University of Zagreb
Faculty of Electrical Engineering and Computing

Biomedical Instrumetation

Electrical stimulation

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Electrical stimulation

- The effect of electric current on excitable cells and tissues:
  - muscle cells
  - nerve cells
- Suitable because it can be carried out with electrodes, and electrical parameters can be easily controlled
- What other possible modes of muscle and nerve excitation do you know?
- What are the goals of the electrical excitation of tissues?

Electrical stimulation - sistematization

- **By function**
  - Diagnostic
    - Nerve conduction velocity, sensitivity ...
  - Therapeutic
    - rehabilitation, functional electrical stimulation of sceletal muscles, electrostimulation of heart (pacing), defibrillation ...
- **By duration of stimulation**
  - Temporary
    - short, periodically short-term (e.g. rehabilitation, defibrilation, suppressing pain,; superficial or subcutaneous electrodes)
  - Permanent
    - maintenance of vital functions (heart, diaphragm), improving the quality of life (deep brain stimulation, "rate adaptive pacing," the suppression of pain ...) ; implantation of electrodes
- **By setting of the stimulator :**
  - Outer (external)
  - Installation (implantation)

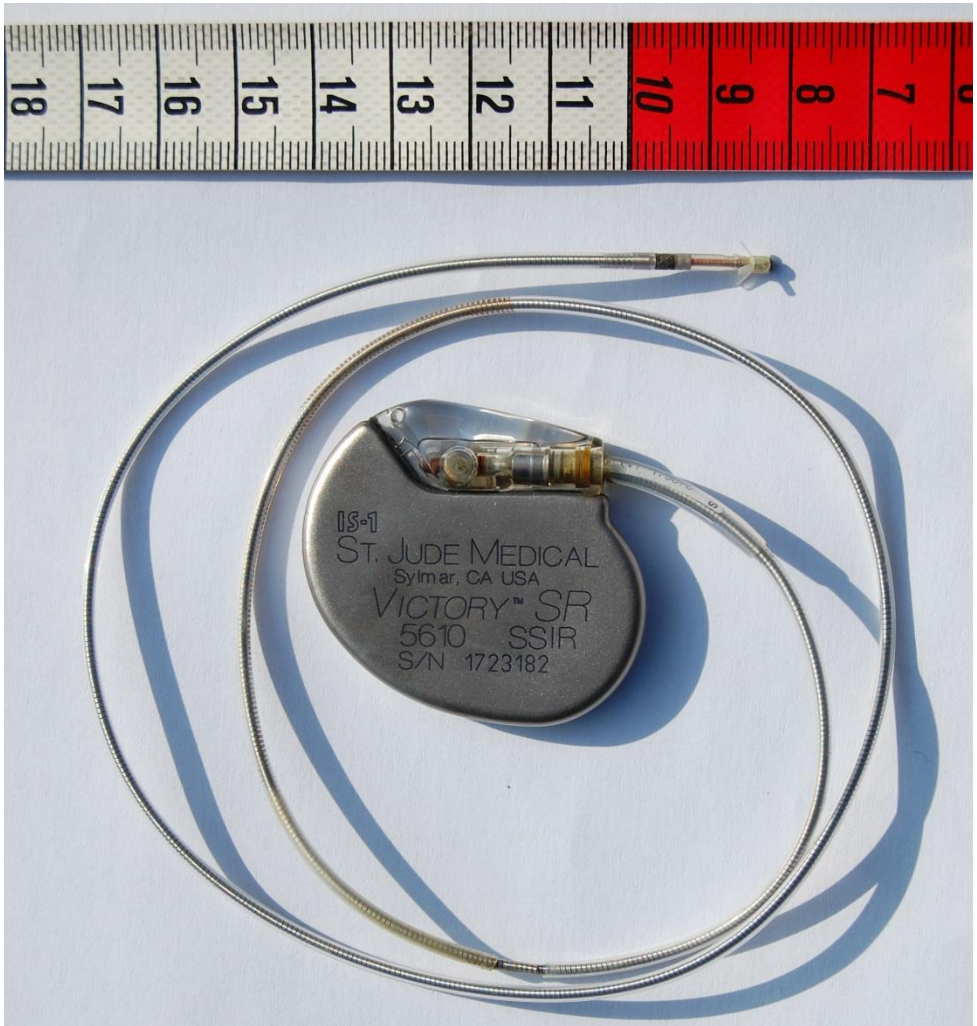
Electrical stimulation - sistematization

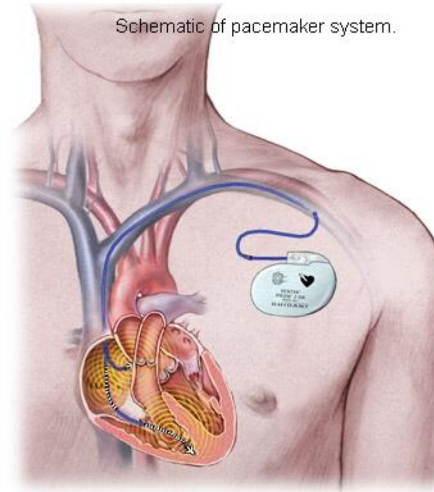
- By the stimulated organ
  - Heart -> occasional or persistent irregular heartbeat, cease, fibrilation
  - Muscles -> enables movement (limb or diaphragm), the treatment of incontinence
  - Brain and nervous system -> replacement or enhancement of sensation, the treatment of disease (epilepsy, hypertension) or symptoms (pain, tremors, breathing)
  - Bones -> acceleration of bone healing
  - Other organs

Clinical indications for el. stimulation

- Pain Management
- Muscle Strengthening
- Stimulation of degenerated muscle
- Wound care
- Fracture Healing
- Increase joint range of motion (ROM)
- Deliver Medication through the skin (Iontophoresis)
- Replace Orthotics
- Reduce spasm and spasticity
- Reduce scoliosis

