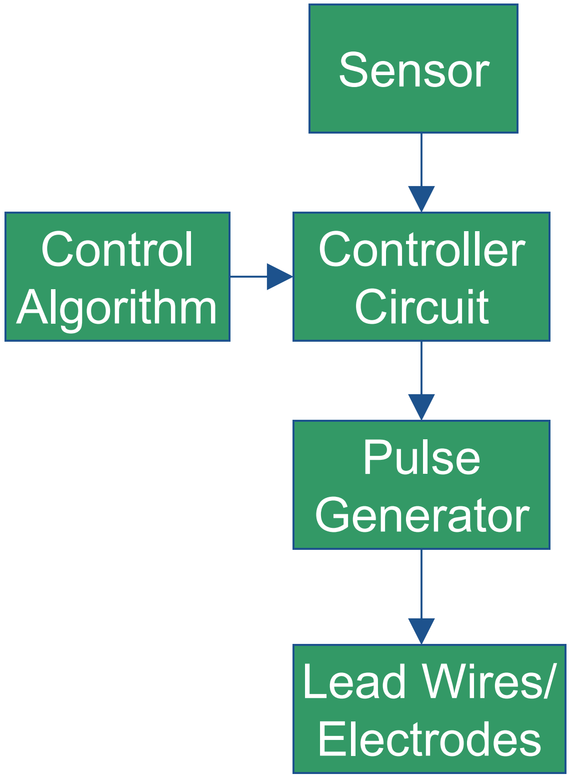
Atrial-Synchronous Pacemaker

- SA node firing triggers the pacemaker
- Delays are used to simulate natural delay from SA to AV node (120ms) and to create a refractory period (500ms)
- Output circuit controls ventricular contraction
- Combining the demand pacemaker with this design allows the device to let natural SA node firing to control the cardiac activity



Rate-Responsive Pacing

- Replicates cardiac function in a physiologically intact individual
- Sensor is used to convert physiological variable to an electrical signal that serves as an input
- Controller circuit changes heart rate based on sensor signal (demand-type pacing can be implemented here)



Rate-Responsive Pacing

Physiological Variable	Sensor
Right-ventricle blood temp	Thermistor
ECG stimulus-to-T-wave interval	ECG electrodes
ECG R-wave area	ECG electrodes
*Blood pH	Electrochemical pH electrodes
*Rate of change of right ventricular pressure	Semiconductor strain-gage pressure sensor
Venous blood S_{O_2}	Optical oximeter
Intracardiac volume changes	Electric-impedance plethysmography
Respiratory rate and/or volume	Thoracic electric-impedance plethysmography
Body vibration	Accelerometer

*Not commercially available

Rate-Responsive Pacing: Sensors

- Atrial Sensing (Atrial-Synchronous Pacing)
  - Signal commonly sensed via insertion of an extra lead in contact with atrial wall
  - Alternatively, a special lead used to stimulate the ventricle can be used
- Direct Metabolic Sensors
  - Used to measure metabolic activity of the body to correlate with cardiac output
  - Examples
    - Central Venous pH
      - Reference Ag-AgCl electrode placed in the pacemaker case and pH-sensitive Ir-IrO_2 electrode placed in right atrium
      - Can detect change in blood pH due to exercise or disease
      - Sensor problems and complexity of relationship between CO and pH are limitations

Rate-Responsive Pacing: Sensors

- Direct Metabolic Sensors
  - Examples (cont'd)
    - Mixed Venous O_2 saturation
      - Two LEDs and a photodiode are used to detect reflectivity of the blood
      - LEDs produce two distinct wavelengths detectable by photodiode
        - Red wavelenght (660nm) used to detect O_2 saturation
        - Infrared (805nm) wavelength used as reference
      - Measurements taken in venous side of the cardiovascular system
      - Low O_2 saturation will result in low reflectivity and low sensor output, which triggers the pacemaker to increase the heart rate for increased cardiac output
      - Power requirements, lead placement and information lag due to time required to cycle through the body are limitations

