ELEC ENG 3BB3:

Cellular Bioelectricity

Notes for Lecture 27

Tuesday, March 18, 2014

12. FUNCTIONAL ELECTRICAL STIMULATION (FES)

We will look at:

- Design of FES
- Electrodes and electrode-tissue behavior
- Nerve excitation
- Recruitment
- Clinical applications

Design of functional electrical stimulation:

In *functional electrical stimulation* (FES), nerve stimulation is achieved by passing current between two or more electrodes implanted in the body.

In order for this system to produce *functional* nerve activation, the appropriate spatial and temporal patterns of stimulation must be determined for the desired stimulus response. This requires an understanding of both the stimulus properties and the resulting nerve response properties.

Design of FES (cont.):

Stimulus design considerations include electrode properties such as:

- number and positions of electrodes,
- material,
- size,
- shape, and

stimulating current properties such as:

- strength, and
- waveform.

Design of FES (cont.):

Example stimulus waveform shapes:

- monophasic,
- biphasic,
- chopped,
- triphasic, and
- asymmetric,

and parameters:

- pulse amplitude,
- pulse width,
- interphase gap, and
- pulse rate.

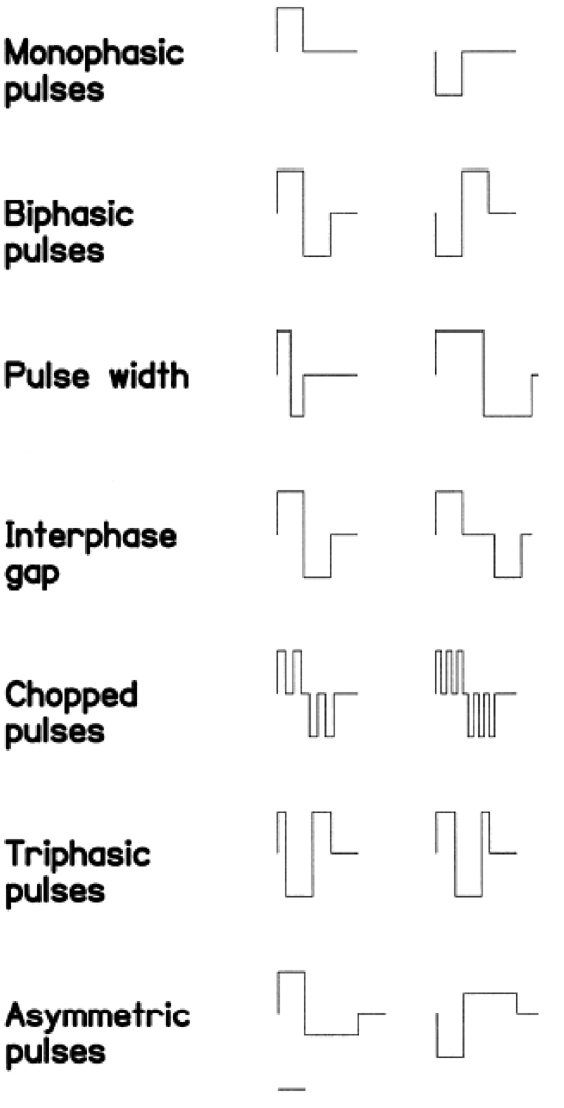


Fig. 1. Diagram illustrating the range of stimulus waveforms used in the present study. Note that all stimuli in the first column deliver an initially anodic current pulse to the most apical electrode.

(From Shepherd & Javel, *Hear. Res.* 1999)

Electrodes and electrode-tissue behavior:

When a closed current loop is created by implanting stimulating electrodes in body tissue, the *current carriers* in the wires and electrodes are *electrons*, whereas current within the tissue is carried by *ions*, primarily sodium, potassium and chloride.

An *electrochemical reaction* must therefore take place at the *electrode-tissue interface* that (in part) *exchanges metal electrons for ions in solution*.

