Basic neurophysiological principles and surgical

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At the end of this presentation you will be able to:

- Describe resting membrane potential, nerve action potential and its propagation
- Describe the methods used for spinal cord monitoring during spinal surgery
- Describe the relationship between intraoperative monitoring changes and functional outcome
- Describe the limitations of intraoperative spinal cord monitoring

Given:

- cell membrane has different permeability to different ions
- active transport leads to unequal distribution of ions across membrane
- membrane acts like a capacitor (voltage storage)

Nernst Equation (equilibrium potential)

- Describes the potential difference needed to ***counteract*** the diffusion of an ion along its [ ] gradient.

$$E\,(m) = 61 \log \frac{[K]o}{[K]i}$$

Resting Membrane Potential

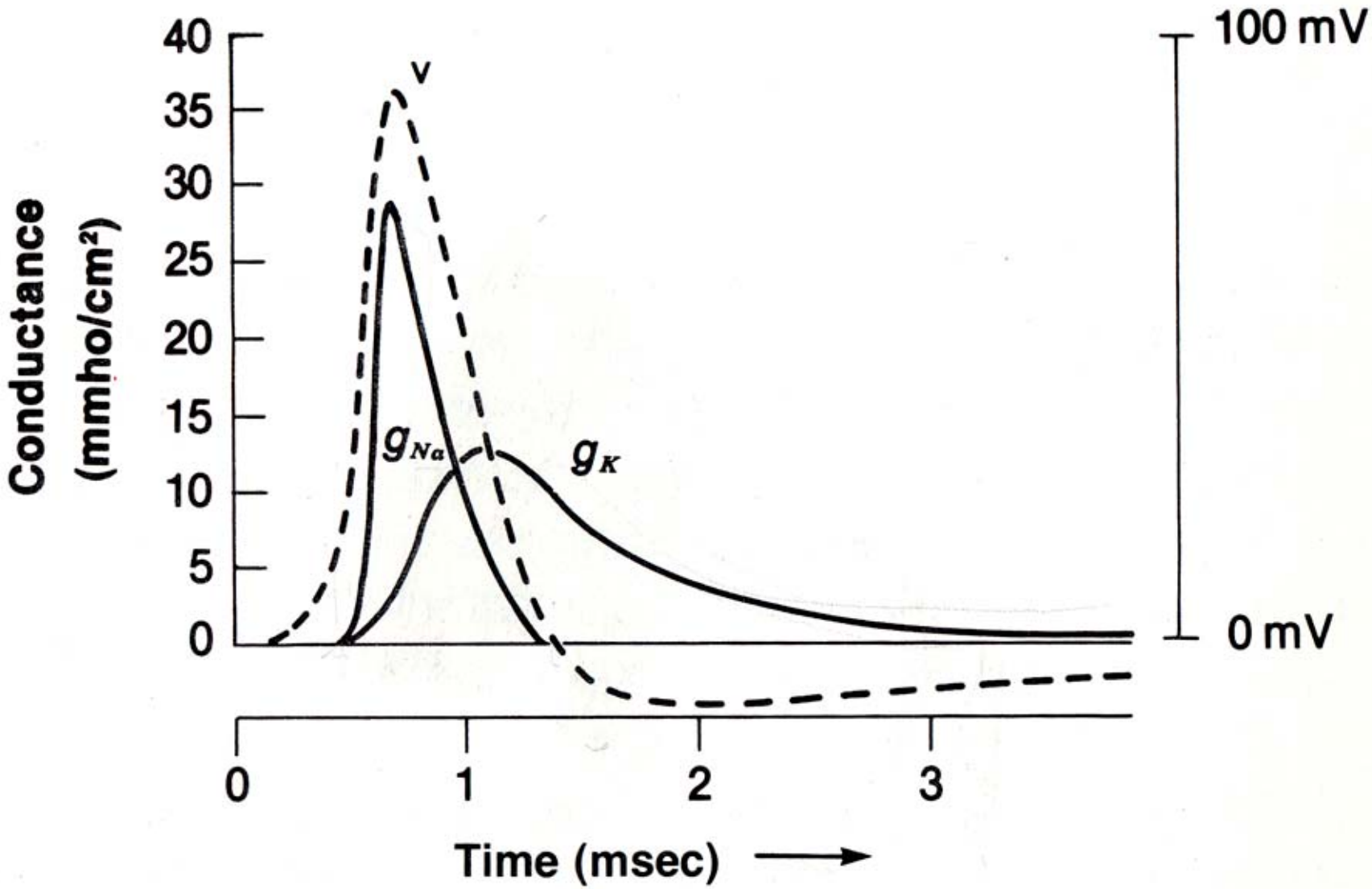
- ***Polarity inside cell, relative to that outside (potential difference);*** related to difference in [ion] across membrane (-70 mV in nerve)