Rate-Responsive Pacing: Sensors

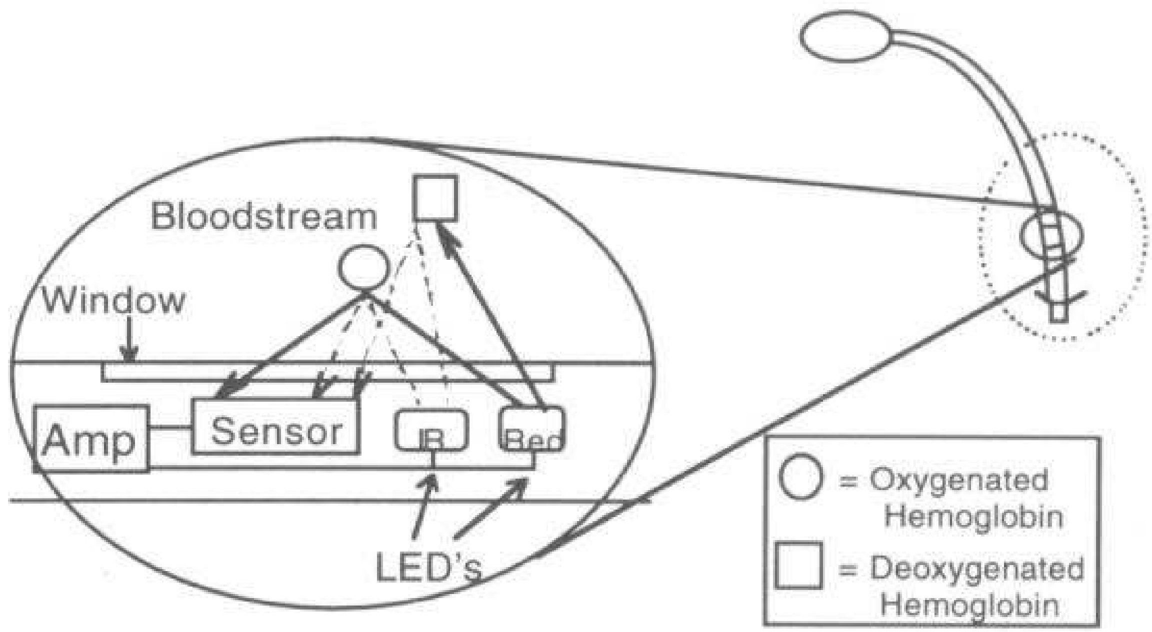


Figure 13.2 Oxygen saturation sensor. Oxygenated hemoglobin in the right ventricle reflects the red LED's light. Conversely the deoxygenated hemoglobin absorbs it. Both reflect infrared light.

Rate-Responsive Pacing: Sensors

- Indirect Metabolic Sensors
  - Allow for estimation of metabolic activity for control of cardiac output
  - Examples
    - Ventilation rate (estimation of oxygen intake)
      - Measured by analyzing the impedance between pacemaker electrode and pacemaker case
      - Three electrode system typically used
      - Changes in chest impedance occur with breathing
      - Signal requires filtering to obtain ventilation rate
      - Motion artifacts of the chest and inability to detect differences in shallow and deep breathing are limitations of this system

Rate-Responsive Pacing: Sensors

- Indirect Metabolic Sensors
  - Examples (cont'd)
    - Mixed Venous Temperature
      - A small ceramic thermistor in a lead is placed in the right ventricle
      - Blood temperature is a good indicator of metabolic need and the sensor is durable
      - A special pacing lead is required and the small and slow signal may result in a slower than desirable response (e.g. a short sprint will not increase body temperature much when heart rate would naturally increase)