Electrodes and electrode-tissue behavior (cont.):

For extracellular metal electrodes:

- **anode** ´ **positive** net charge in the electrode, and
- **cathode** ´ **negative** net charge in the electrode.

In the extracellular electrolyte, an opposite charge develops that is separated from the electrode by a molecular layer of water adsorbed on the metal surface.

Electrodes and electrode-tissue behavior (cont.):

This charged layer corresponds to a charged capacitance.

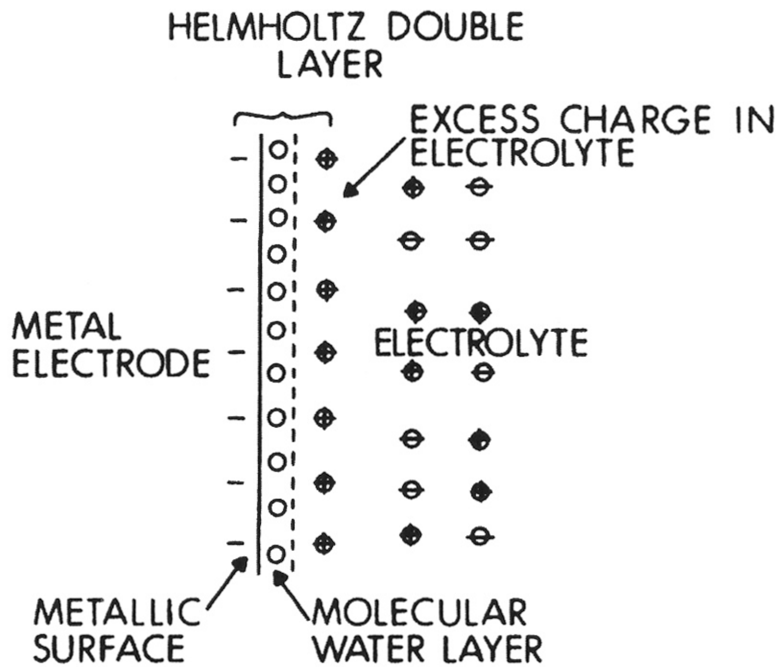


Figure 12.1. Idealized cross-sectional view of the metal–tissue interface of an electrode (cathode) under very low (zero) current conditions. [From A. M. Dymond, Characteristics of the metal–tissue interface of stimulation electrodes. *IEEE Trans. Biomed. Eng.* **BME-23**:274–280 (1976), copyright 1976, IEEE.]

Electrodes and electrode-tissue behavior (cont.):

The equivalent electrical circuit of the electrode-tissue interface will therefore incorporate this capacitance in parallel with a resistance that reflects the electrode-electrolyte charge movement that results from both *reversible* and *irreversible* electrochemical *Faradaic* reactions.

An experimental set-up for analysing this behaviour is shown on the next slide.

Electrodes and electrode-tissue behavior (cont.):