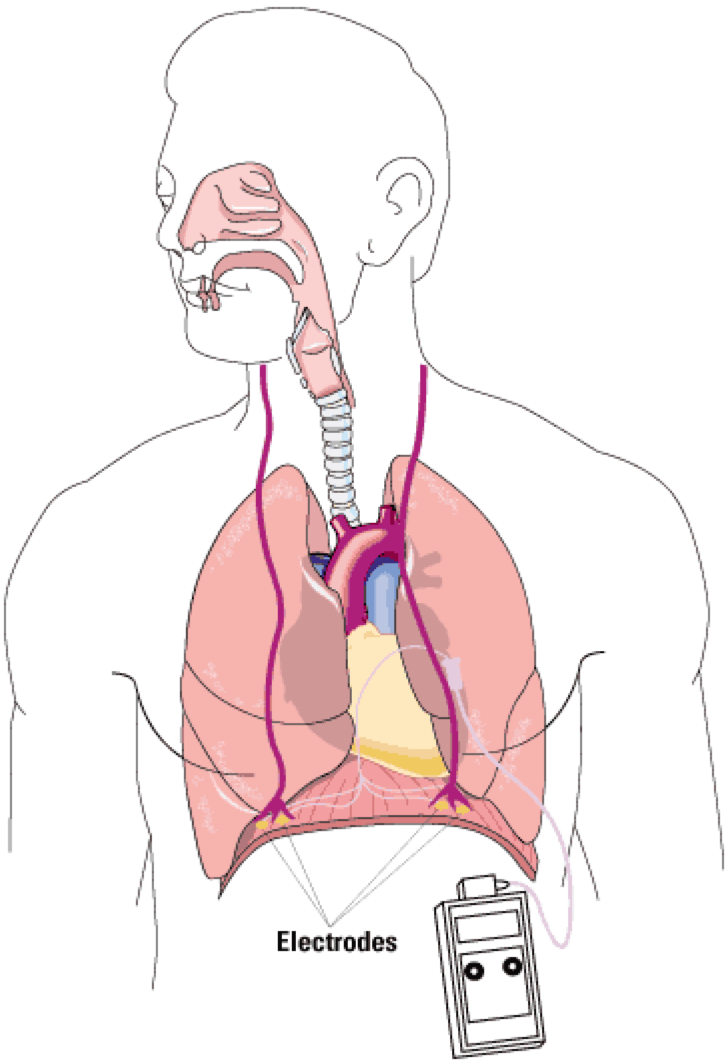
Implantable pacemaker

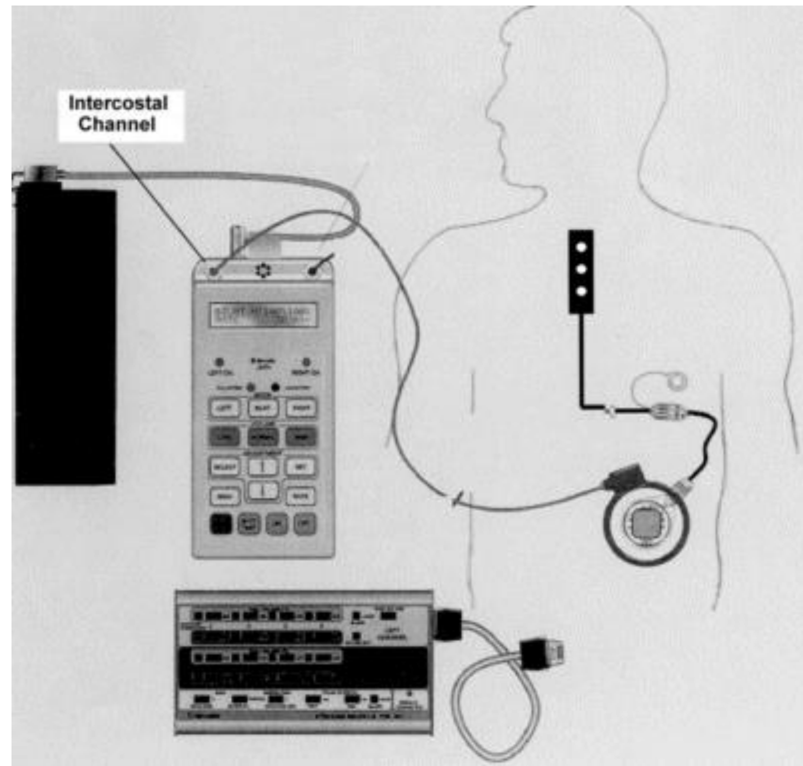




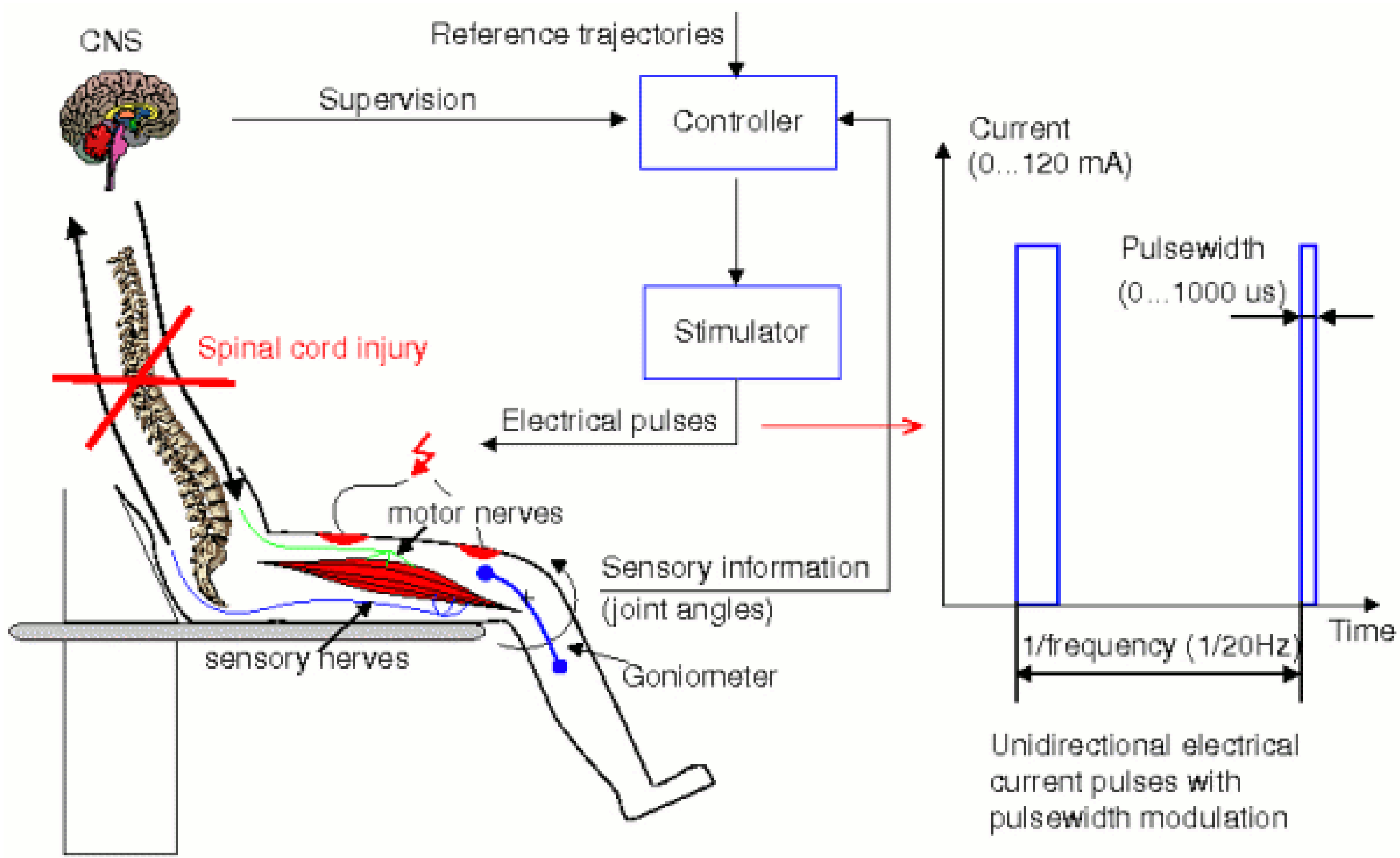
Defibrillators

Diaphragm stimulation

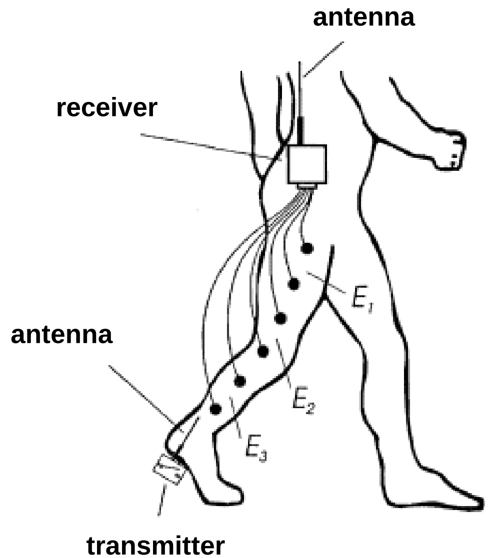


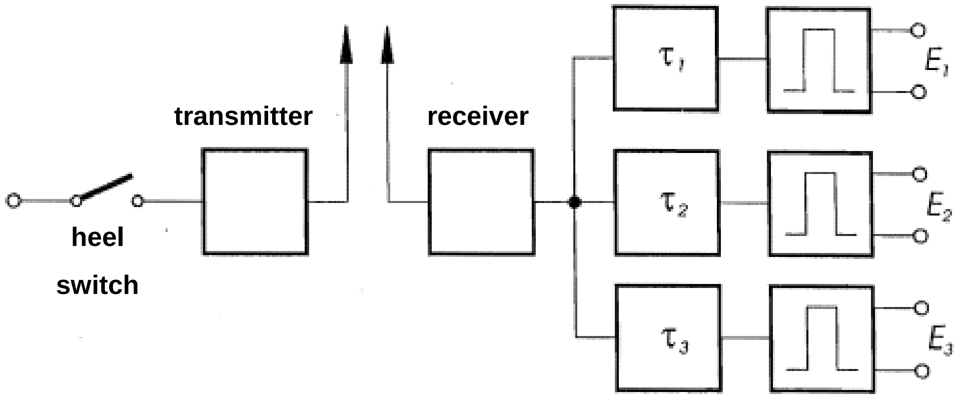


Functional Electrical Stimulation



Electrical Stimulation – implantable FES

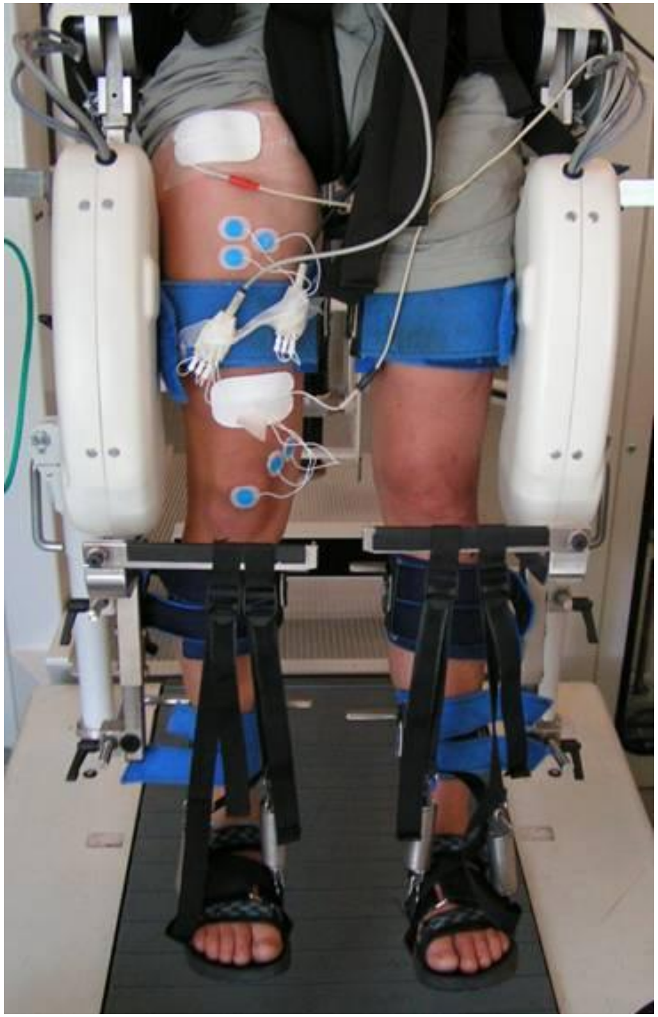


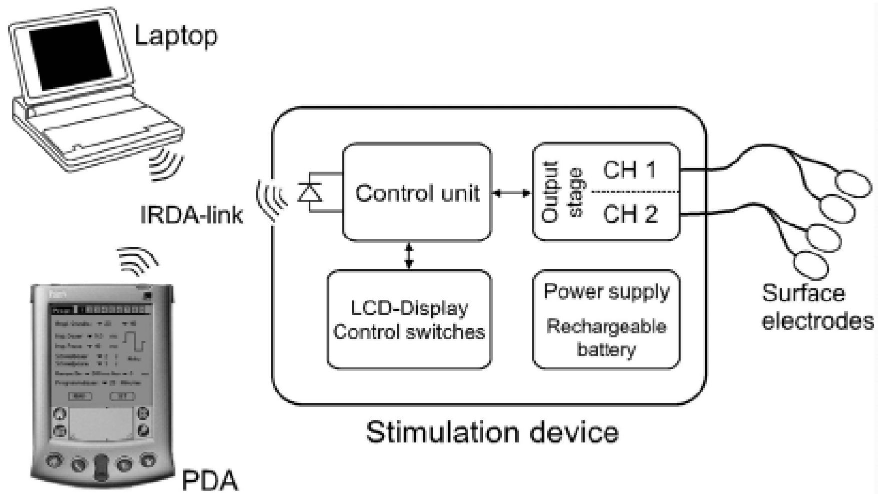


a) Peroneal braces - el. pulses are synchronized by means of switches in the patient's shoes

b) Schematic diagram of three-channel implanted stimulator; stimuli on the electrodes with different time delays for the synchronization of muscles to achieve motion

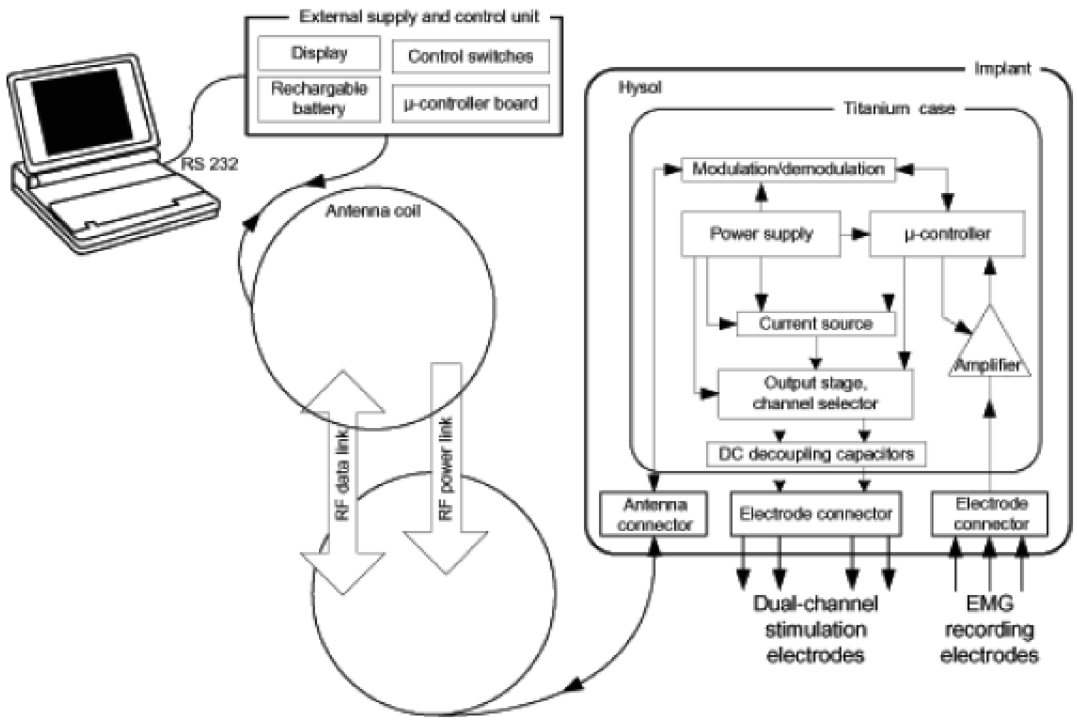
Functional Electrical Stimulation





Two-channel electrical stimulator for surface-denervated muscles - setting the parameters of electrical stimulation