Rate-Responsive Pacing: Sensors

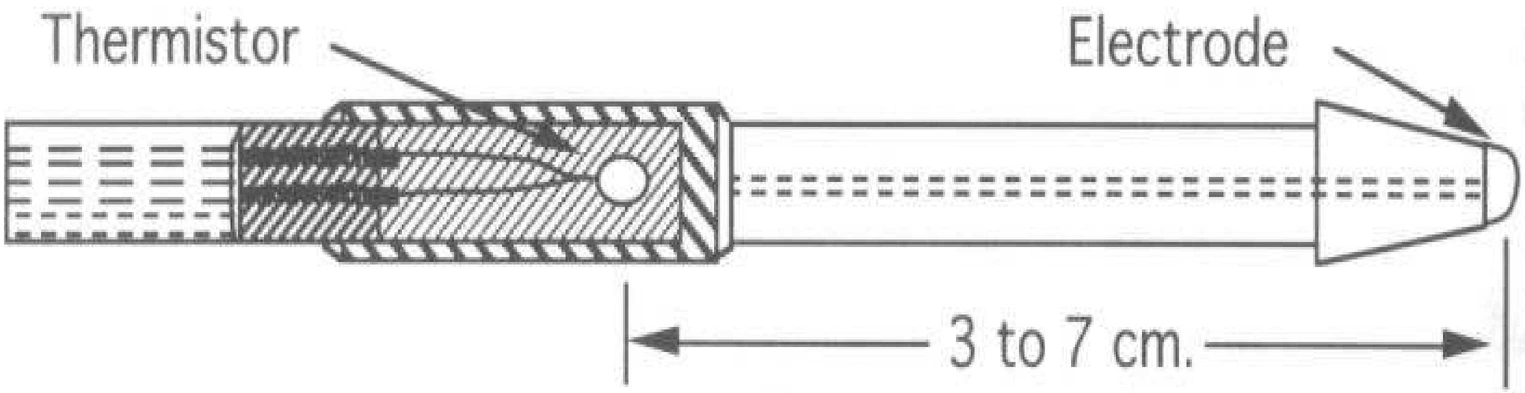


Figure 15.6 Pacing/sensing electrode with integrated thermistor Adapted from Cook et al. (1985).

Rate-Responsive Pacing: Sensors

- Non-metabolic Physiological Sensors
  - Used to detect changes that would naturally cause an increased heart rate
  - Examples
    - Q-T Interval
      - Measures the time between the QRS wave and the T wave
      - During exercise or stress, the Q-T interval decreases due to natural catecholamine production
      - Pacing leads are used to detect intracardiac ventricular electrogram
      - This is the most successful physiological sensor
        - Standard leads are used
        - Little to no additional power is required
        - Rapid response time
      - Some problems occur with detection of repolarization signals

Rate-Responsive Pacing: Sensors

- Non-metabolic Physiological Sensors
  - Examples (cont'd)
    - Ventricular Depolarization Gradient (VDG) or Evoked Ventricular Potential
      - Similar to Q-T Interval sensors, but measure area under the paced QRS wave
      - The area is affected by heart rate
        - VDG is directly proportional to heart rate
      - Standard pacing electrodes are used
      - No additional power is required
      - Rapid response time
      - Can also detect emotion and stress
      - Are affected by some drugs and electrode polarization

Rate-Responsive Pacing: Sensors

- Non-metabolic Physiological Sensors
  - Examples (cont'd)
    - Systolic Indices
      - Stroke Volume
        - Measured via impedance measurements
        - Increases with exercise
      - Pre-ejection Phase
        - The time between the onset of ventricular depolarization and the opening of the aortic valve
        - Measured via impedance measurements
        - Decreases with exercise
      - Motion artifacts and power requirements are limitations

Rate-Responsive Pacing: Sensors

- Non-metabolic Physiological Sensors
  - Examples (cont'd)
    - Pressure
      - Mean arterial blood pressure is naturally maintained to be constant
      - Magnitude and rate of change of pressure increases with exercise
      - Piezoelectric sensor is placed in the right ventricle
        - Measures rate of change of pressure, from which mean pressure can be inferred
      - Silicon strain gage pressure sensor can be used to directly measure mean pressure
      - Specialized leads are required