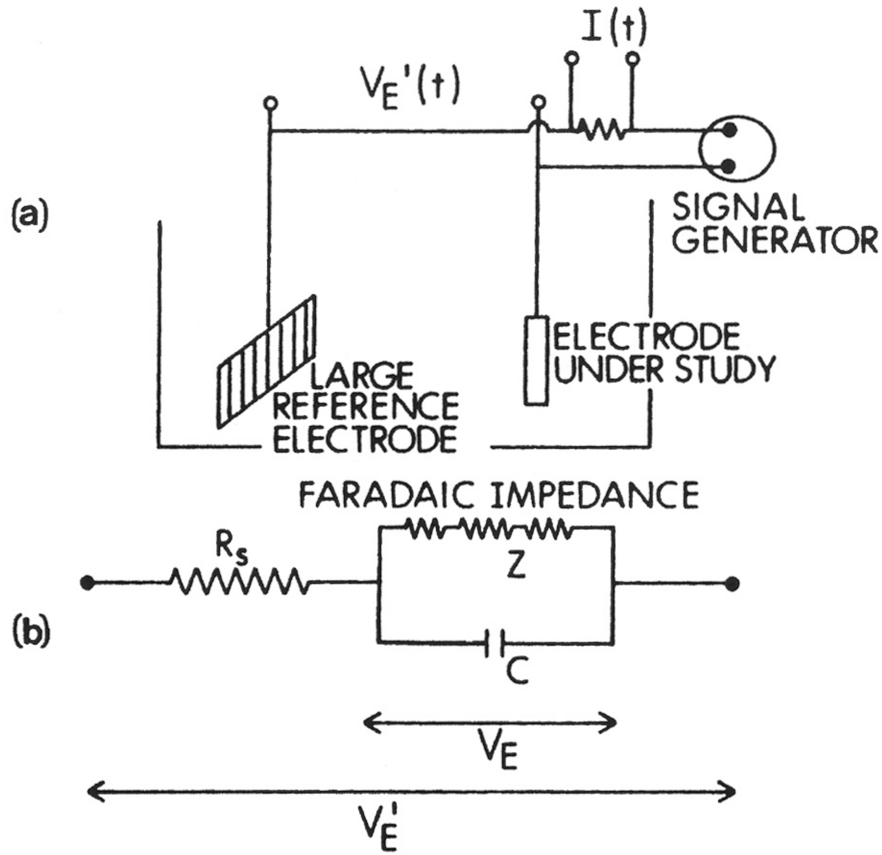


Figure 12.2. (a) Apparatus used in biomedical studies of electrode impedance where current $I(t)$ and total electrode voltage $V_E'(t)$ are monitored. (b) Equivalent circuit for system in (a). R_s is the solution resistance, C is the double-layer capacitance, and Z is the Faradaic impedance (the latter consisting of charge-transfer resistance, diffusional impedance, and reaction impedance). [From A. M. Dymond, Characteristics of the metal–tissue interface of stimulation electrodes, *IEEE Trans. Biomed. Eng.* **BME-23**:274–280 (1976), copyright 1976, IEEE.]

Electrodes and electrode-tissue behavior (cont.):

An RC voltage response is consequently observed in the electrode-tissue interface response to a current step.

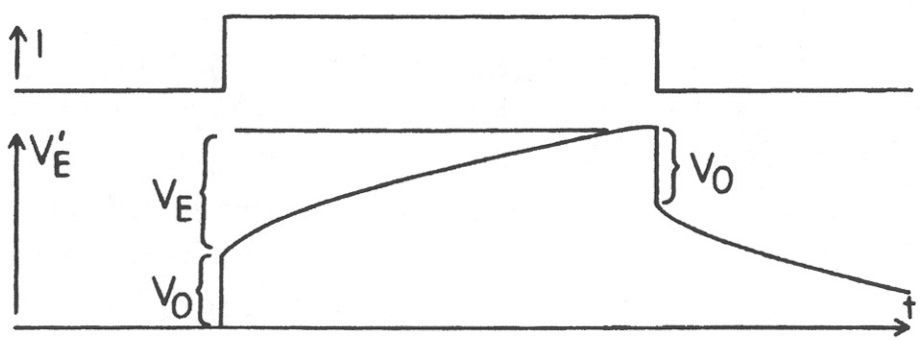


Figure 12.3. Voltage waveform observed between test electrode and reference electrode in response to the constant current pulse shown. V_0 is the voltage across the electrolyte path (IR_s) while V_E is that across the electrode–electrolyte capacitive interface. (From J. T. Mortimer, Motor prostheses, in *Handbook of Physiology*, Sec. I: *The Nervous System*, Vol. II, *Motor Control*, Part I, American Physiological Society, Bethesda, Maryland, 1981, pp. 155–187.)

Electrodes and electrode-tissue behavior (cont.):

The operating characteristics of an electrode depend on:

- the effective capacitance per unit area, and
- the reversible or irreversible electrochemical reaction between the electrode and electrolyte.

A graphical scheme for analysing electrode performance is shown on the next slide.