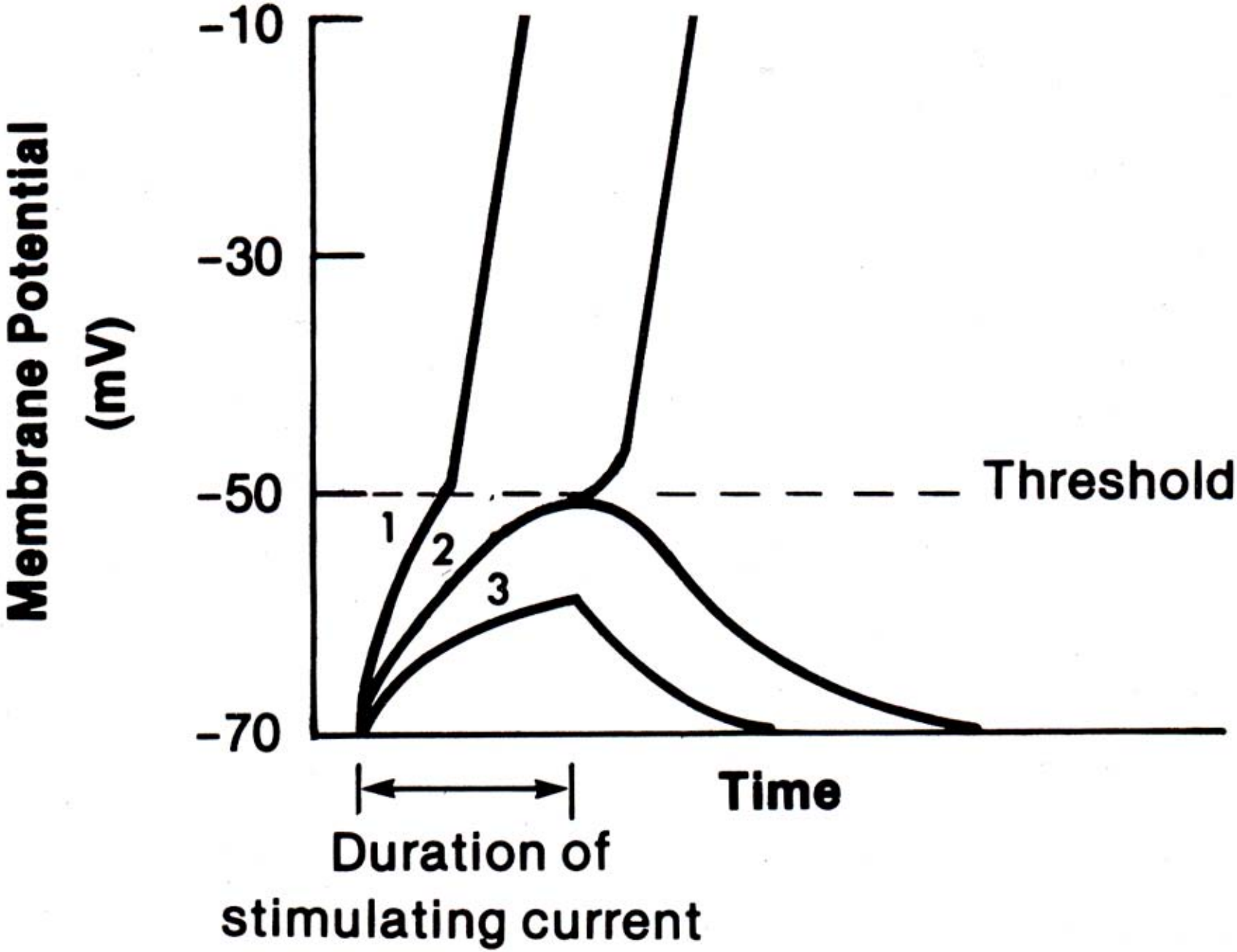
$$E\ (rmp) = 61 \log \frac{P[K]o + P[Na]o + P[Cl]i}{P[K]i + P[Na]i + P[Cl]o}$$

P = permeability

Action Potential

- ***Transient reversal of membrane potential*** due to temporary change in membrane permeability
- Biphasic current flow: rapid initial inward flow of Na (reversal); longer outward flow of K (repolarization)