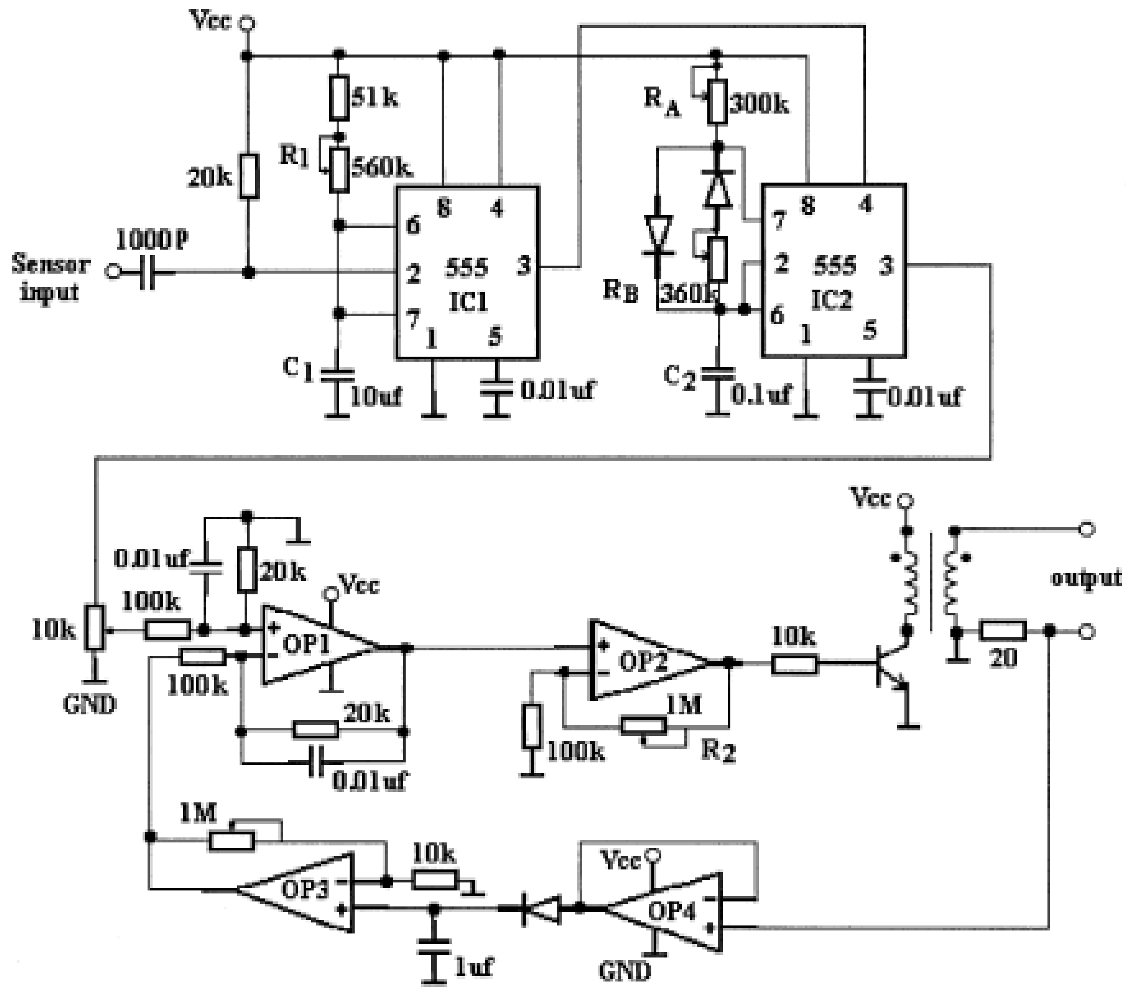
Schematic diagram for the stimulator



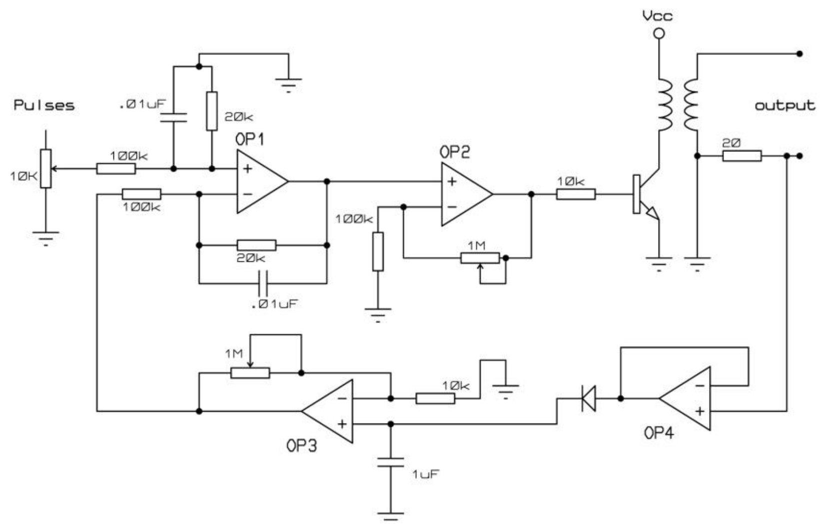
Two-channel electrical stimulator for denervated muscle stimulation – implanted part and control part

Electrical diagram of a stimulator

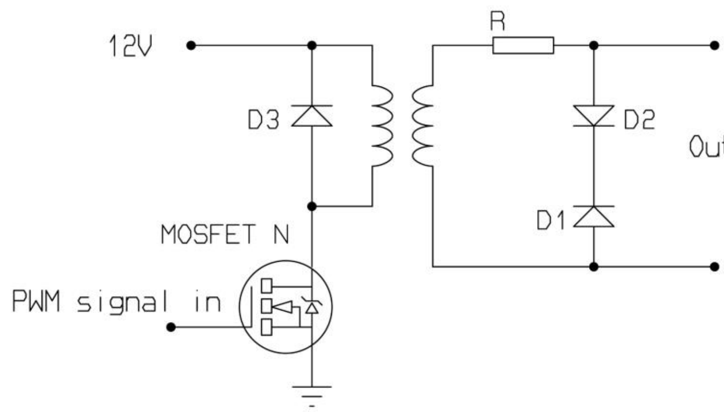
Single-channel electrical stimulator with Galvanic Isolation



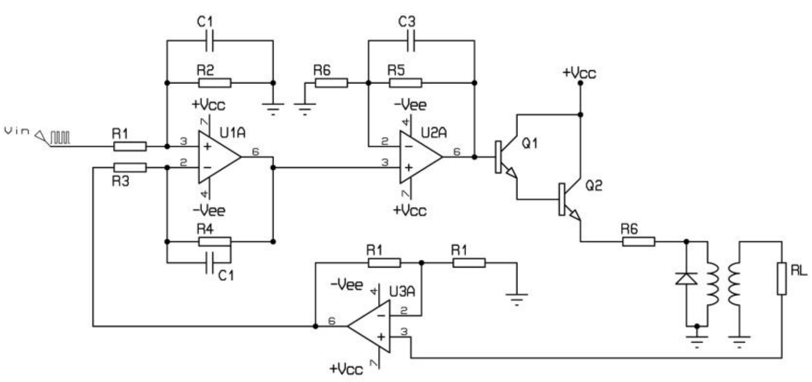
Electrical diagram of a stimulator



(a)



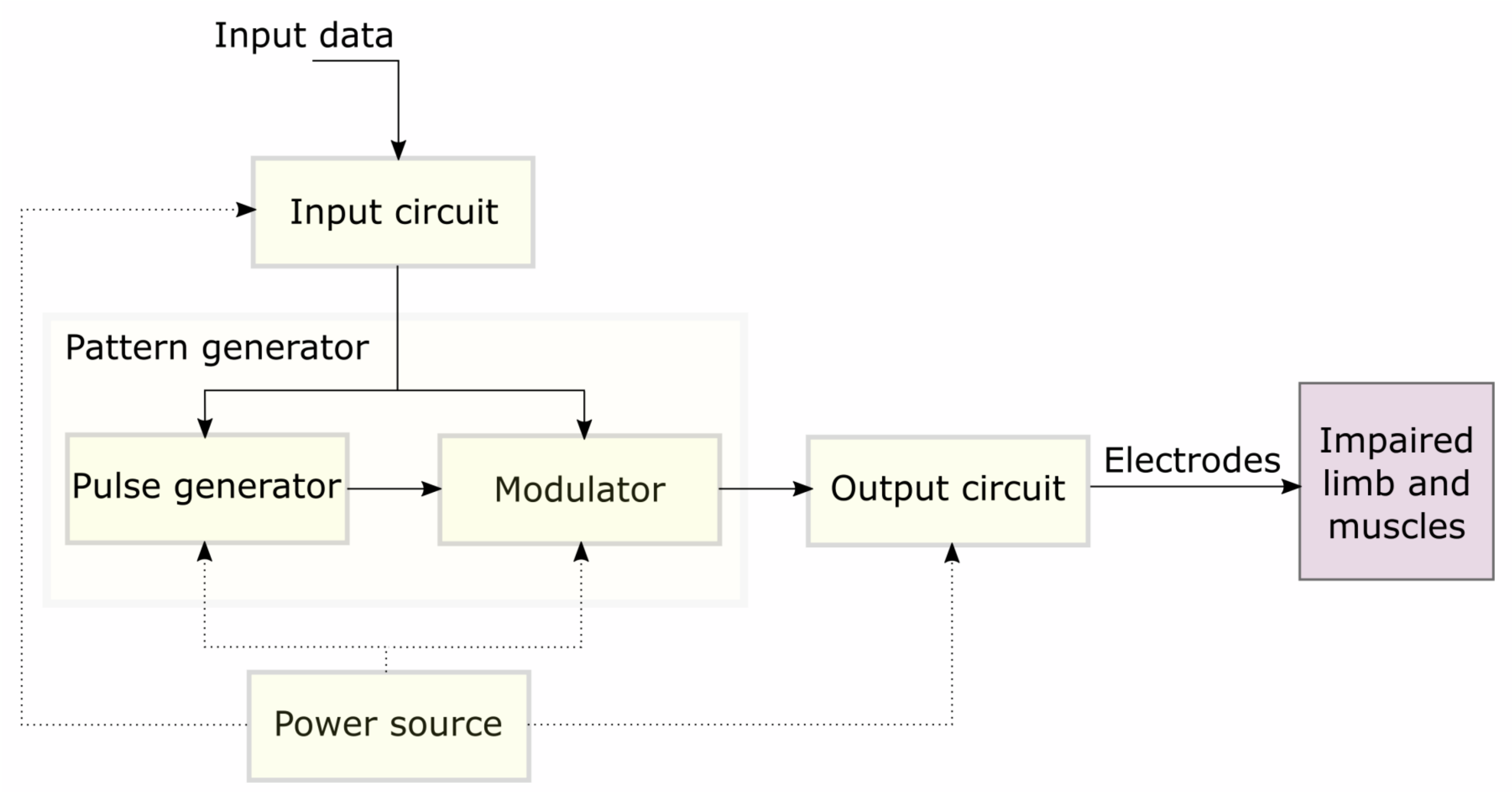
(c)



(b)

Transformer based stimulator circuits [(a) extracted from Cheng et al. (2004), (b) extracted from Velloso and Souza (2007), and (c) extracted from Chen et al. (2013)].

Electrical diagram of a stimulator



General block diagram of a typical electrical stimulator or FES device [adapted from Delmar Carvalho de Souza et al.: Power amplifier circuits for functional electrical stimulation systems, Res. Biomed. Eng. vol.33 no.2 Rio de Janeiro Apr./June 2017

Types of Electrodes

- **Metal Plate Electrodes** - early version, limited sizes, required wet sponge conduction medium, difficult to secure in place
- **Carbon - Impregnated Rubber Electrodes** - degrade over time and become non-uniform with "hot spots", many shapes and sizes, rinse and dry after each use and replaced every 12 months to ensure conductivity.
- **Self-Adhering or Single use Electrodes** - flexible conductors, convenient application, no strapping or taping to keep in place, resealable bag for multiple uses, often high impendence, possibility of cross-contamination, used most frequently these days.

