Introduction

- As with all NIOM, the goal is to identify and minimize any compromise to neurologic function

- Spine surgeries especially with pedicle screw placement, cord untethering, resection of spinal cord tumors all pose risk to spinal nerve root function
Surgical risks

- Neural complications
- Vascular complications
  - Risk to aorta, vertebral vessels, pleural cavity
- Impaired stability of construct
Surgical risks

- Mechanical injury:
  - Central-peripheral transitional region. The axons at this point are enclosed by a thin root sheath, cerebrospinal fluid, and meninges, and lack the protective covering of epineurium and perineurium that is present in peripheral nerve.
  - Area of hypovascularity at the junction of the proximal and middle one-third of the dorsal and ventral roots. This is a point of anastomosis.

Surgical risks

- Postoperative nerve deficit following lumbar spine surgery: 1 -10%
- Most commonly foot drop from L5 injury
- C5 nerve root injury most common with cervical procedures

Monitoring spinal nerve roots

- X-ray
  - Missing 3-D perspective, rotational deformity
- Fluoroscopy
- CT
- Stereotaxic imaging
- Neurophysiology
Anatomy

- Main efferent pathway is corticospinal tract
- Motor cortex to internal capsule to medullary pyramid to lateral spinal cord to anterior horn cell to ventral roots to muscle fibers
  - C1 passes above C1 vertebra
  - C8 passes between C7 and T1 vertebrae
  - L5 passes below L5 vertebra
Anatomy

- Adult spinal cord ends across L1 vertebra
- At birth, the spinal cord ends at L1-L2
- Individual lumbosacral nerve roots descend as cauda equina
Mixed nerve somatosensory evoked potentials (SEPs) and transcranial electrical motor evoked potentials monitor the spinal cord but are not sensitive to detect nerve root injuries.

EMG most often used to monitor nerve root function:
- Continuous/free-run
- Triggered
Continuous free-run EMG

- Able to be monitored from multiple channels simultaneously
- Loudspeaker on equipment provides instantaneous feedback
- Immediate results without averaging
- More sensitive than SEPs and DSEPs
Continuous free-running EMG

- Significant EMG activity occurs in ~80% of monitored lumbosacral spine surgeries
- New neurologic deficits in 7%
  - High sensitivity, low specificity, low positive predictive value (100%, 24%, 0.09)
  - SEPs have low sensitivity, high specificity, high positive predictive value (29%, 95%, 0.9)

Continuous free-running EMG

- Monitored from muscles (limb, anal sphincter) innervated by nerve roots considered to be at risk for injury during surgery
- Time base: 100-200 ms/div
- Display sensitivity: 50-100 μV/div
- Filters: 30 Hz/3000Hz
- Subdermal needle electrodes.
  - Looking for all-or-nothing responses
  - Monopolar needles for deeper muscles
Continuous free-running EMG

- Monopolar needles v. subdermal needles v. surface electrodes
- Bipolar configuration – increased proportion of muscle sampled; activity specific to muscle of interest
- Monopolar configuration – higher amplitude
- Number of sampling sites in a given muscle may be more valuable than number of muscles as any given muscle may be innervated by multiple roots
**Continuous free-running EMG**

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Root levels</th>
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</thead>
<tbody>
<tr>
<td>Abdominal obliques</td>
<td>T7-12</td>
</tr>
<tr>
<td>Iliacus</td>
<td>L1-2</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>L2-4</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>L4-5</td>
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<tr>
<td>Medial gastrocnemius</td>
<td>S1-2</td>
</tr>
<tr>
<td>Anal/urethral sphincter</td>
<td>S3-5</td>
</tr>
</tbody>
</table>

* Target large, superficial muscles*
Continuous free-running EMG

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Root levels</th>
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</thead>
<tbody>
<tr>
<td>Deltoid</td>
<td>C5</td>
</tr>
<tr>
<td>Biceps</td>
<td>C5-6</td>
</tr>
<tr>
<td>Extensor Carpi Radialis</td>
<td>C6</td>
</tr>
<tr>
<td>Triceps, Flexor Carpi Radialis</td>
<td>C7</td>
</tr>
<tr>
<td>Abductor Pollicis Brevis</td>
<td>C8-T1</td>
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</table>
Continuous free-running EMG