RATE-RESPONSIVE PACING: SENSORS

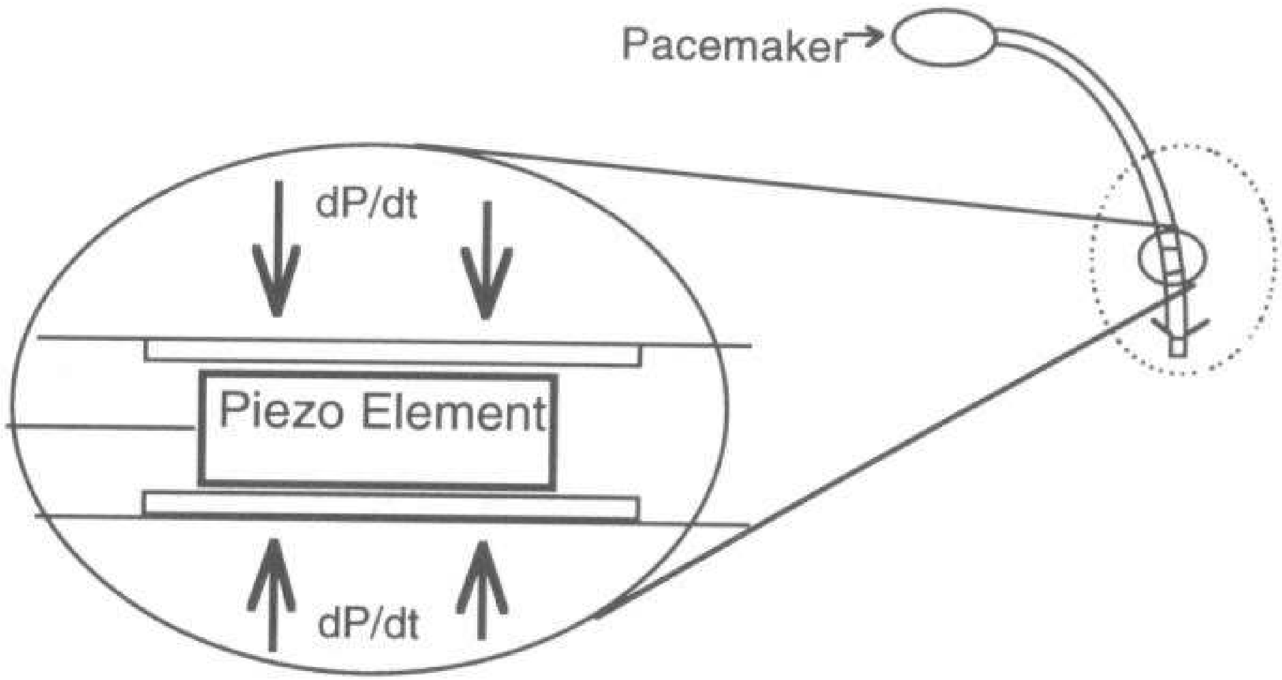


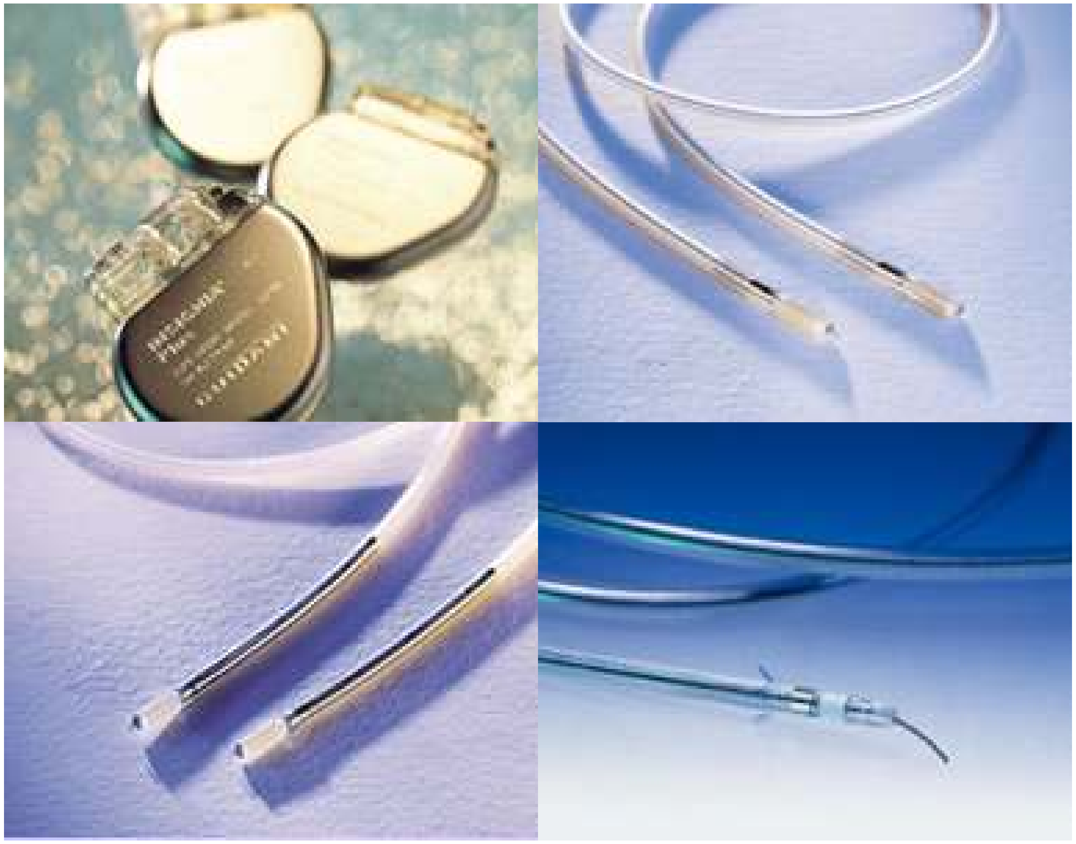
Figure 13.3 Blood pressure derivative sensor. As the blood pressure changes around the sensor, the wall deflection will change. Deflections of the wall apply a force on the piezo element, which creates an electrical signal.

