Biosciences in the 21st century

Lecture 2: Innovations and Challenges

Dr. Michael Burger
Outline:

Review of last time

Organization of the nervous system (in brief)

The mapping concept

Bionic implants and our cyborg future

Auditory function and cochlear implants

Restoring paralysis: promising technology
Nervous system is segmented in invertebrates

Each segment is controlled by its “own” bit of brain
and in vertebrates........

Each segment has repeatable structures

http://embryology.med.unsw.edu.au/wwwhuman/Stages/Stage10L.htm
Each segment has its own inputs and outputs

Afferents (inputs; i.e. sensory neurons)

Efferents (outputs; i.e. motor neurons)
Let’s consider the somatosensory system....
each vertebral segment is connected to a particular patch of skin

The area of skin innervated by one segment is called a “dermatome”

You will see that this organization is preserved at every level of processing
The brain (also segmented) has its own afferent and efferent nerves
The neocortex is an elaboration of the foremost segment, and it has a highly organized structure.
The cortex has functionally distinct regions

a closer look at the somatosensory cortex...

http://www.emc.maricopa.edu/faculty/farabee/BIOBK/cerebrum_1.gif
The somatosensory and motor cortex contain orderly maps of the body surface. The representation is distorted because more brain tissue is devoted to the most sensitive areas.
This distorted representation gave rise to the concept of the homunculus or “little man in the brain”.

The point is: the brain is organized into maps of important features and functions.
The point is: the brain contains maps of features and functions.

The more that we understand about the structure and function of each region of the nervous system, the more likely we are to be able to develop an intervention when things go wrong.....
Neurological Medicine:

**Today:** mainly concerned with limiting damage as it happens, or slowing degenerative processes.

Sometimes medication can correct deficiencies in neurotransmitter systems etc.

**Long term:** stem cells, tissue engineering, gene therapies will correct the *mechanisms* of disease, not just the symptoms

**The intermediate term:** current research in nanoscale engineering, computer science, and neuroscience will lead to technological interventions that provide solutions to neurological disease
The dawn of the brain machine interface...

welcome to your cyborg future....
The most successful machine/neuron interface thus far is the cochlear implant.
Sound is defined by frequency
Outer ear

Middle ear

inner ear (neural)

The cochlea
Organ of Corti
- hair cells
- support cells
- basilar membrane
- Primary Auditory Afferents!!
Organ of Corti
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- Primary Auditory Afferents!!
The inner ear translates stimulus frequency to a topographic place.

This “tonotopic” organization is the primary mapping feature in the auditory brain.
The most common cause of hearing loss is hair cell damage and death; in mammals they do not regenerate.
The cochlear implant is an electrode array positioned to stimulate the auditory afferents directly, in the absence of hair cell function.
Cochlear Implant

- Two elements
  - External
  - Internal

- A microphone
- A speech processor
- A transmitter and receiver/stimulator
- An electrode array

- Bypasses damaged part of the ear
- Directly stimulates auditory nerve
Age Matters
Vocabulary

Normal ears
< 2.5 years
2.5-3.5 yrs
3.6-7 yrs
7.1-10 yrs

The point here: deaf children can recover near normal language ability if they are implanted early enough

(Connor et al. 2006)
The limit of implantation, is frequency resolution because today's best electrode has a max of 23 inputs to the ear.

Normal Hearing
The limit of implantation, is frequency resolution

6 channel hearing
The limit of implantation, is frequency resolution

4 channel hearing
Cochlear implants compress sound into bandpass filter channels, but only a few are needed to make sense of the world....

<table>
<thead>
<tr>
<th>Frequency</th>
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<tbody>
<tr>
<td>32 16 8 4 2 1</td>
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Time
Cochlear implants compress sound into bandpass filter channels, but only a few are needed to make sense of the world....