Electrodes and electrode-tissue behavior (cont.):

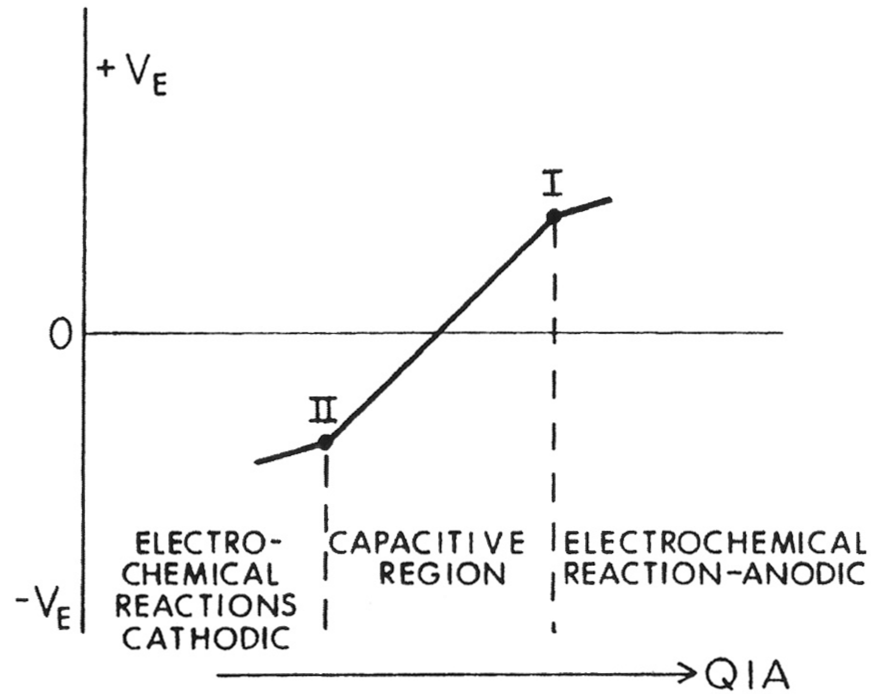


Figure 12.4. Idealized representation of relationship between electrode potential V_E and charge density (charge per unit of real electrode area, Q/A). Charge injection in the central region involves processes that are capacitive and therefore completely reversible. Charge injection in regions to right of point I or left of point II involve electrochemical reactions. These are reversible if, by driving current in the opposite direction, no new species are introduced. Irreversibility involves diffusion of new chemical species away from the electrode. (Modified from J. T. Mortimer, Motor prostheses, in *Handbook of Physiology*, Sec. I: *The Nervous System*, Vol. II, *Motor Control*, Part I, American Physiological Society, Bethesda, Maryland, 1981, pp. 155–187.)

Electrodes and electrode-tissue behavior (cont.):

In the central region, the capacitance of the electrode-electrolyte interface dominates. It is desirable to operate within this region and thus avoid Faradaic reactions at the interface, but the charge delivered may not be sufficient to achieve nerve activation.

Exceeding the limits of the linear region, i.e., delivering charge beyond points I or II (or both), introduces Faradaic conditions (i.e., electrochemical reactions).

Electrodes and electrode-tissue behavior (cont.):

For example, a *stainless steel* electrode that is driven beyond point I by an *anodic* potential may experience the *irreversible* reaction:

$$\mathrm{Fe} \longrightarrow \mathrm{Fe}^{++} + 2e^{-}\,, \qquad (12.2)$$

which leads to dissolution of the iron.

For *cathodic* potentials beyond point II the reaction may be of the form:

$$2\mathrm{H_2O} + 2e^{-} \longrightarrow \mathrm{H_2} \uparrow \mathrm{OH}^{-}\,, \qquad (12.3)$$

which is again irreversible and produces a pH increase that could cause tissue damage.

Electrodes and electrode-tissue behavior (cont.):

On the other hand, for a *platinum* electrode the *anodic* reaction may be:

$$\mathrm{Pt} + \mathrm{H_2O} \rightarrow \mathrm{PtO} + 2\mathrm{H}^{+} + 2e^{-}\,, \quad (12.4)$$

which is *reversible*.