Rate-Responsive Pacing: Sensors

- Direct Activity Sensors
  - Most common is the Motion-Detecting Pacemaker
    - Uses an accelerometer or a vibration sensor placed in the case to estimate activity
    - Long-term reliability, minimal power requirements and rapid response are advantages
    - Current specificity level of the sensor is a problem
      - e.g. Going up stairs is harder work than going down; however, the latter causes heavier footsteps and thus stronger pressure waves in the chest, which could cause a higher heart rate when going down than when going up the stairs
- Multiple Sensors
  - A combination of sensors is often used

Commercial Examples

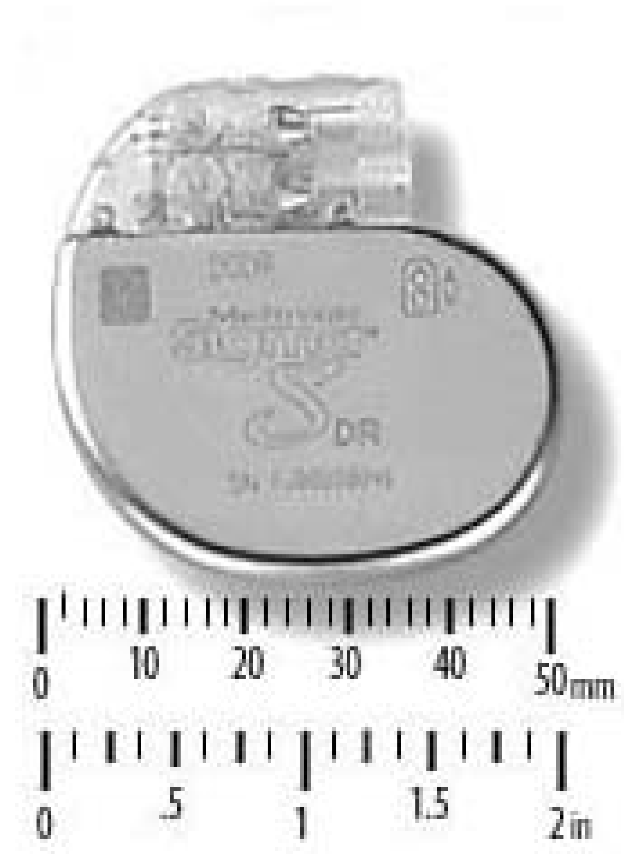
- Major Cardiac Rhythm Management Companies
  - Guidant (J & J)
  - Medtronic
  - St. Jude
- Standard pacemaker packaging and design
- Various lead designs serve several different purposes



Taken from www.guidant.com

Commercial Examples

- Typical size and shape of the implantable pacemaker
- Upper portion is used for interfacing with the leads



Taken from www.medtronic.com

Defibrillators

- Used to reverse fibrillation of the heart
- Fibrillation leads to loss of cardiac output and irreversible brain damage or death if not reversed within 5 minutes of onset
- Electric shock can be used to reestablish normal activity
- Four basic types of defibrillators
  - AC defibrillator
  - Capacitive-discharge defibrillator
  - Capacitive-discharge delay-line defibrillator
  - Rectangular-wave defibrillator