Electrode Size and Current Density

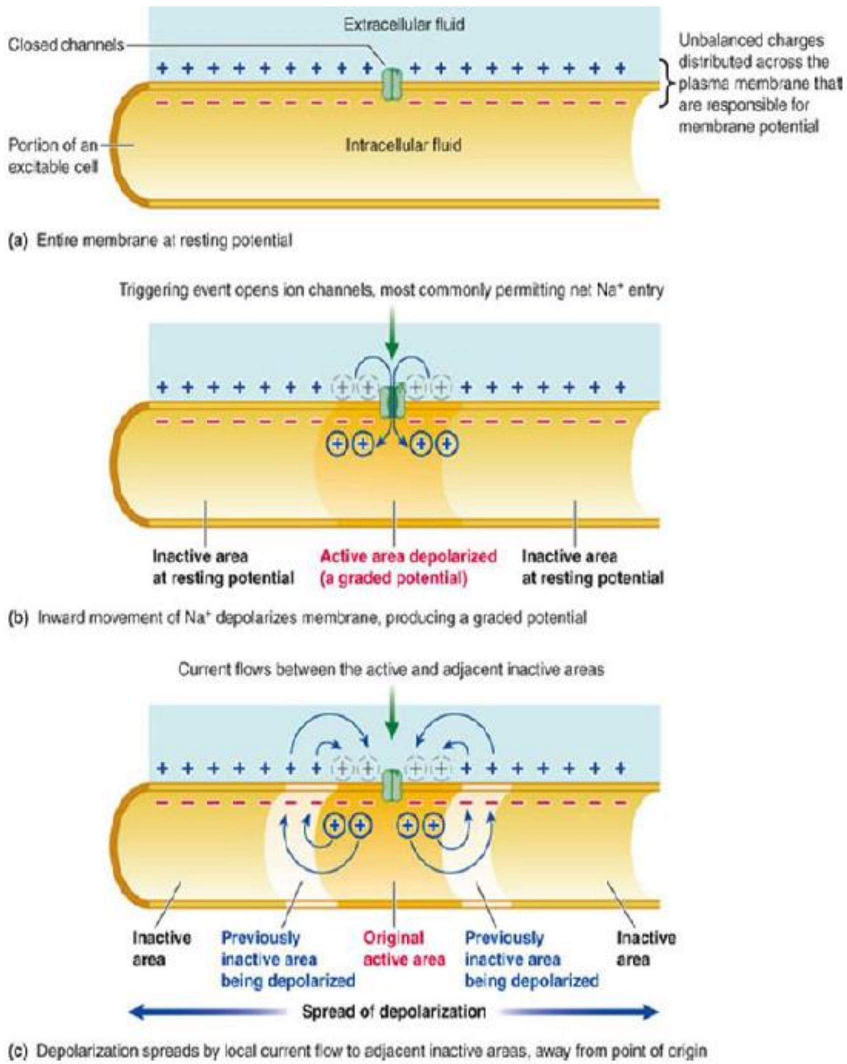
- Current density is the concentration of current under an electrodes.
- Electrode surface area is inversely proportional to current flow. (Larger electrode = current is less dense as it is distributed over a larger area; the smaller the electrode, the more intense the same current becomes over a smaller area.
- Keep the electrode in proportion with size of body area being treated. If the electrode is too large for the area, there could be unwanted carryover to other surrounding structures; if too small, the current is too dense and may not be tolerated to elicit the desired response.

Nerve and Muscle response to el. stimulation

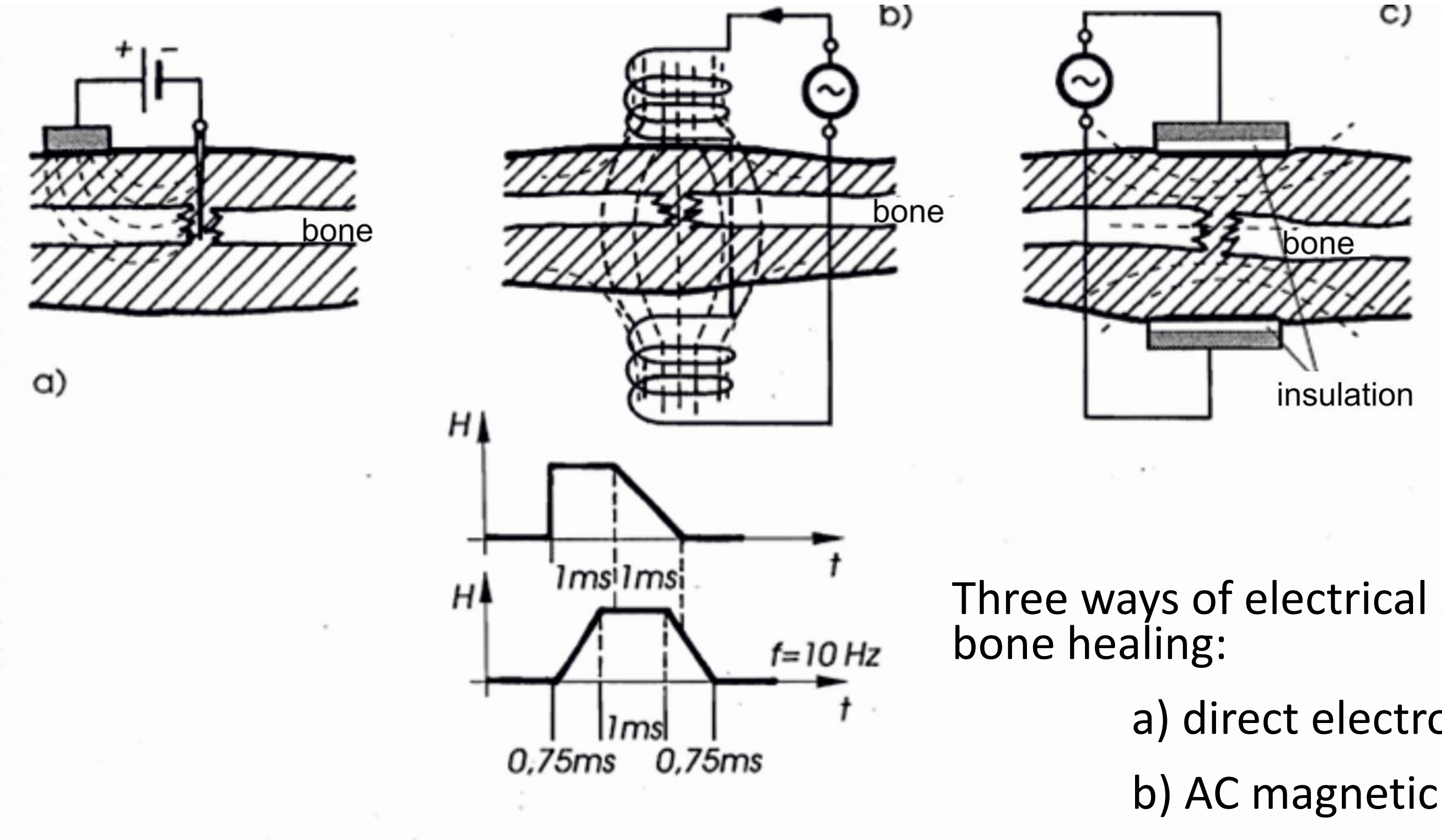
Resting potential
Action potential
Depolarization
Propagation of action potential
Absolute Refractory period
Re-polarization
All-or-none Principle

Changing intensity and types of contraction influenced by;

- Frequency
- Intensity
- Pulse duration
- Number of motor unit recruited



Electrical stimulation of biological tissue growth



Three ways of electrical stimulation for bone healing:

a) direct electrode connection

b) AC magnetic field

c) electric field

Therapeutic goals of el. stimulation

Type of Electrical Stimulation	**Goal**
Electrical Muscle Stimulation (EMS)	stimulation of denervated muscle to maintain viability
Electrical Stimulation for Tissue Repair (ESTR)	stimulation for edema reduction, increased circulation, and wound management
Neuromuscular Electrical Stimulation (NMES)	stimulation of innervated muscle to restore function including muscle strength, reduction of spasm/spasticity, prevention of atrophy, increase ROM, and muscle reeducation
Functional Electrical Stimulation (FES)	neural implantation for long term muscle activation to perform functional activities
Transcutaneus Electrical Nerve Stimulation (TENS)	portable, superficial stimulation across the skin for pain management

Muscle structure

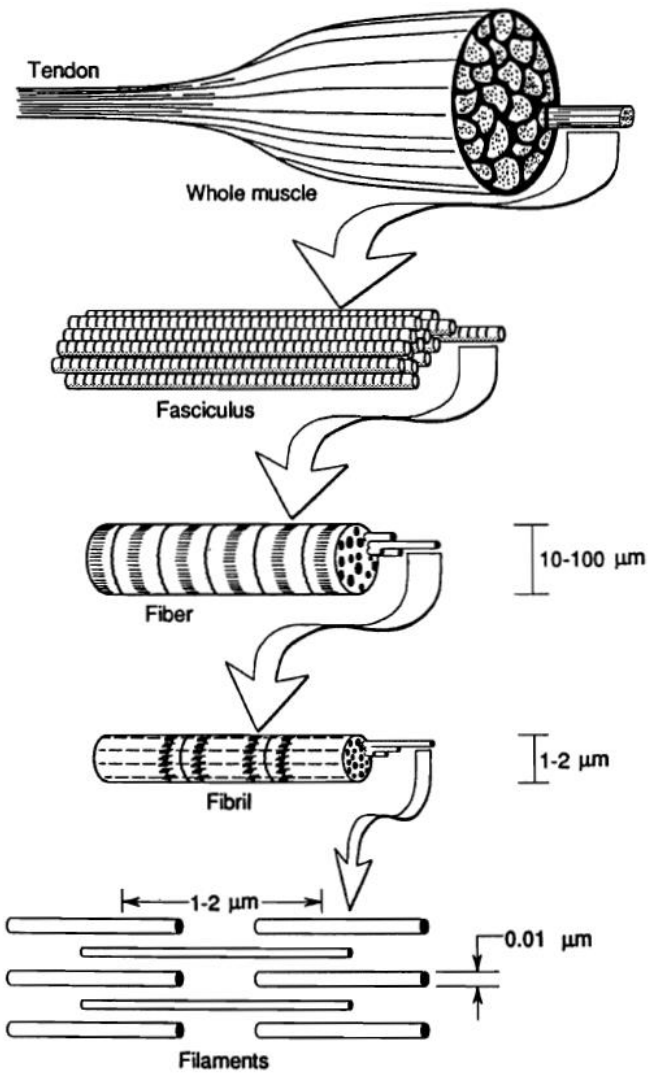


Figure 3.23 Skeletal muscle and filament structure of striated muscle.

