Deep Brain Stimulation

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Introduction

- Deep brain stimulation (DBS) is a surgical procedure consisting of:
  - Implanted pulse generator (IPG)
  - Lead with 4 platinum iridium electrodes
  - Extension
Introduction

- Psychiatric neurosurgery consistently yields improvement in 35-70% of cases
- Nonablative procedure
- Flexible and reversible modulation of brain function
- Mechanisms not clear, typically managed by trial-and-error
- Used to treat Parkinson’s disease, tremor disorders, dystonia, chronic pain, depression, and OCD
- In 2009, US FDA granted approval for DBS to be used on OCD, the first approval for psychiatric illness.
Outline

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Background

- First report of human cortical stimulation appeared in 1874
- 1950s effects of stimulation were investigated
- Early 1960s, reported that high frequency (100 Hz) stimulation could diminish tremor
- 1960s came idea of treating neurologic disorders with chronic stimulation
- 1990s pacemaker technology was combined with implanted deep brain electrodes which developed first DBS
Background on OCD

- Obsessive Compulsive Disorder (OCD) characterized by
  - Intrusive thoughts and impulses - Obsessions
  - Repetitive intentional behaviors - Compulsions
  - Overwhelming anxiety
  - Typically chronic

- Pathogenesis of OCD is unknown
  - The development of the disease

- Pathophysiology is known, but not completely.
  - The changes of normal functions caused by a disease
More on OCD

- Affects 2-3% of the population
- Estimated that over 20% of OCD patients may not be yielding to current available treatments.
- Potential surgical candidates
  - Aggressive treatment trials
  - Social stability
  - Proximity to treatment center
  - Resources for long term care
Neurocircuitry Model of OCD

- OCD points to abnormalities in frontal basal ganglia-thalamic circuits
  - Orbital frontal cortex, OFC
  - Anterior cingulated cortex, ACC
- Structural neuroimaging found differences in OFC volumes in OCD patients vs controls.
- Magnetic resonance spectroscopy (MRS) studies provided evidence of abnormalities in this circuitry.

http://www.arthursclipart.org/medical/nervous/page_01.htm
Fundamentals

- Fundamental purpose of DBS is to modulate neural activity with extracellular electric fields.

\[ E = \frac{F}{q} \]
- F is electric force
- q is charge
- E is electric field

\[ E = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{r} \]
- q is charge
- E is electric field
- r is distance
- \( \hat{r} \) is unit vector
- \( \varepsilon_0 \) is electric constant

Gauss’s Law

\[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \]
- E is electric field
- \( \rho \) is charge density
- \( \varepsilon_0 \) is electric constant
Risks

- Is nonablative, however some damage to brain tissue
  - Generally about 1.3mm diameter from leads
- Hemorrhages on device are rare, about 0.5% per implantation.
- Infection is possible. Found in 2/17 patients in one study for subthalamic DBS.
- Long-term presence of device has not been identified yet
Procedure

- Small diameter (1.27mm) brain leads implanted through burr holes in skull
- Craniotomy done under local anesthesia, patient sedated but awake
- Lead placement guided by multimodal imaging and computerized targeting platforms
- Unlike DBS with Parkinson's, microelectrode recording is not used for target identification.
- Lead is stimulated to check location
- Separate phase, neurostimulator is implanted, often in upper chest wall. Connected to brain leads by extension wires under skin.

http://www.webmd.com/parkinsons-disease/deep-brain-stimulation
Parameters

- General parameters for tremor based DBS were found using trial and error
- 1-5 V stimulus amplitude
- 60-200 us stimulus pulse duration
- 120-180 Hz frequency

- Can’t be used for OCD because effects are not immediate, can takes weeks to months
Optimizing Parameters

• Parameters include
  • amplitudes
  • pulse widths
  • frequencies
  • activation of individual electrodes

• Parameter settings initially borrowed from DBS for movement disorders

• Typically performed by trained psychiatrist, can be time consuming with long term follow up