For *cathodic* potentials the reaction may be of the form:

$$\mathrm{Pt} + \mathrm{H}^{+} + e^{-} \longrightarrow \mathrm{Pt\text{-}H}\,, \qquad (12.5)$$

which is again reversible. Note that neither of these reactions introduces new chemical species.

Electrodes and electrode-tissue behavior (cont.):

For *monophasic* stimulation, the charge continually builds up at the electrode interface.

For anodic pulses, the build-up reaches point I, after which electrochemical reactions take place that result in the loss of charge.

For cathodic pulses, the build-up reaches point II.

Consequently, monophasic stimuli are rarely used.

Electrodes and electrode-tissue behavior (cont.):

- The build up of charge is normally avoided by using *charge-balanced biphasic* current pulses.
- Charge balance is usually ensured by the use of a capacitor in series with the electrode.
- In the ideal case, the operating point does not drift from charge build-up, and the range of charges delivered stays within the linear (capacitive) region of the V_E versus Q/ A curve, so that Faradaic charge losses are not incurred.

Electrodes and electrode-tissue behavior (cont.):

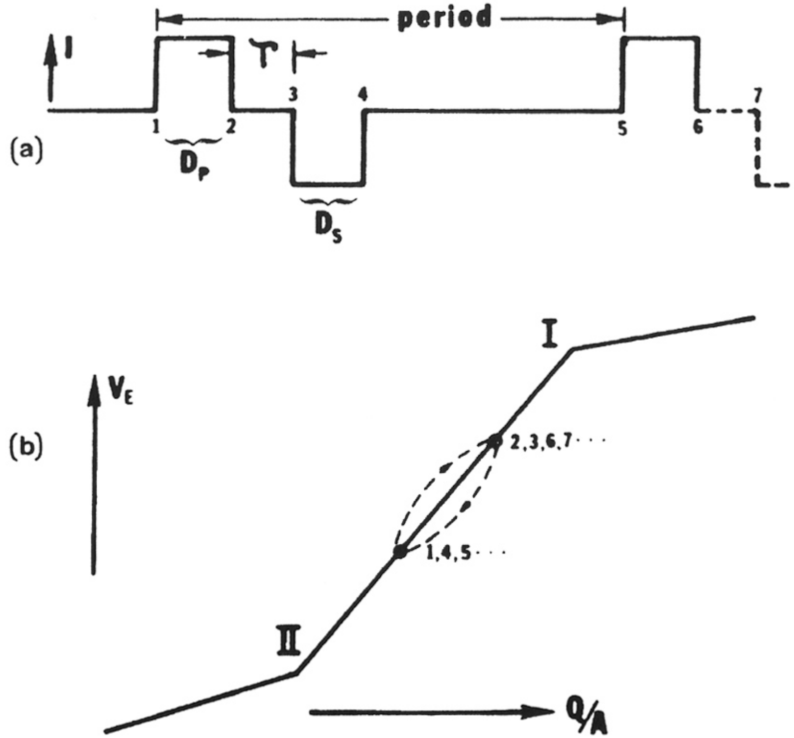


Figure 12.5. Balanced-charge biphasic stimulation. (a) Stimulus waveform with zero net charge transfer per cycle ["period" >> $(D_p + \tau + D_s)$]. (b) Variation in electrode potential, for conditions where charge is accommodated entirely within capacitive region. *I* and *D* refer to current pulse amplitude and pulse duration. Subscripts *P* and *S* refer to primary and secondary stimulus pulses, respectively. Parameter τ is the time delay between the end of the primary pulse and the beginning of the secondary pulse. Balanced charge requires that $I_P D_P = I_S D_S$. Points 1–7 in (a) correspond to points in (b). (From J. T. Mortimer, Motor prostheses, in *Handbook of Physiology*, Sec. I: *The Nervous System,* Vol. II, *Motor Control*, Part I, American Physiological Society, Bethesda, Maryland, 1981, pp. 155–187.)