Defibrillators

- Defibrillation by electric shock is carried out by passing current through electrodes placed:
  - Directly on the heart – requires low level of current and surgical exposure of the heart
  - Transthoracically, by using large-area electrodes on the anterior thorax – requires higher level of current

Defibrillator: Capacitive-Discharge

- A short high-amplitude defibrillation pulse is created using this circuit
- The clinician discharges the capacitor by pressing a switch when the electrodes are firmly in place
- Once complete, the switch automatically returns to the original position

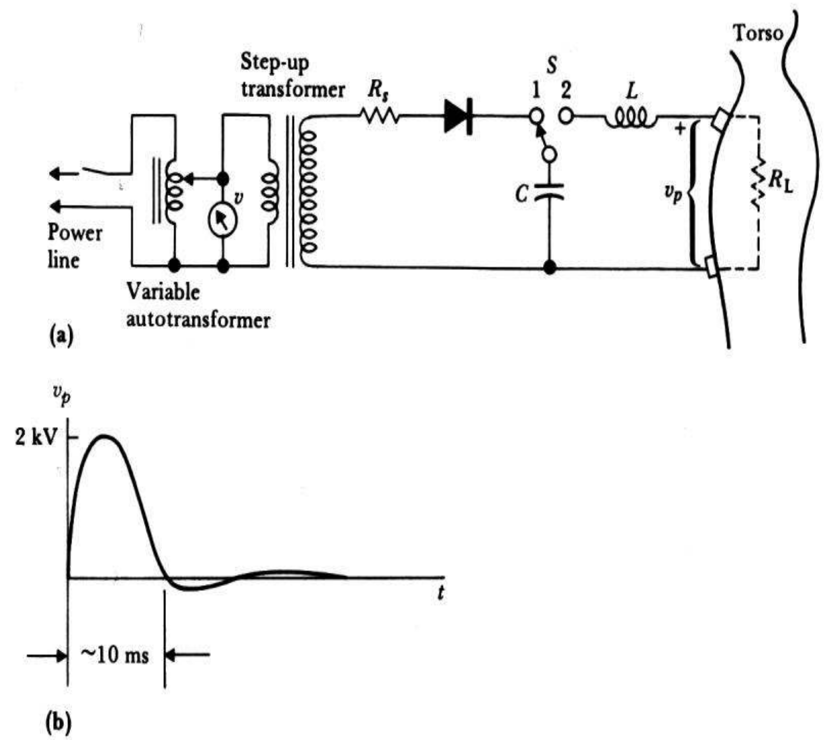


Figure 13.9 (a) Basic circuit diagram for a capacitive-discharge type of cardiac defibrillator. (b) A typical waveform of the discharge pulse. The actual waveshape is strongly dependent on the values of L, C, and the torso resistance R_L.

Defibrillator: Power Supply

- Using this design, defibrillation uses:
  - 50 to 100 Joules of energy when electrodes are applied directly to the heart
  - Up to 400 Joules when applied externally
- Energy stored in the capacitor follows:

$$E = \frac{Cv^2}{2}$$

- Capacitors used range from 10 to 50μF
- Voltage using these capacitors and max energy (400J) ranges from 1 to 3 kV
- Energy loss result in the delivery of less than theoretical energy to the heart

Defibrillator: Power Supply

- Lithium silver vanadium pentoxide battery is used
  - High energy density
  - Low internal resistance provides information regarding the end of battery life (not easy to detect in some other batteries)
- Lithium iodine battery used to power low-voltage circuits

Defibrillator: Rectangular-Wave

- Capacitor is discharged through the subject by turning on a series silicon-controlled rectifier
- When sufficient energy has been delivered to the subject, a shunt silicon-controlled rectifier short-circuits the capacitor and terminates the pulse, eliminating a long discharge tail of the waveform
- Output control can be obtained by varying:
  - Voltage on the capacitor
  - Duration of discharge
- Advantages of this design:
  - Requires less peak current
  - Requires no inductor
  - Makes it possible to use physically smaller electrolytic capacitors
  - Does not require relays

Defibrillator: Output Pulses

Figure 19.7 Defibrillation wave forms. The monophasic truncated exponential waveform is produced from a capacitor discharge that is truncated at about 5 ms. The biphasic truncated exponential waveform has its leads switched half way through.