- Blunt mechanical trauma to nerve root leads to depolarization identified as motor unit potential
- Minor nerve root manipulation leads to short burst of motor unit potentials
- Severe mechanical root injury or retraction causes neurotonic discharges (prolonged trains of high frequency motor unit potentials)
- Myokymic discharges indicate very severe nerve injury
Continuous free-running EMG

- **Pitfalls**
  - EMG may be quiet following sharp nerve transection
  - Distal nerve stump can be activated by mechanical irritation and electrical stimulation
  - Mechanical trauma less likely to evoke neurotonic discharges in abnormal motor nerves
Continuous free-running EMG

- Mimics
  - Spontaneous fibrillations
    - Continuous
    - Slow and regular rate of firing
  - Voluntary motor unit potentials
    - Light anesthesia
    - Simultaneous from bilateral myotomes
  - Electrocautery artifact
  - Needle electrode movement
Stimulus-triggered EMG

- To verify the integrity of the neuroaxis in surgeries to the vertebral column
- To facilitate nerve root sectioning during exposure and tumor resection, especially for ventral masses
  - Stimulate filum terminale higher - to 100V v. 10V (20mA)
  - Dermatomes for thoracic nerve roots overlap
  - Radicular arteries that supply the spinal cord itself travel in dural sheaths of nerve roots
Stimulus-triggered EMG

- Time base 5-10 ms/div
- Sensitivity 50-100 μV/div
- Filters: 30 Hz/3000Hz
- Direct stimulation
  - 0.05-1V in children, 0.1-7V in adults with constant voltage stimulator
  - 0.1-10mA for constant current stimulator
  - Nationwide Children’s Hospital: 0.1-0.5 mA
Stimulus-triggered EMG

- **Monopolar stim** – stimulate large region to determine if neural elements present
  - Stimulating probe
  - Moving the stimulating electrode causes an increase in EMG amplitude closer to the innervating nerve

- **Bipolar stim** – focal current delivery to distinguish between two nerves
  - Electrocautery forceps can be used as bipolar electrode.
  - More difficult to use as orientation is important
Pedicle screws are point of fixation for spine instrumentation

Drilled blindly through narrow pedicles into the vertebral body

Postoperative symptoms related to irritation or nerve root injury caused by misplaced screws in 5-10% cases

Intraoperative fluoroscopy and x-ray attempt to verify correct placement
Stimulus-triggered EMG monitoring helps verify correct placement of pedicle screws.

When placed correctly, cortical bony layer separates screw/hole from adjacent roots:

- High impedance to passage of electrical current

Compound muscle action potentials are evoked at low stimulation intensity when screw/hole lies against nerve roots.
Stimulus-triggered EMG – Pedicle Screw Stimulation

- Monopolar stimulating electrode
- Electrocautery should be well-grounded to prevent burns at sites of EMG needle insertion
- Screw stimulation along exposed shank of screw
- Hole stimulation at level of pedicle rather than deep in vertebral body
  - Consider testing tract circumferentially
- In case of perforation, redirecting the hole can push bone fragments into the perforation
Stimulus-triggered EMG – Pedicle Screw Stimulation

- Constant current stimulation
- Decreased stimulation duration should increase thresholds
- S1 may have thinner cortex than lumbar
- Thoracic pedicles more challenging because smaller size and more variability
- Looking for minimal deflection
Well positioned pedicle screws in L1 and L2.
The right L1 screw passes through the right lateral aspect of the spinal canal, paralleling the right-sided pedicle. The screw is positioned 6 mm medial to the medial cortex of the right pedicle.