- Muscles are the executive elements in biological systems (actuators)
- The execution (of an action) is achieved by shortening the muscle (contraction)
- The immediate cause of contraction is action potential that spreads from the neuromuscular connections along the muscle fibers
- When a muscle is stimulated by electrical impulses, individual fibrils shorten and cause muscle twitch

The frequency of stimulation

- During stimulation, increasing the frequency of stimulation makes it impossible to distinguish between individual convulsions caused by stimuli (pulses). We say that **tetanic contraction** occurred
- Muscle individual twitches are no longer visible, but the muscle is tight and smooth (notice a little difference in tension while stimulation pulse frequency is 40 Hz and 80 Hz)

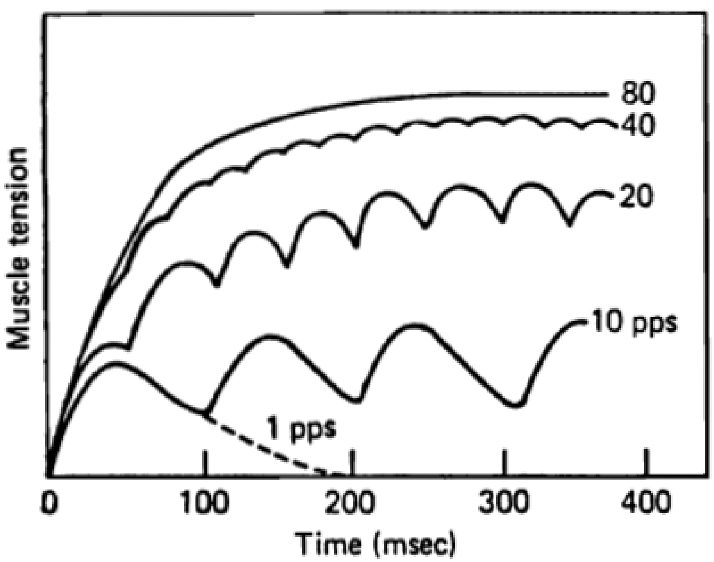
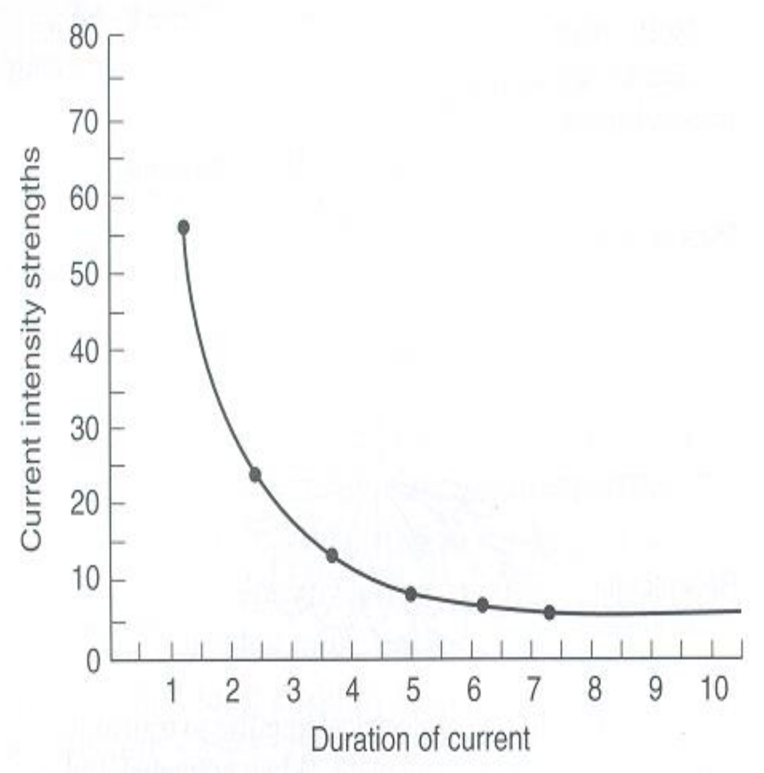


Figure 3.24 Effects of AP rate on muscle tension. [Adapted from McNeal and Bowman (1985a). Reprinted by permission from *Neural Stimulation*, vol. II. CRC Press Inc., Boca Raton, FL.]

Frequency range	Muscle contraction types
< 20Hz	Individual twitch
20-35Hz	Individual twitches become less distinguishable summation
≥50	Tetanic muscle contraction
Mechanical adaption	
Increase amount between pulse (inter-pulse duration allows muscles fibers to recovery form fatigue	

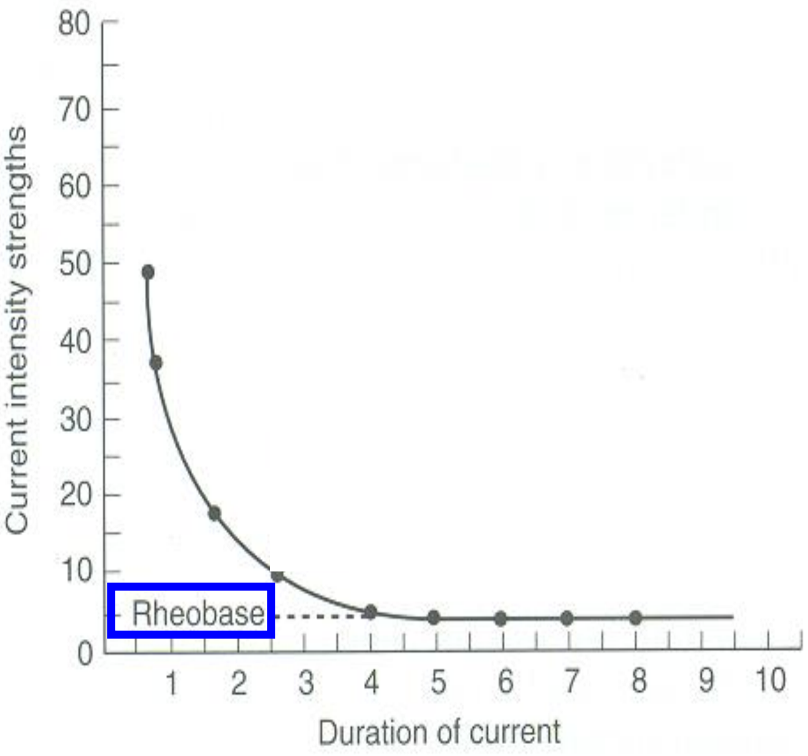
Strength - Duration Curve

- Shape of the curve relates intensity of electrical stimulus (strength) and length of time (duration) necessary to cause the tissue to depolarize



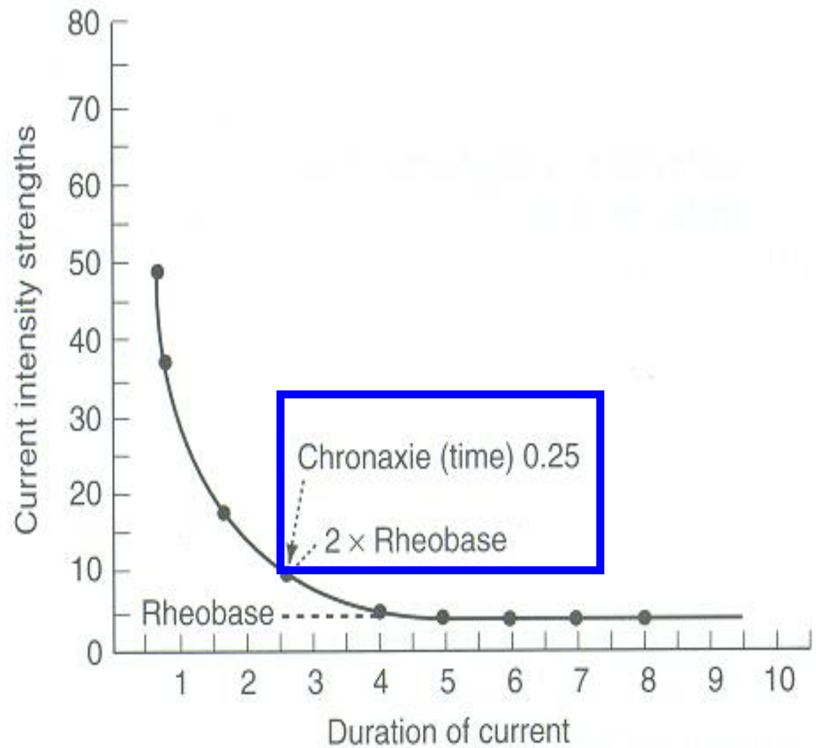
Strength - Duration Curves

- *Rheobase* describes minimum intensity of current necessary to cause tissue excitation when applied for a maximum duration



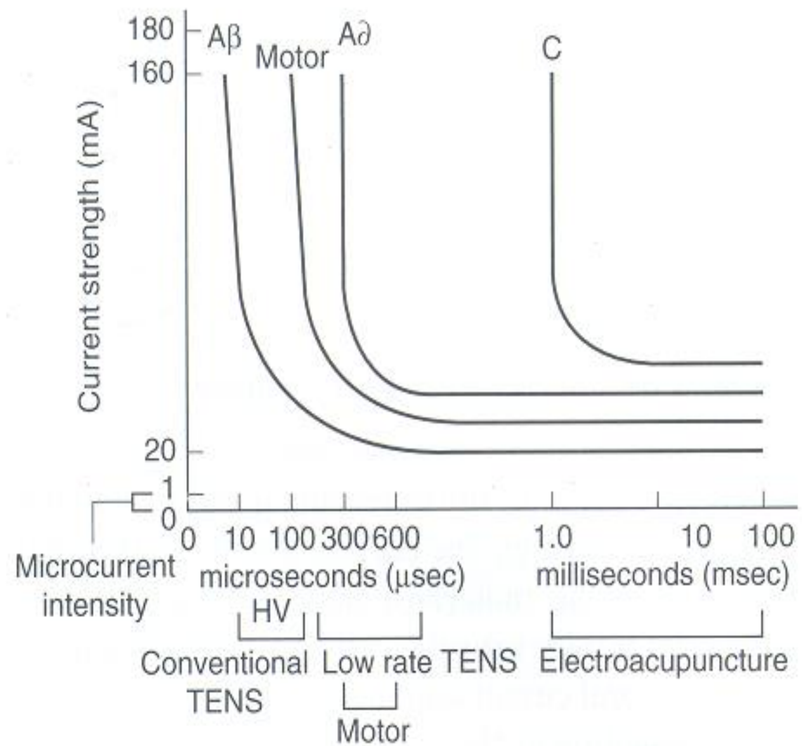
Strength - Duration Curves

- *Chronaxie* describes length of time (duration) required for a current of twice the intensity of the rheobase current to produce tissue excitation



Strength - Duration Curves

- Aß sensory, motor, Aδ sensory, and C pain nerve fibers
- Durations of several electrical stimulators are indicated along the lower axis
- Corresponding intensities would be necessary to create a depolarizing stimulus for any of the nerve fibers



Excitability modelling

- Cellular membranes or isolated segment of excitable tissue can be modeled by a linear electrical circuit consisting of a parallel circuit with membrane resistance r_m and capacitance c_m, so the total excitation current value is

$$i(t) = i_c(t) + i_R(t)$$

And the membrane voltage value is

$$\frac{1}{c_m}\int i_c(t)\,dt = i_R(t)R$$

- If such a membrane is excitated with rectangular current pulse $i(t) = I$ (for $t \geq 0$), membrane voltage will increace exponentially

$$v_m(t) = i_R(t)R = IR(1 - e^{-t/\tau_m})$$

- where τ_m is a membrane time constant. If the stimulation (depolarization) of cells needed excitation voltage V_T, minimum current required for stimulation of these cells and tissue can be determined

$$I_T = \frac{V_T/R}{1 - e^{-t/\tau_m}}$$

Excitability modelling

- For an infinitely long current pulse (t -> ∞), the intensity of electrical impulses must reach a value of $I\ (t \to \infty) = I_0 = V_T/R$. Current I_0 is called **rheobase current**. Minimum charge Q_0 required to achieve the limit of stimulation can also be determined:

$$Q_T = I_T t = \frac{I_0 t}{1 - e^{-t/\tau_m}}$$

- Minimum charge Q_0 is achieved with very short pulses, when t -> 0

$$\frac{Q_T}{Q_0} = \frac{t/\tau_m}{1 - e^{-t/\tau_m}}$$

- Normalized energy required for the stimulation:

$$\frac{E_T}{I_0^2 R} = \frac{t}{(1 - e^{-t/\tau_m})^2}$$

- Minimum energy required for the stimulation of $t = 1.25\ \tau_e$,where τ_e is **chronaxie**, can be determined

$$E_0 = 2.46 I_0^2 R \tau_e$$

Intensity-time curve

- or abbreviated I - t curve, normalized to chronaxie for current, charge and energy

Chronaxie is the Stimulus Duration that yields a response when the Stimulus Strength is set to exactly 2´rheobase.