Electrodes and electrode-tissue behavior (cont.):

If $Q_P \neq$ ¡ Q_S, then steady-state operation must involve some irreversible behaviour.

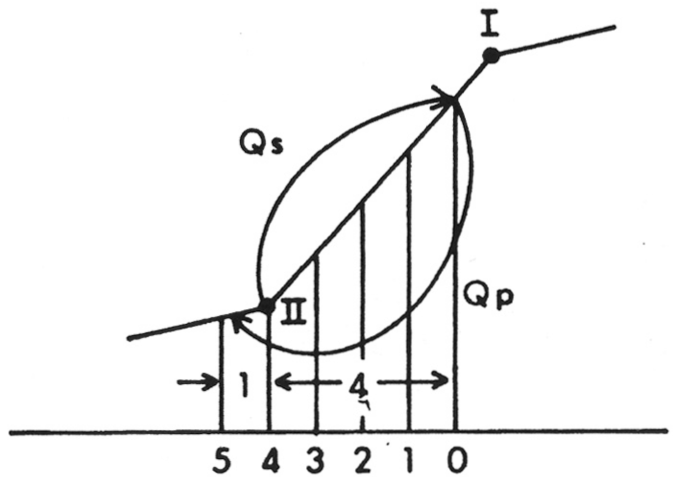


Figure 12.6. Behavior when $Q_p = -5$ units and $Q_s = 4$. Owing to charge imbalance 1 cathodic unit is lost beyond II.

If the irreversible reaction produces OH¡ , as per Eqn. (12.3), this process may be tolerable, because the blood can buffer some OH¡ .

Electrodes and electrode-tissue behavior (cont.):

Note:

- Comparable anodic irreversibility is never tolerated, because the result is irreparable electrode damage.
- The capacitive region may be expanded by:
    1. coating the electrode with a dielectric (i.e., insulator) or,
    2. roughening the electrode surface to increase its effective surface area.

Electrodes and electrode-tissue behavior (cont.):

Factors to consider when choosing electrode material include:

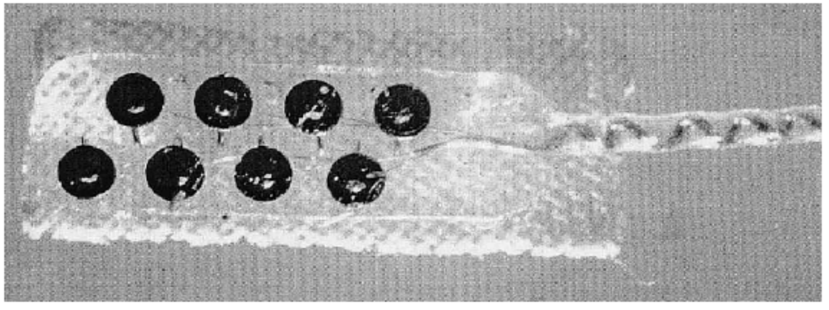
1. passive *biocompatibility* with the tissue,
2. extent of reversible behaviour (capacitive region + region of reversible electrochemical reactions), and
3. mechanical compatibility with the tissue.

The most widely used electrode materials are platinum, platinum-iridium and 316 stainless steel (SUS 316L).

Electrodes and electrode-tissue behavior (cont.):