The left L2 screw appears to slightly breach the medial cortex of the left L2 pedicle without significantly transgressing the spinal canal.
Stimulus-triggered EMG – Pedicle Screw Stimulation

- At Nationwide Children’s Hospital, start at 0 mA and increase by 0.5 mA to 14 mA
- Some institutions screen with stimulation at 7-10 mA
- Stimulus threshold <6 mA is most worrisome
- Stimulus threshold >8 mA has a very low likelihood of screw malposition
<table>
<thead>
<tr>
<th>Stimulus threshold</th>
<th>Probability of malposition</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;8 mA</td>
<td>0.31%</td>
<td>86%</td>
<td>94%</td>
</tr>
<tr>
<td>4-8 mA</td>
<td>17.4%</td>
<td></td>
<td></td>
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<tr>
<td>&lt;4 mA</td>
<td>54.2%</td>
<td>36%</td>
<td>99%</td>
</tr>
<tr>
<td>&lt;2.8 mA</td>
<td>100%</td>
<td>8.4%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Pitfalls

- Certain screws may have high electrical resistance and lead to a false-negative
- May see false positive in osteoporosis with lower impedance despite intact bone
- May see false negative if excess fluid in field shunts current
- May see false negative in pre-existing radiculopathy
  - Suspect pre-existing axonotmetic nerve root injury in presence of chronic pre-op radicular motor deficits or abnormal pre-op EMG.
  - Consider testing up to 20 mA or 5 mA higher than direct-stimulation response
Stimulus-triggered EMG – Pedicle Screw Stimulation

- Pitfalls
  - Neuromuscular blockade
    - Neuromuscular blockade up to 50-75% acceptable using short-acting agents such as atracurium or vecuronium.
    - Monitor with train-of four (repetitive nerve) peripheral stimulation. 4 CMAP responses at supramaximal stim of 2 Hz
    - Reversal agent such as neostigmine may be delayed and reversal should not be attempted until 10-20% function has returned
Train of Four

- Assesses degree of neuromuscular blockade
- Pulse width 200-300 microseconds
- Current 30 mA
- Nerve root threshold CMAP unreliable with NMB >80%
Train of Four

<table>
<thead>
<tr>
<th></th>
<th>T1 amplitude</th>
<th>Blockade</th>
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<tr>
<td>T4 disappears</td>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td>T3 disappears</td>
<td>20%</td>
<td>80%</td>
</tr>
<tr>
<td>T2 disappears</td>
<td>10%</td>
<td>90%</td>
</tr>
<tr>
<td>T1 disappears</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Similar technique of stimulus-triggered EMG using a handheld stimulator in the operative field can identify nerve roots during spinal cord surgeries for tethered cord release and tumor resection.

Spinal cord tumors account for 2-4% of primary central nervous system tumors.
Stimulus-triggered EMG: cord lesions

- Tethered cord syndrome lead to sensorimotor dysfunction in lower extremities and sphincter dysfunction
- Most commonly tethered to lipomyelomeningocele or spinal lipoma
- NIOM helps to isolate nerves from nonneural tissue and localize nerve roots by level
  - Stimulate filum terminale at higher intensity to ensure no neural elements present
Stimulus-triggered EMG: cord lesions

- Quadriceps femoris: L2-4
- Tibialis anterior: L4-5
- Extensor hallucis longus: L5-S1
- Hamstrings: L5-S2
- Gluteus maximus: L5-S2
- Medial gastrocnemius: S1-2
Plan for monitoring?
Plan for monitoring?

- Upper and lower SSEPs
- Upper and lower MEPs
- Free run EMG
- Set up for triggered EMG with nerve monitor
Plan for monitoring

- Upper and lower SSEPs ✔ Median and Post tib
- Upper and lower MEPs ✗ VP shunt
- Free run EMG ✔
- Triggered EMG with nerve monitor ✔
  - Vastus lateralis, tibialis anterior, gluteus maximus, medial gastrocnemius, abductor hallucis brevis, sphincter
* Dissection carried out between the last spinous process and dorsal aspect of the sacrum until the thecal sac was identified

* Spinal cord beneath the thecal sac appeared scarred bilaterally

* Surgeon requests nerve monitor to stimulate the scar tissue and apparent nerve roots
Rocuronium given at 09:56
Neostigmine given at 11:06
Stimulus-triggered EMG: SDR