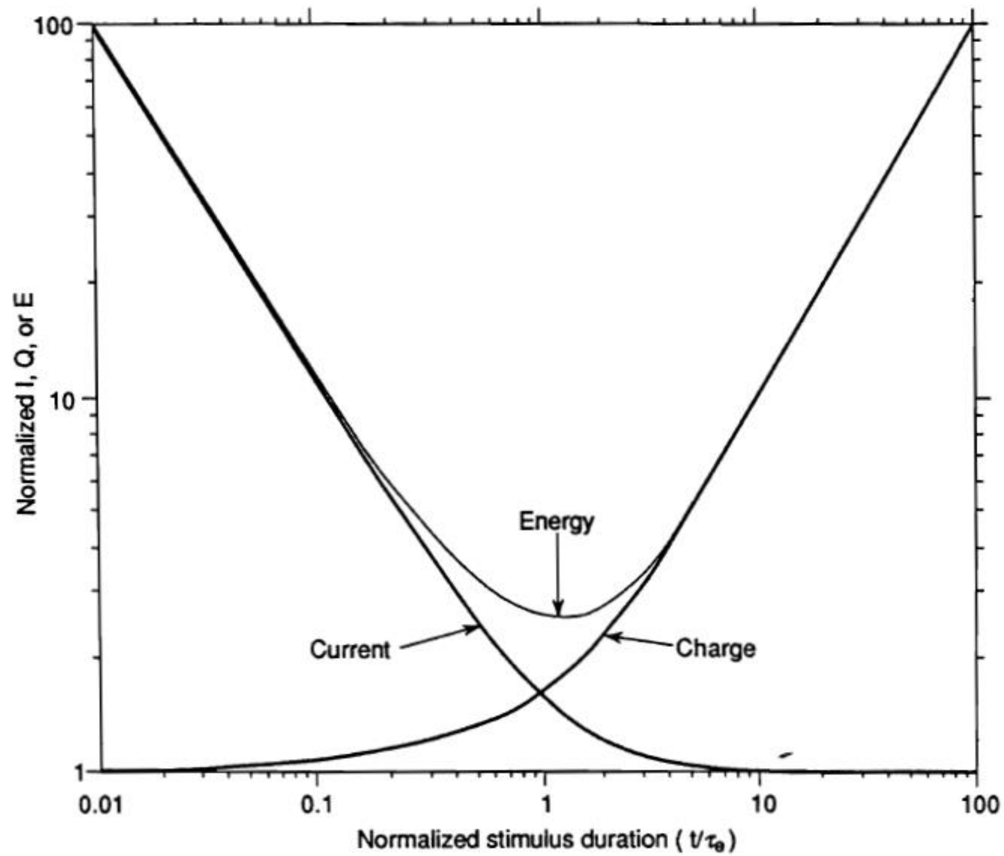


Figure 4.2 Calculated strength-duration relationships for square-wave monophasic current.

Empirical model of excitability

- The terms current reobaze and chronaxie are derived from the first experimental model of excitability, which is described with the hyperbolic function:

$$I_T = I_0\left(1 + \frac{\tau_e}{t}\right)$$

$$I_T = I_0\left[1 - \exp\left(\frac{-t}{\tau_e}\right)\right]^{-1}$$

$$Q_T = Q_0\left(1 + \frac{t}{\tau_e}\right)$$

Rheobase= I_0

Chronaxie = τe (empirical model)

Chronaxie = τe ln2 (exponential formula)

$$\tau_e = \frac{Q_0}{I_0}$$

Stimuli penetration

Increase intensity will increase

- **Strength of stimulus sensory and motor (e.g. contraction).**
- **Depth of penetration of current to deeper tissue (nerve & muscles)**
- **Number of motor unit recruited**

Nerves always depolarize in the following orders

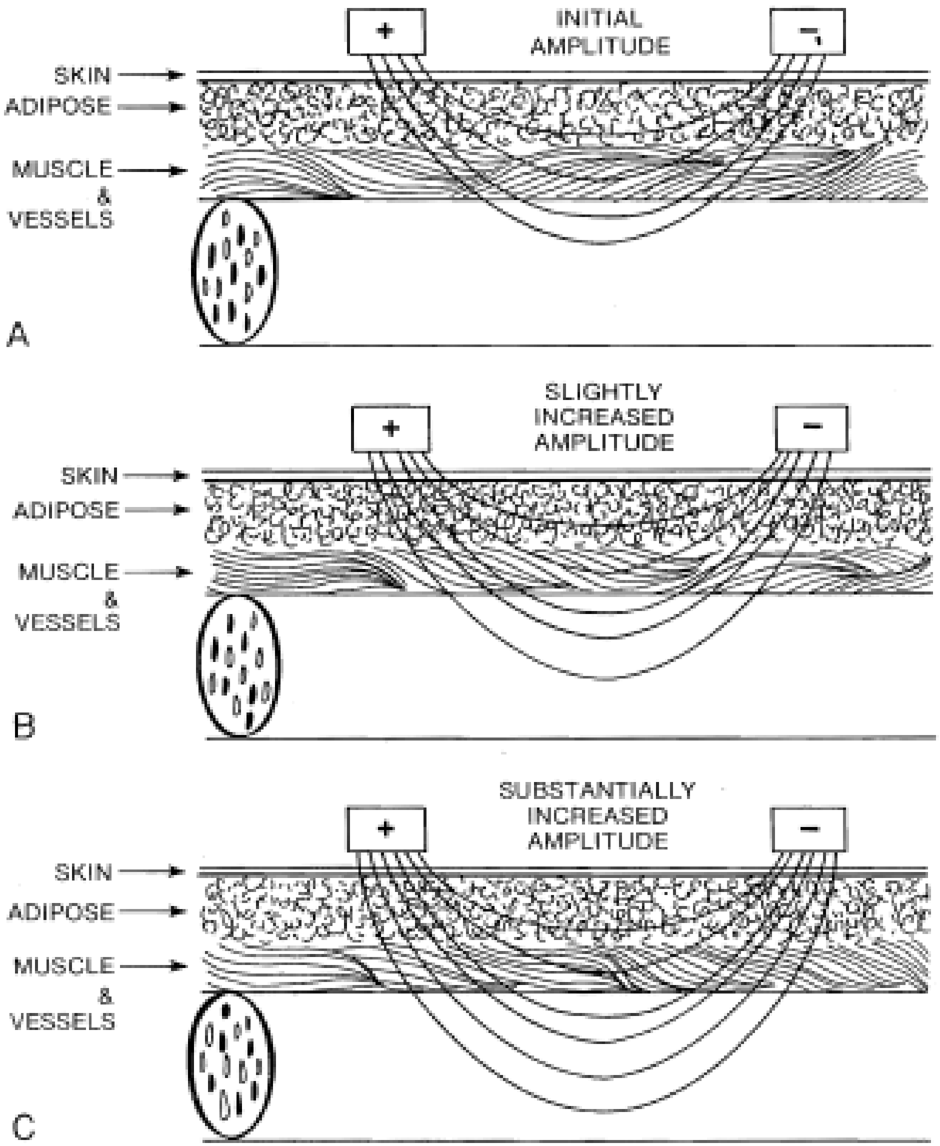
- Sensory nerves
- Motor nerves
- Pain nerves
- Muscle fiber

Based on the

Cross-sectional diameter : Large-diameter nerves depolarize first

Location of the nerve: Superficial nerves depolarize first

Stimuli penetration



- Increased intensity of the stimulus increases the depth of current penetration and the number of fibers embraced by stimulation

Waveforms of stimuli

- Discussion:
  - Why do we use precisely rectangular pulses to stimulate?
  - Can you use any other stimulus waveforms?

Constant Current vs. Constant Voltage Stimulator

- **Constant Current Stimulators** produce a contant current independent of resistance encountered. The voltage adjusts to maintain constant current flow. The advantage of this type of of stimulator is to ensure a consistency physiologic response during the treatment. The negative is potential pain when the voltage increases to overcome resistance.
- **Constant Voltage Stimulators**, conversely, produce a constant voltage. The current adjusts to depending on changes in resistance. This unit is advantageous in preventing discomfort with changes in resistance, such as an electrode losing full contact, but quality of response can be decreased with these automatic resistance changes.

Basic waveforms in therapeutic electrical stimulation

- **Direct Current (DC) or Galvanic**
  - Continuous unidirectional flow of charged particles with a duration of at least 1 second.
  - One electrode is always the anode (+) and one is always the cathode (-) for the entire event.
  - There is a build-up of charge since it is moving in one direction causing a strong chemical effect on the tissue under the electrode
- **Alternating Current (AC)**
  - Uniterupted bidirectional flow of charged particles changing direction at least once per second.
  - Electrodes continuously changes polarity each cycle, therefore no build-up of charge under the electrodes
  - Often used in interferential or Russian commercial stimulators
- **Pulsed Current (pulsed)**
  - Can be unidirectional (like DC) or bidirectional (like AC)
  - Flow of charged particles stops periodically for less than 1 second before the next event
  - Pulses can occur individually or in a series

Basic waveforms in therapeutic electrical stimulation

- **Monophasic** - single phase, unidirectional pulse from baseline to either positive OR negative
  - Do not confuse this with Direct Current (DC). The similarity is that one electrode is always positive and one electrode is always negative, however, pulsed monophasic waves have interuptions, shorter duration, and less strength than DC making this wave unable to perform like DC. Monophasic waveforms do not cause the same magnitude of chemical changes as DC.
  - High voltage comercial machines
- **Biphasic** - two phase, bidirectional wave with one positive phase and one negative phase.
  - Like Alternating Current in that the electrodes change polarity
  - Can be symmetrical (identical phases that cancel each other out) or asymmetrical (non-identical phases that can be either balanced with no net charge or unbalance yielding a net charge)
  - Most commercial TENS units and some battery powered neuromuscular units produce asymmetrical biphasic waves; Variable Muscle Stimulator (VMS) units and some battery powered neuromuscular units produce symmetrical biphasic waves
- **Polyphasic** - bidirectional wave with three or more phases in bursts
  - All polyphasic pulses are bursts but not all bursts are polyphasic

Waveforms of stimuli

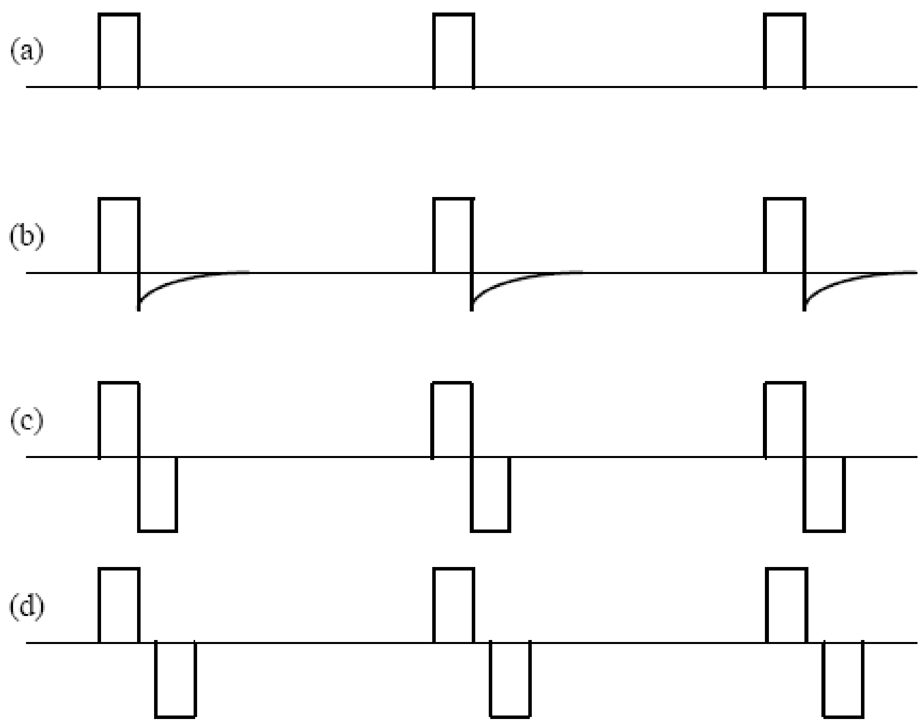


Fig. 3. Common stimulus output trains: (a) Monophasic (b) Asymmetric biphasic (c) Symmetric biphasic (d) Symmetric biphasic with interpulse interval.