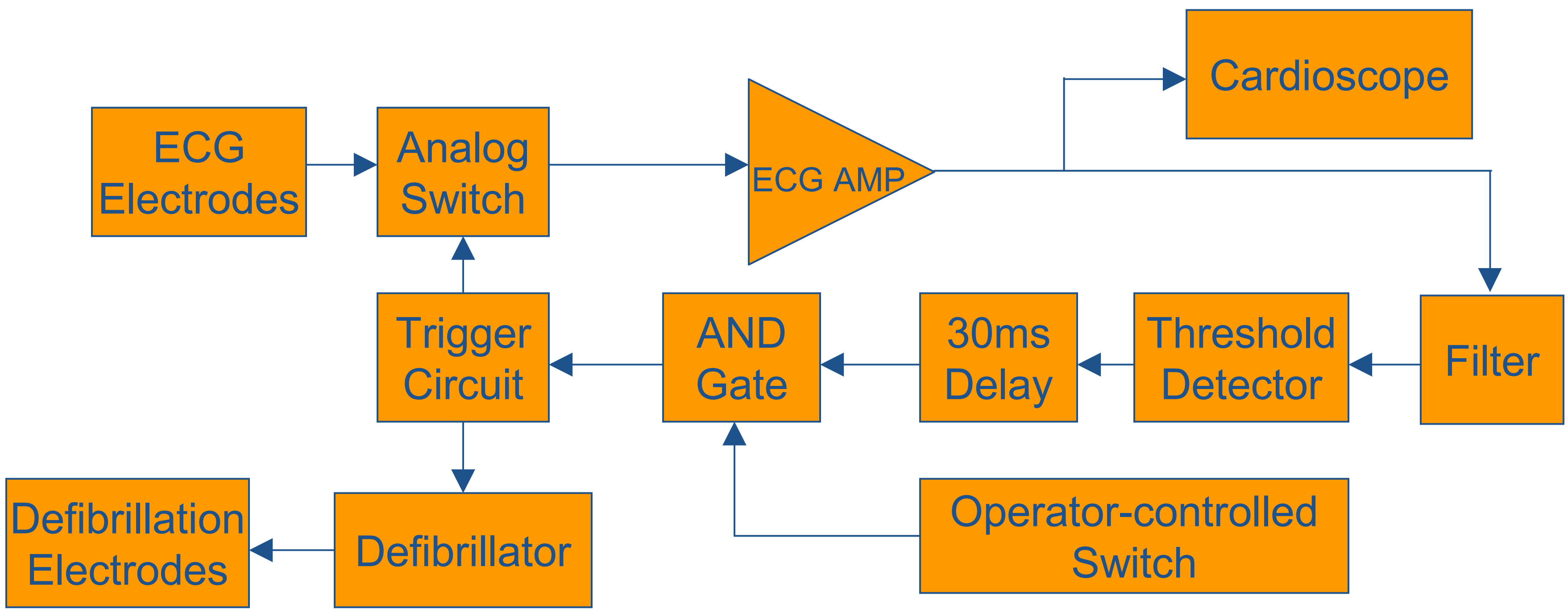
- Monophasic pulse width is typically programmable from 3.0 to 12.0 msec
- Biphasic positive pulse width is typically programmable from 3.0 to 10.0 msec, while the negative pulse is from 1.0 to 10.0 msec
- Studies suggest that biphasic pulses yield increased defibrillation efficacy with respect to monophasic pulses

Defibrillator: Electrodes

- Excellent contact with the body is essential
  - Serious burns can occur if proper contact is not maintained during discharge
- Sufficient insulation is required
  - Prevents discharge into the physician
- Three types are used:
  - Internal – used for direct cardiac stimulation
  - External – used for transthoracic stimulation
  - Disposable – used externally

Cardioverters

- Special defibrillator constructed to have synchronizing circuitry so that the output occurs immediately following an R wave
  - In patients with atrial arrhythmia
- The design is a combination of a cardiac monitor and a defibrillator



Implantable Automatic Defibrillators

- Similar in appearance to the implantable pacemakers, consisting of:
  - A means of sensing cardiac fibrillation or tachycardia
  - A power supply and energy storage component
  - Electrodes for delivery of stimuli
- Defibrillation electrodes are used to detect electrophysiological signals
- Processing of signals is used to control stimulation
- Energy storage is necessary to provide stimuli of 5 to 30 Joules