# of band filters
Cochlear implants compress sound into bandpass filter channels, but only a few are needed to make sense of the world....
music appreciation requires many more channels
music appreciation requires many more channels

These audio demos available at...

http://www.hei.org/research/aip/audiodemos.htm
New technology is allowing researchers and their patients to control machines with only the power of thought, and the help of computers.
The cortex has functionally distinct regions

1. Motor neurons fire predictable patterns before movement

http://www.emc.maricopa.edu/faculty/farabee/BIOBK/cerebrum_1.gif
The cortex has functionally distinct regions

2. computer programmers are getting sophisticated enough to have algorithms that interpret the output of 100’s of neurons
The cortex has functionally distinct regions

3. computers can then send complex commands to robots

http://www.emc.maricopa.edu/faculty/farabee/BIOBK/cerebrum_1.gif
New tiny electrode arrays can sample the activity of many neurons at once, and cause minimal tissue damage.
In 1999, researchers succeeded in demonstrating that a rat could control a single arm robot with signals from motor cortex neurons.

Fig. 1. Experimental protocol. (a) 'Lever-movement/robot-arm' mode: rats were trained to press a lever (b) for a water reward; displacement was electronically translated to proportionally move a robot arm (c) from rest position through a slot in barrier (d) to a water dropper (e). The robot arm/water drop moved passively to the rest position (to the rat). (f) 'Neuronal-population-function/robot-arm' mode: Rats were chronically implanted with multi-electrode recording arrays in the MI cortex and VL thalamus, yielding simultaneous recordings of up to 46 discriminated single neurons. (g) Superimposed waveforms of 24 such neurons. (h) Sample spike trains of two neurons (N1, N2) over 2.0 s. (i) Neuronal-population (NP) function extracting the first principal component of a 32-neuron population. (j) Switch to determine input source (lever movement or NP function) for controlling robot-arm position. In experiments, rats typically began moving the lever. The input was then switched to the NP function, allowing the animal to obtain water through direct neural control of the robot arm.

Chapin et al. *Nature* 2:664
By 2002, researchers demonstrated that monkeys could control robot arms in 3D and computer cursors on a monitor with brain activity alone.

Figure 2. A BMI with multiple feedback loops being developed at the Duke University Center for Neuroengineering. A rhesus macaque is operating an artificial robotic manipulator that reaches and grasps different objects. The manipulator is equipped with touch, proximity and position sensors. Signals from the sensors are delivered to the control computer (right), which processes them and converts to microstimulation pulses delivered to the sensory areas in the brain of the monkey, to provide it with feedback information (red loop). A series of microstimulation pulses is illustrated in the inset on the left. Neuronal activity is recorded in multiple brain areas and translated to commands to the actuator, via the control computer and multiple decoding algorithms (blue loop). Arm position is monitored using an optical tracking system that tracks the position of several markers mounted on the arm (green loop). We hypothesize that continuous operation of this interface would lead to incorporation of the external actuator into the representation of the body in the brain. Figure designed by Nathan Fitzsimmons.
Movies....
From the following article:

**Cortical control of a prosthetic arm for self-feeding**
Meel Velliste, Sagi Perel, M. Chance Spalding, Andrew S. Whitford & Andrew B. Schwartz

doi:10.1038/nature06996
For videos of human brain/computer interface technologies....

http://bci.tugraz.at/downloads.html

For video of monkey brain/computer interface technologies....

http://www.youtube.com/watch?v=iys5wvQD72Y&feature=related
Human brain implants are just around the corner with some devices already in clinical trials....

Figure 3. How a fully-implantable BMI could restore limb mobility in paralyzed subjects or amputees. Although the details of this system have to be worked out through future research, it is clear that the BMI for human clinical applications should be encased in the patient's body as much as possible. Wireless telemetry offers a viable solution for this purpose. The prosthesis not only should have the functionality of the human arm in terms of power and accuracy of the actuators, but also should be equipped with the sensors of touch and position from which signals can be transmitted back to the subject's brain.
Summary:

The brain is highly organized into functional maps (somatotopic, tonotopic, etc.) where neighboring neurons process similar information.

One function of the ear is to transmit sound frequency information to the brain.

Auditory transduction is achieved by hair cells that translate mechanical energy into electrical energy.

Cochlear implants bypass hair cells by stimulating auditory nerve fibers directly.
Summary:

Small electrode arrays and computers can bypass motor systems to operate prosthetic devices etc. This strategy is highly likely to help patients with neurological disease.