- Rectangular pulses are the most commonly used forms
- Duration and amplitude of pulses are set according to time-intensity curve for each muscle, muscle group or nerve

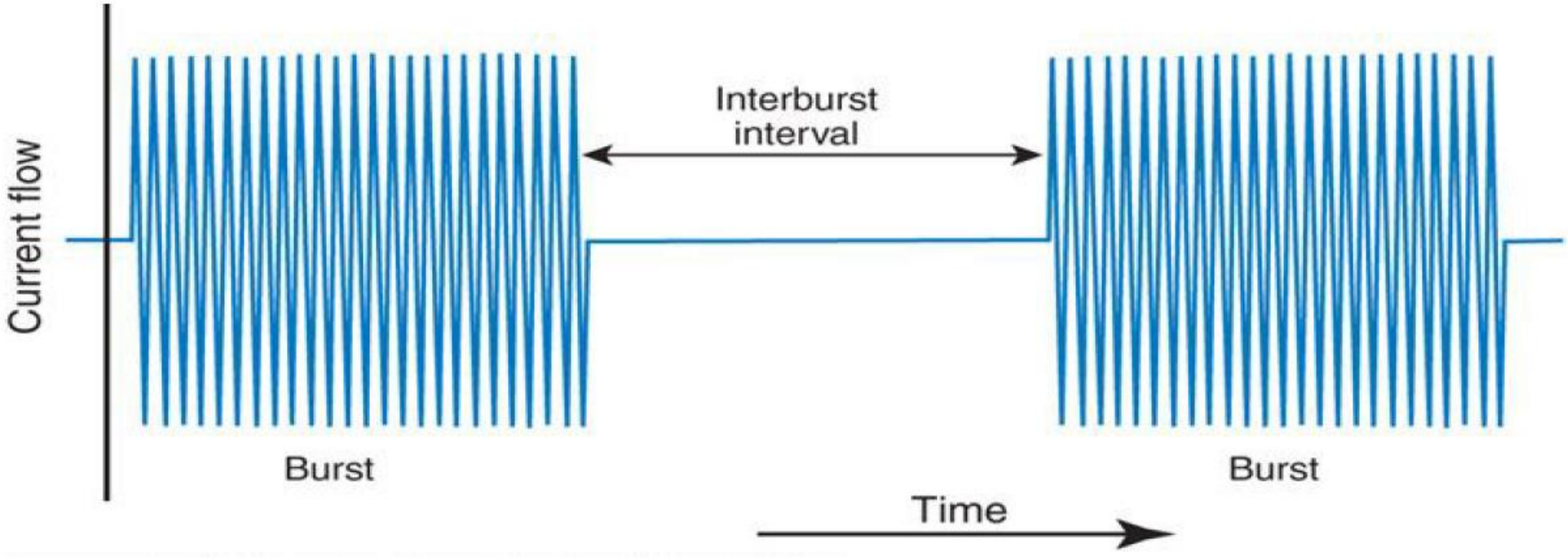
Pulsed stimuli

Burst A finite series of pulses flowing for a limited time, followed by no current flow.

Burst period = burst interval (BI) + inter-burst interval (IBI).

1-Burst interval (BI) is the length of the time during which burst occurs.

2-Interburst interval (IBI) is length of the time between two successive bursts, and current flow is "off"



Stimuli atributes

Pulse Train: individual patterns of waveforms, durations &/or frequencies that are linked together (repeat @ regular intervals)

Amplitude Ramp: gradual rise &/or fall in amplitude of a pulse train (causes a gradual ↑ in the force of MS. contractions by progressive recruitment of motor units)

Ramp up

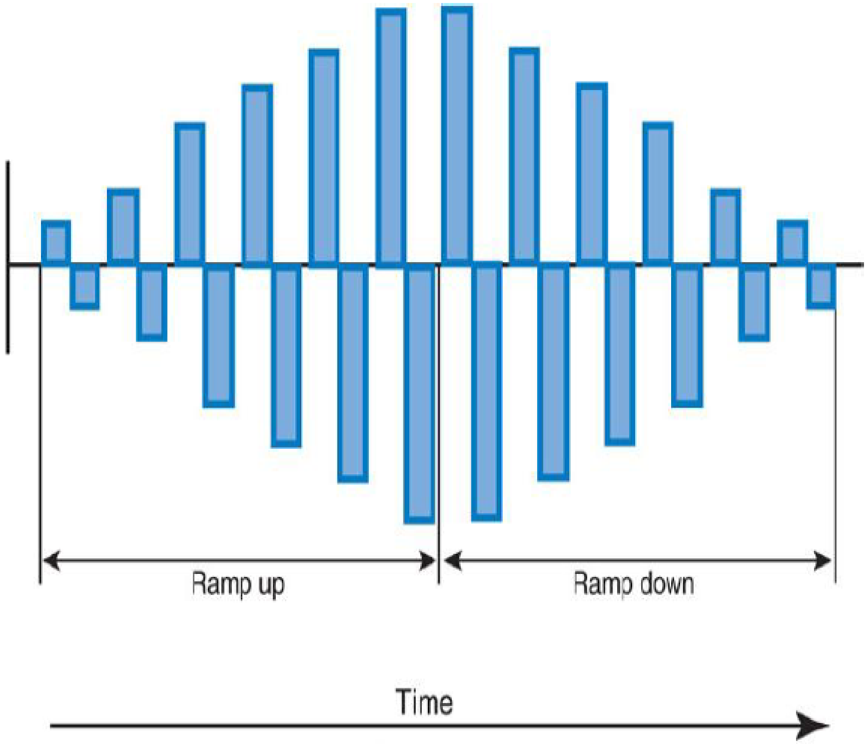
Time during which the intensity increases

Plateau

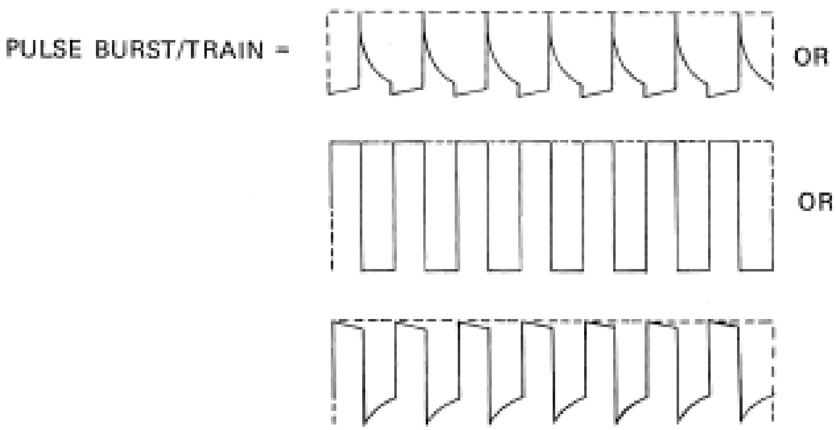
Time during which pulses remain at maximum preset intensity

Ramp down

Time during which the intensity decreases



Pain suppression by el. stimulation



- Typical waveforms and parameters used for the suppression of pain by electrical stimulation

TABLE 6-1. Summary of Recommended Baseline Settings for Modes of Stimulation

High-Rate Conventional Mode	Low-Rate, Acupuncture-like Mode	Brief, Intense Mode
A = strong, comfortable sensory stimulation	A = visible muscle twitches	A = strong sensory stimulation; muscle fasciculations may occur
W = less than 200 μsec; 40–60 μsec base	W = 200–300 μsec	W = 150 ± sec
R = 70–150 pps; 80/85 pps base	R = 1–4 pps (single impulse) or 7 pulses each at 2–4 burst/sec (pulse burst/chain) (no longer than 45 min)	R = 150 pps (no longer than 15 min each period with 2–3 min off/rest period, 15 min may be repeated. Sequence until procedure completed

Excitability dependence of the pulse polarity

- Cathodic vs. anodic stimulation

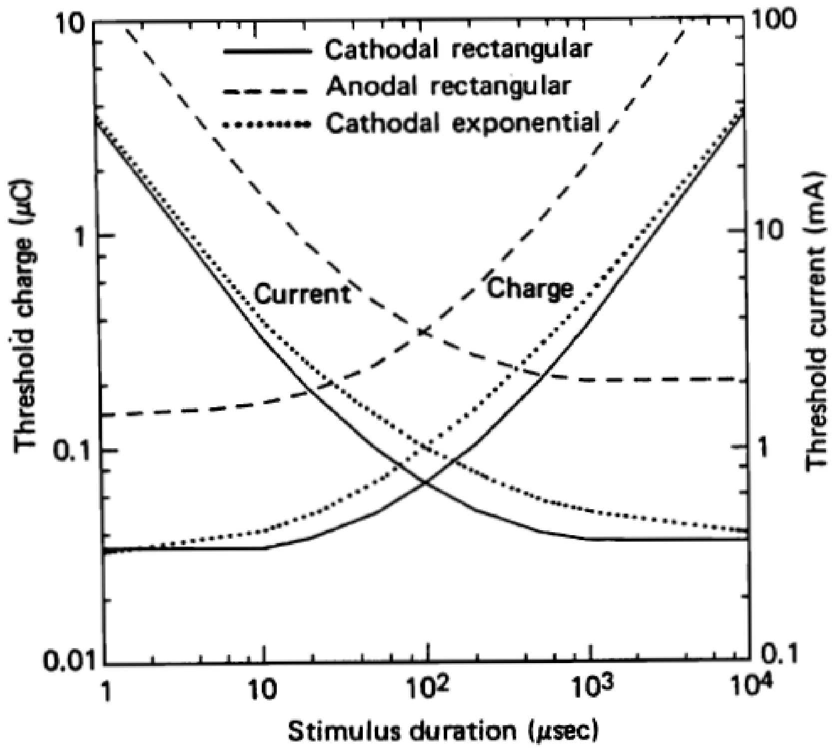


Figure 4.14 Myelinated nerve model strength-duration curves for monophasic stimuli. The left vertical axis indicates threshold charge for AP initiation. The right vertical axis indicates threshold current. The horizontal axis represents pulse duration for a rectangular stimulus or decay time constant for an exponential stimulus. (From Reilly et al., 1985.)