Implantable Automatic Defibrillators

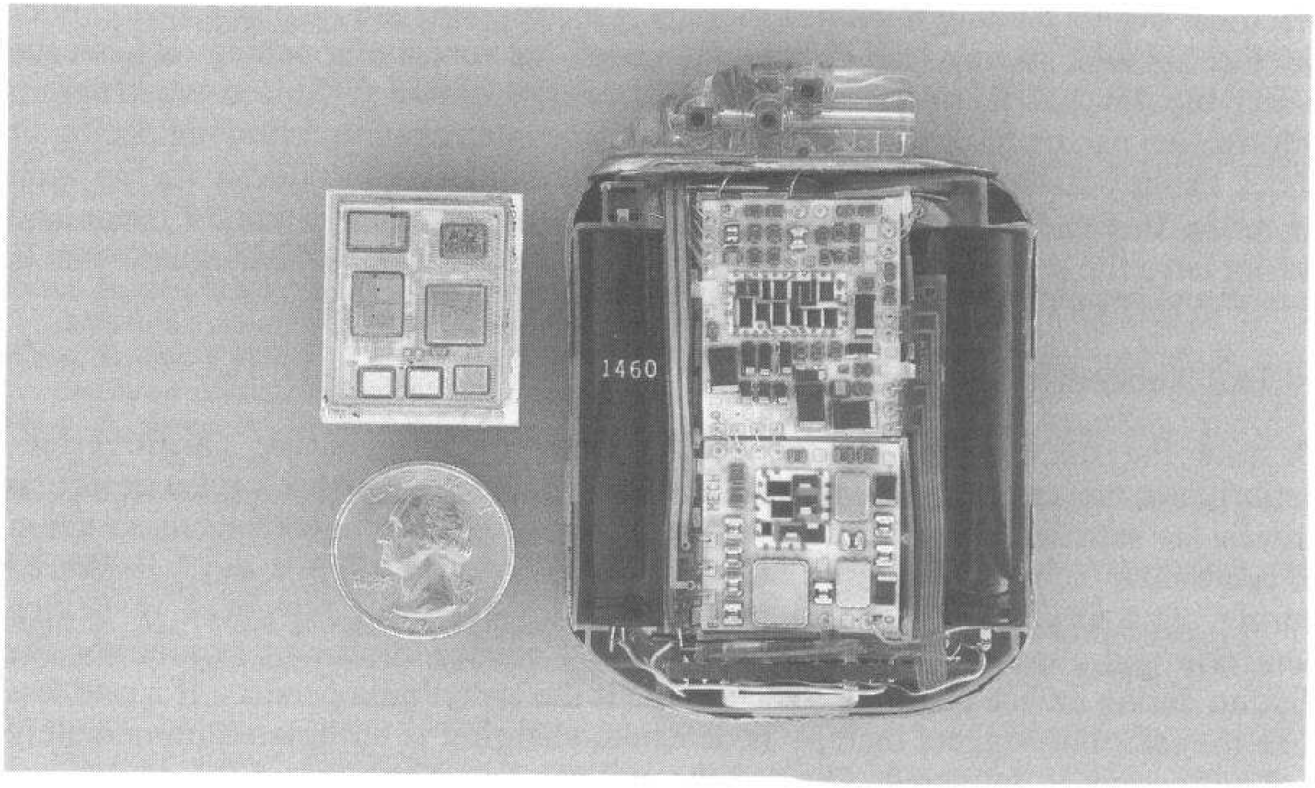


Figure 19.13 This cutaway view of a Jewel™PCD® Model 7219D implantable cardioverter–defibrillator from Medtronic, Inc., Minneapolis, MN shows that the battery and capacitor consume a large portion of the volume.

Commercial Examples

Taken from www.guidant.com

Taken from www.medtronic.com

References

- Webster, JG (1998). Medical Instrumentation. John Wiley & Sons, Inc., New York, NY.
- Webster, JG (1995). Design of Cardiac Pacemakers. IEEE Press, Piscataway, NJ.

Modern External Defibrillator

External Defibrillator At A Railway Station

Algorithm For Using Defibrillator