- Spasticity in patients with cerebral palsy results from reduced inhibition from descending corticospinal tract and enhanced sensory input to anterior horn cells
  - Best candidates do not rely on spasticity to ambulate
- Selective dorsal rhizotomy (SDR)
  - Ablation of abnormal sensory rootlets
- Complete dorsal rhizotomy = hypotonia
Record muscles innervated by L2-S2 with most attention to thigh adductors and knee extensors

- Advise caution in sectioning S1 nerve rootlets and rootlets otherwise associated with anal sphincter responses
- Sectioning S2 rootlets risks lower urinary tract and sexual dysfunction
- Assign 5-level grading to responses by a 1-sec 50 Hz train
## Stimulus-triggered EMG: SDR

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Nerve</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh adductors</td>
<td>obturator</td>
<td>L2-4</td>
</tr>
<tr>
<td>Quadriceps femoris</td>
<td>Femoral</td>
<td>L2-4</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>d. peroneal</td>
<td>L4-5</td>
</tr>
<tr>
<td>Short head, biceps femoris</td>
<td>sciatic</td>
<td>L5-S1</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>tibial</td>
<td>S1-2</td>
</tr>
<tr>
<td>External anal sphincter</td>
<td>pudendal</td>
<td>S2-4</td>
</tr>
</tbody>
</table>
Stimulus-triggered EMG: SDR

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No sustained discharge</td>
</tr>
<tr>
<td>1+</td>
<td>Sustained response only in muscles innervated by stimulated segmental level</td>
</tr>
<tr>
<td>2+</td>
<td>Sustained response in muscles of stimulated segmental level and additional level</td>
</tr>
<tr>
<td>3+</td>
<td>Sustained response in muscles of multiple ipsilateral segmental levels</td>
</tr>
<tr>
<td>4+</td>
<td>Sustained response with spread to contralateral leg</td>
</tr>
<tr>
<td>Root Level</td>
<td>Stimulation Result</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Right L2 ---4 rootlets:</td>
<td>3; 2; 2+ ;3</td>
</tr>
<tr>
<td>Right L3--3 rootlets:</td>
<td>2; 1; 1</td>
</tr>
<tr>
<td>Right L4--5 rootlets:</td>
<td>1; 2; 3; 3+; 3</td>
</tr>
<tr>
<td>Right L5--5 rootlets:</td>
<td>4; 4; 3+; 4; 4</td>
</tr>
<tr>
<td>Right S1--3 rootlets:</td>
<td>3; 1; 1</td>
</tr>
<tr>
<td>Left L2--4 rootlets:</td>
<td>3; 3; 3+; 3+</td>
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<tr>
<td>Left L3--4 rootlets:</td>
<td>4; 3; 3+; 3+</td>
</tr>
<tr>
<td>Left L4--4 rootlets:</td>
<td>1; 2; 1; 1</td>
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<tr>
<td>Left L5--4 rootlets:</td>
<td>2; 2; 3; 1</td>
</tr>
<tr>
<td>Left S1--4 rootlets</td>
<td>1; 1; 1</td>
</tr>
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# Ashworth scores

<table>
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<tr>
<th></th>
<th>Elbow ext</th>
<th>Elbow flx</th>
<th>Wrist ext</th>
<th>Wrist ext</th>
<th>Hip Abd</th>
<th>Hip ext</th>
<th>Hip flx</th>
<th>Knee ext</th>
<th>Knee flx</th>
<th>Ankle ext</th>
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<td>4</td>
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</tbody>
</table>
Bulbocavernosus reflex

- Polysynaptic, S1-S3
- Afferent from pudendal nerve (dorsal penis or clitoral nerve)
- Efferent to contraction of external anal sphincter
- Affected by inhalational anesthetics

Spinal nerve roots are susceptible to orthopedic and neurovascular surgeries of the spine.
Closing thoughts

- Spinal nerve roots are susceptible to orthopedic and neurovascular surgeries of the spine
- NIOM with EMG detects early and potentially reversible surgical nerve root irritation with high sensitivity
Closing thoughts

- Spinal nerve roots are susceptible to orthopedic and neurovascular surgeries of the spine
- NIOM with EMG detects early and potentially reversible surgical nerve root irritation with high sensitivity
- EMG monitoring is susceptible to medication, namely paralytics