Excitability dependence of the pulse waveforms

- Monopolar vs. bipolar pulses, sinusoidal current

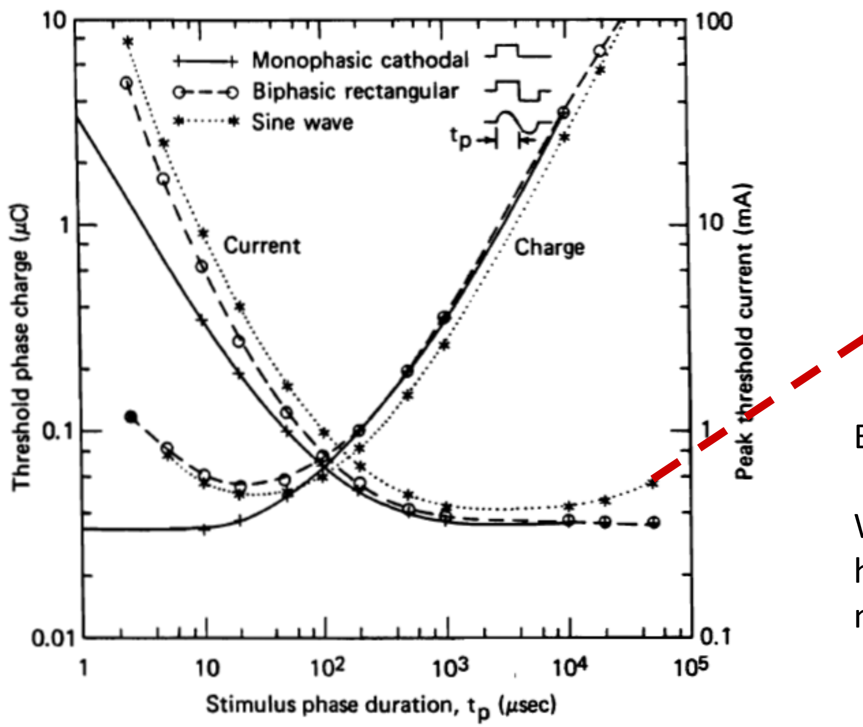


Figure 4.15 Strength-duration relationships derived from the myelinated nerve model: current thresholds and charge thresholds for single-pulse monophasic and for single-cycle biphasic stimuli with initial cathodal phase, point electrode 2 mm distant from 20-µm fiber. Threshold current refers to the peak of the stimulus waveform. Charge refers to a single phase for biphasic stimuli. (From Reilly et al., 1985.)

Extrapolation of sinusoidal current

What is the duration of the half-cycle sine current to achieve maximum excitability?

Excitability dependence of the pulse waveforms

- Monopolar vs. bipolar pulses, pulse duration and the interval between pulses

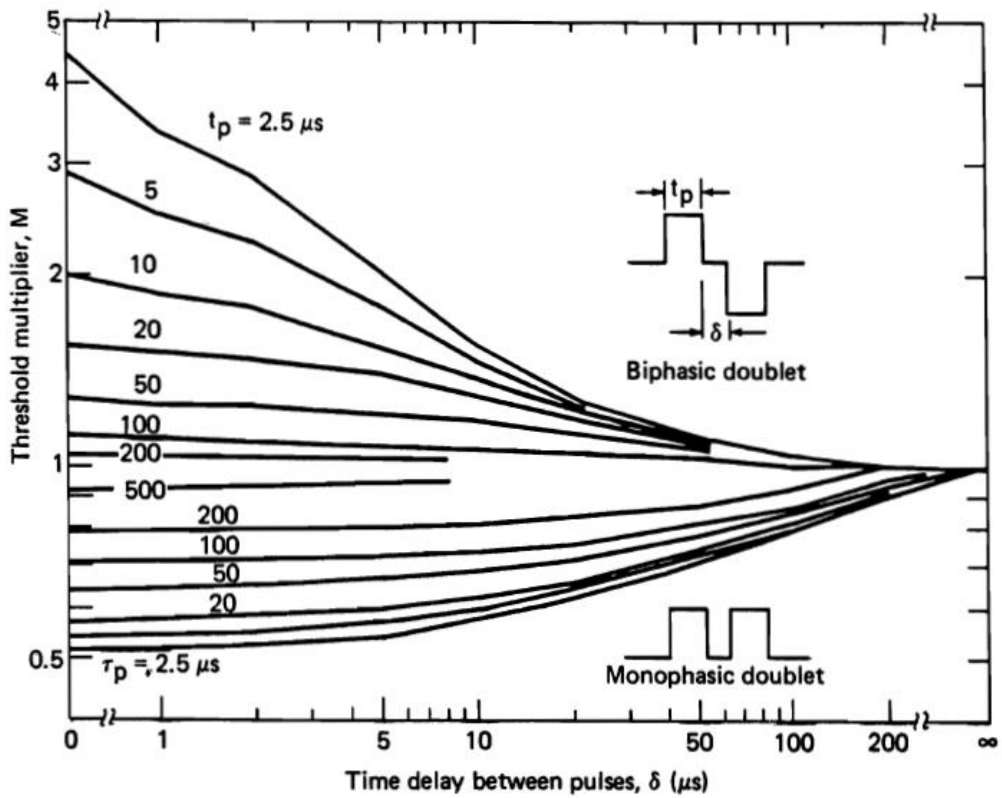


Figure 4.16 Threshold multipliers for biphasic and monophasic pulse doublets: Uniform field excitation of truncated axon. (From Reilly, 1988.)

I – t curves for sensory and motor responses

Subsensory	No nerve fiber activation No sensory awareness
Sensory	Tingling, prickling, or pins and needles Cutaneous A-beta nerve fiber activation
Motor	Strong paresthesias Muscle contraction A-alpha nerve fiber activation
Noxious	Strong, uncomfortable paresthesias Strong muscle contraction Sharp or burning pain sensation A-delta and C-fiber activation

I – t curves for sensory and motor responses

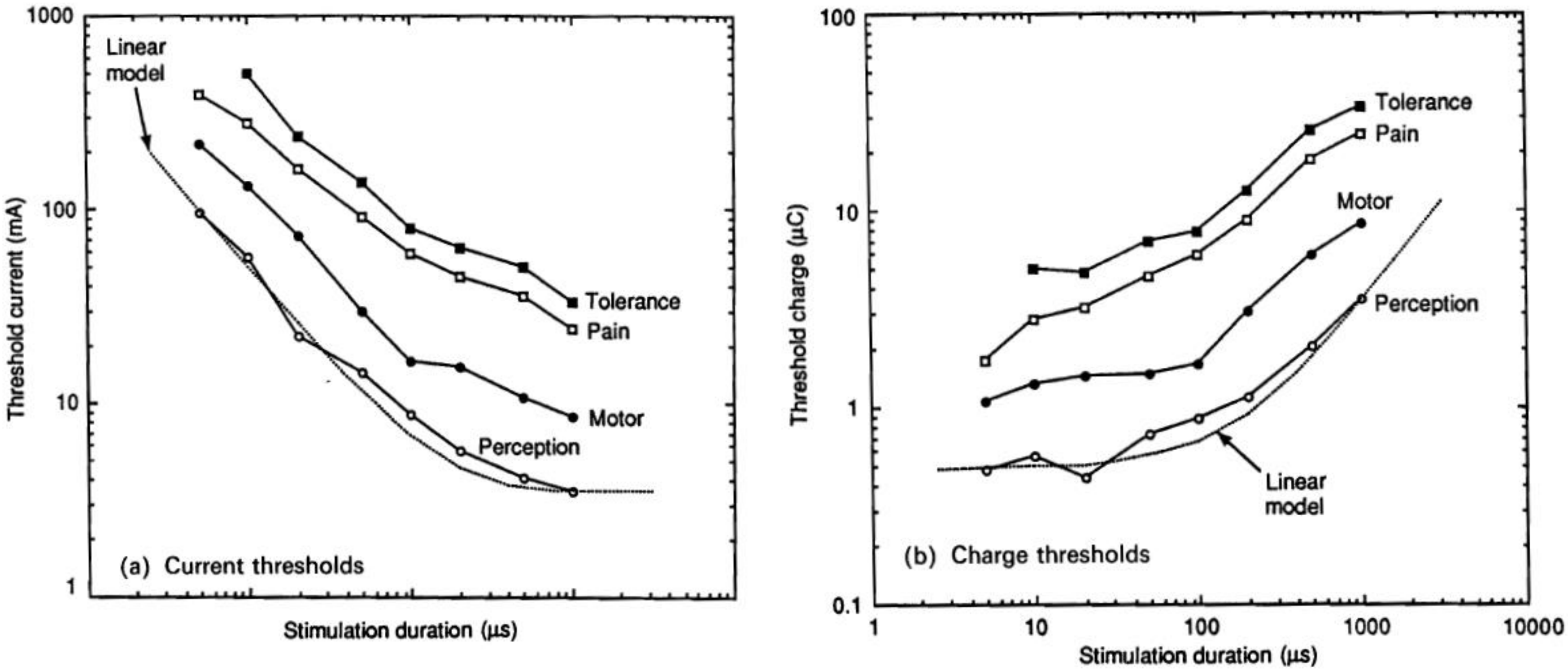
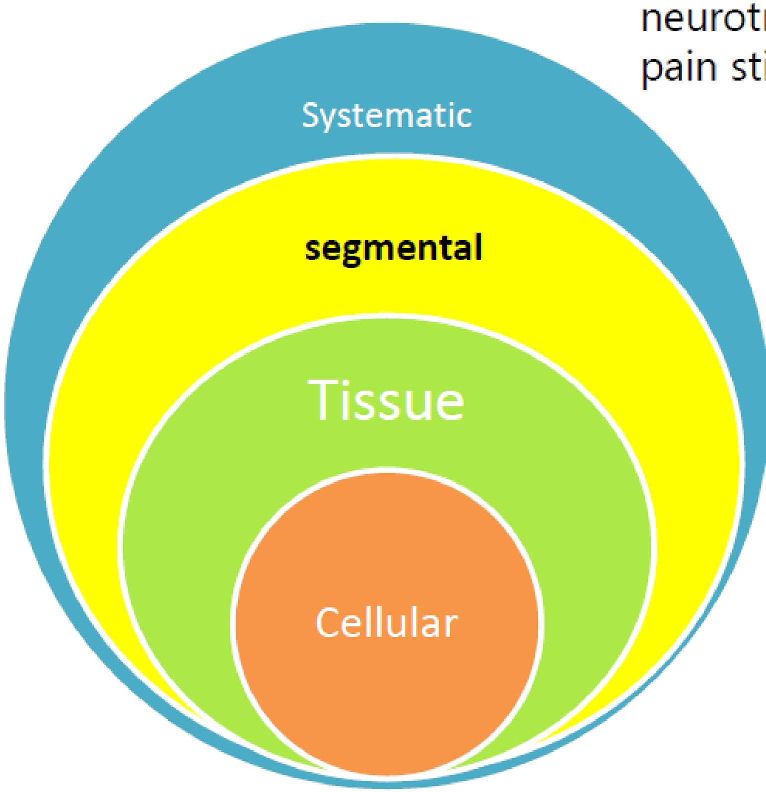


Figure 7.3 Strength-duration curves for sensory and motor reactions to square-wave pulses; forearm stimulation, 4-cm^2 electrode. (Data from Alon et al., 1983.)

Physiologic response to el. stimulation



- Analgesic effects secondary to endogenous pain suppressors released.
- Analgesic effects from the stimulation of certain neurotransmitters to control neural activity in the presence of pain stimuli

- Modification of joint mobility
- Change circulation & lymphatic activity

- Skeletal muscle contraction
- Smooth muscle contraction
- Tissue regeneration

- Excitation of nerve cells
- Changes in cell membrane permeability
- Protein synthesis
- Stimulation of fibrobloast, osteoblast
- Modification of microcirculation

Excitability limit - example

Table 7.7. *Calculated sensory thresholds for single monophasic stimuli to finger or hand (threshold in μC for short-duration currents)*

Electrode area (cm^2)	Finger, hand threshold (μC)				Forearm threshold (μC)			
	Percept.	Annoy.	Pain.	Tol.	Percept.	Annoy.	Pain.	Tol.
0.01	0.11	0.25	0.39	0.78	0.09	0.31	0.48	0.97
0.1	0.16	0.37	0.56	1.14	0.19	0.66	1.04	2.08
1.0	0.23	0.53	0.81	1.63	0.41	1.43	2.24	4.49
10.0	0.34	0.78	1.19	2.41	0.88	3.08	4.84	9.68
100.0	0.51	1.17	1.79	3.62	1.89	6.62	10.40	20.79

Notes: Median threshold for adults. Contact to finger or hand. Brief-duration (< 20-μs) currents. Area power law $= \frac{1}{6}$ for finger/hand; $\frac{1}{3}$ for arm. Suprathreshold multiples from Table 7.2.

Literature

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