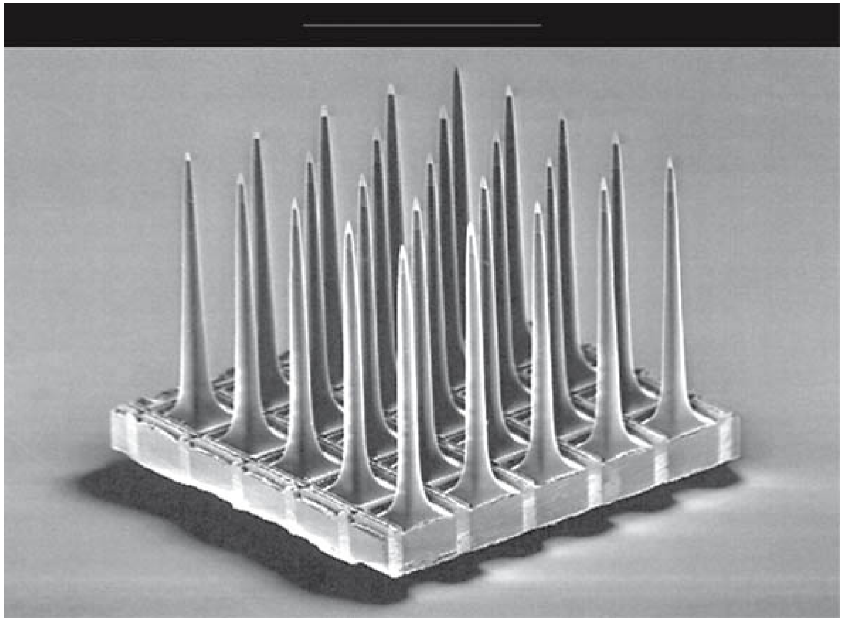
Types of electrodes for specific applications:

1. A — Brain: surface electrodes
   a. Passive biocompatibility – minimal trauma to brain tissue; become encapsulated mainly on the superficial side.
   b. Active biocompatibility – mainly platinum is used; only low-intensity charged-balanced biphasic stimulation is safe.



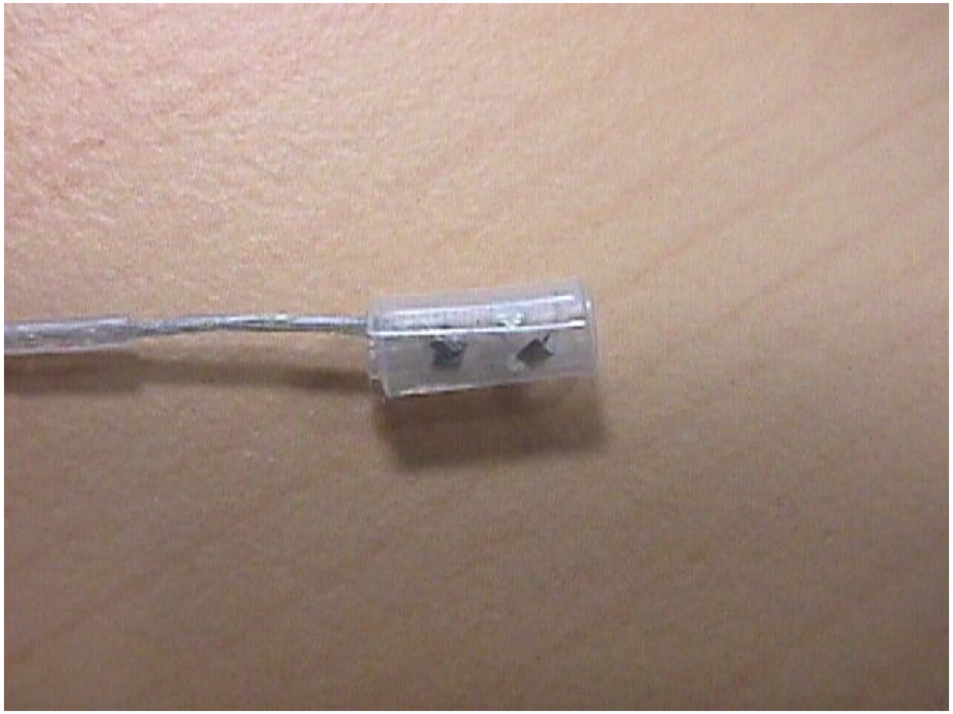
Electrodes and electrode-tissue behavior (cont.):

1. B — Brain: penetrating electrodes
   a. Passive biocompatibility – can cause trauma to brain tissue.
   b. Active biocompatibility – mainly silicon based.