• Permits adjustable, and reversible modulation of the brain.
Modeling DBS

- Original DBS systems adapted from cardiac pacing technology
  - Around 20 years old
  - Had limited knowledge of neural stimulation
- New technology can improve DBS electrode designs
  - Neural engineering design tools
  - Computer modeling
- Predicts the volume of tissue activated during simulation using DBS electrode model.
Modeling DBS

- Quantitative measurements used to predict 3-d volume of tissue activated by the electric field
  - Volume of tissue activated (VTA)
  - Shape of tissue activated (STA)
- Finite element model (FEM) consists of
  - Brain tissue
  - DBS electrode contacts
- Used to address effects of DBS in homogeneous isotropic medium
- 2\textsuperscript{nd} derivative of potential distribution used as predictor of VTA and STA
DBS Electrode Element Model

- DBS FEM, with 4 electrodes and brain tissue
- Left to right, electrodes 1-4
- Approximately 300,000 nodes.
- Tissue medium is homogeneous and isotropic
- Conductivity $\sigma=0.3$ S/m
- Lead modeled as electrical insulator

T.M. Choi and Y.T. Lee, “Modeling Deep Brain Stimulation”
Simulation Steps

- Finite element model (FEM) is created
- Stimulation waveform applied to electrode
- System is solved using FEM solver
- Resulting space-dependent voltages used to calculate activating function threshold for neural fibers
- VTA is determined using thresholds
Finite Element Potential Contour

- Electrical potential result of DBS FEM
- Contains 4-contact platinum electrodes and brain tissue.
- -1V applied to electrode 2, others are set to 0V

T.M. Choi and Y.T. Lee, “Modeling Deep Brain Stimulation”
VTA Contours

- Shows the volume of tissue being activated
- Relation between electrode height and VTA
- Black parts are stimulation electrodes
- VTA contour gets longer with electrode height
- Direct relationship

T.M. Choi and Y.T. Lee, “Modeling Deep Brain Stimulation”
Other FEM models

- Axisymmetric FEM created with electrode lead and single electrode contact, matching surface area of the IPG
- Models contained cathode and anode to mimic monopolar stimulation condition
- Voltage within volume solved using FEM solver to determine potential distribution
- Solver used Poisson equations at 512 frequencies between 0 Hz and 5000 Hz, then FFT of the stimulation waveform to find time dependent waveform
**Axisymmetric model of DBS**

- Right side - DBS electrode surrounded by a volume conductor
- FEM mesh and voltage solution shown for $-1$ V stimulus.
- The left side - equivalent circuit model of DBS system
- $-1$ V source, wires, electrode contact capacitance electrode encapsulation layer, bulk tissue and IPG encapsulation layer.

Parameters: conductor height ($H$) and length ($L$); thickness around lead ($t_{Ec}$) and IPG ($t_{Ea}$); contact height ($h$) and radius ($r$); bulk tissue conductivity ($\sigma_T$), electrode conductivity ($\sigma_{Ec}$) and IPG conductivity ($\sigma_{Ea}$).
Impedance Models

- Impedance models can be low, medium, or high
- Generate different VTA
- Parameter settings were
  - -1.5 to -3 V amplitude
  - 90 us pulse duration
  - 130 Hz stimulus train
- VTA was inversely correlated with impedance
Impedance Models

- Plots of stimulation for common DBS settings with low, medium, and high impedance models

- 3D model using Medtronic 3387 electrode implanted in thalamus to show relative MRI slices

C. R. Butson, et al. “Sources and effects of electrode impedance during deep brain stimulation”
Conclusions

• Electrode impedance helps define current delivered to tissue in DBS and effects VTA
• Volume conduction simulations can be used to study VTA for electrical stimulation
• Various electrode designs can be considered with FEM models
• Using models helps reduce amount of trial-and-error used in DBS, especially when treating OCD
References

- C. C. McIntyre, et al. “Uncovering the mechanism(s) of deep brain stimulation: activation, inhibition, or both” *Clinical Neurophysiology*, vol. 115, pp. 1239-1248, 2004