Electrodes and electrode-tissue behavior (cont.):

2. Nerve (cuff electrodes)
   Surround nerve bundle for confined stimulation, reducing the required current.

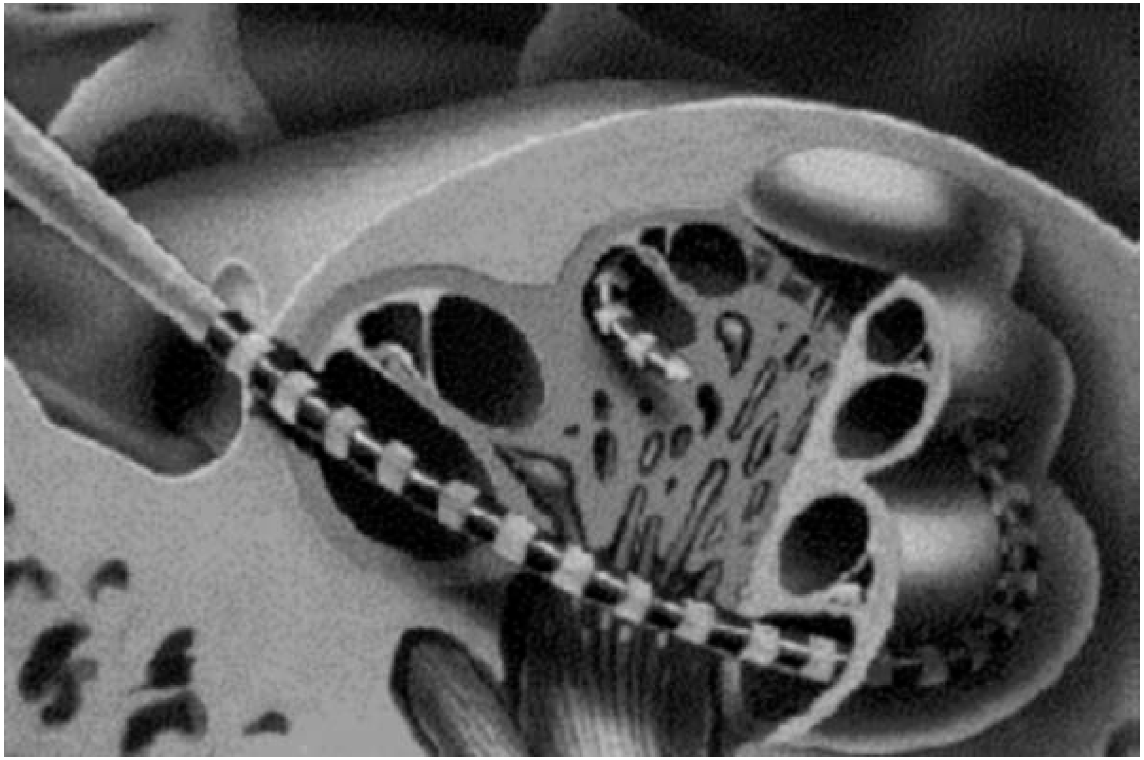


Electrodes and electrode-tissue behavior (cont.):

3. Intramuscular (coiled-wire electrodes)
   a. Passive biocompatibility – subjected to mechanical strains; become encapsulated.
   b. Active biocompatibility – actually stimulate motor axons, *not* muscle fibers.
      i. monophasic: some irreversible cathodic processes tolerated for low currents;
      ii. balanced biphasic: moderate-high currents can be used without degrading electrode;
      iii. imbalanced biphasic: moderate currents are permissible because of blood buffering.

Electrodes and electrode-tissue behavior (cont.):

4. Intra-cochlear (electrode arrays)
   Stimulate different populations of auditory nerve fibers coding for different pitches.



Electrodes and electrode-tissue behavior (cont.):

5. Retinal (electrode arrays)
   Stimulate different populations of retinal cells coding for different spatial positions.