Conductance
(mmho/cm²)
40
35
30
25
20
15
10
5
0
V
g_{Na}
g_K
100 mV
0 mV
0
1
2
3
Time (msec)


Membrane Potential
(mV)
-10
-30
-50
-70
Threshold
1
2
3
Time
Duration of
stimulating current

Refractory period

- Absolute: ***During AP, unable to produce another AP,*** due to decrease Na permeability and increase in K permeability after AP

- Relative: ***During repolarization, can produce AP***, but threshold is increased

Propagation of AP in myelinated nerve

- Inside cell: current flow toward ***inactive*** node
- Outside cell: current flow toward ***active*** node
- Myelin a) increases CV by current jumping and b) decreases energy requirement for AP propagation

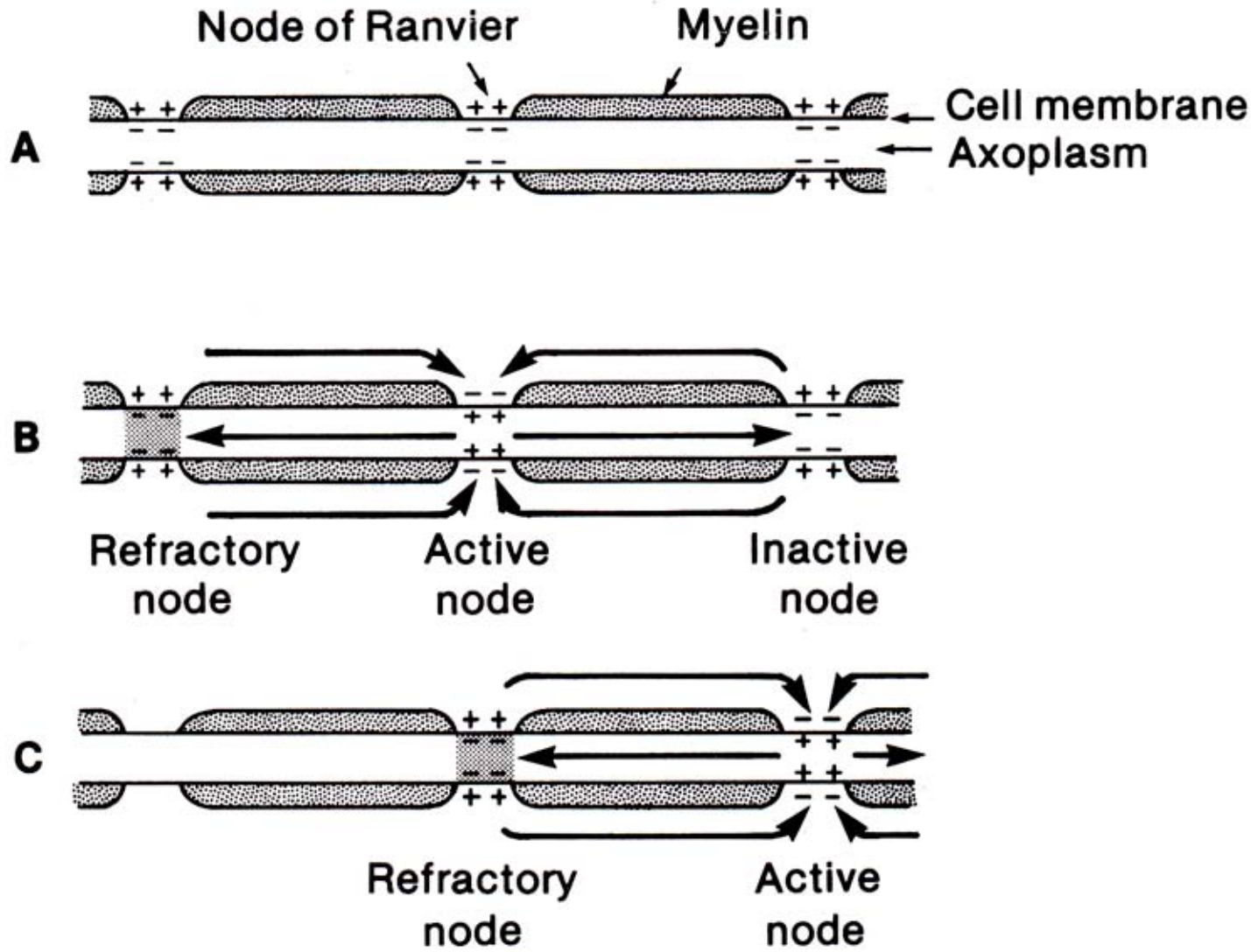
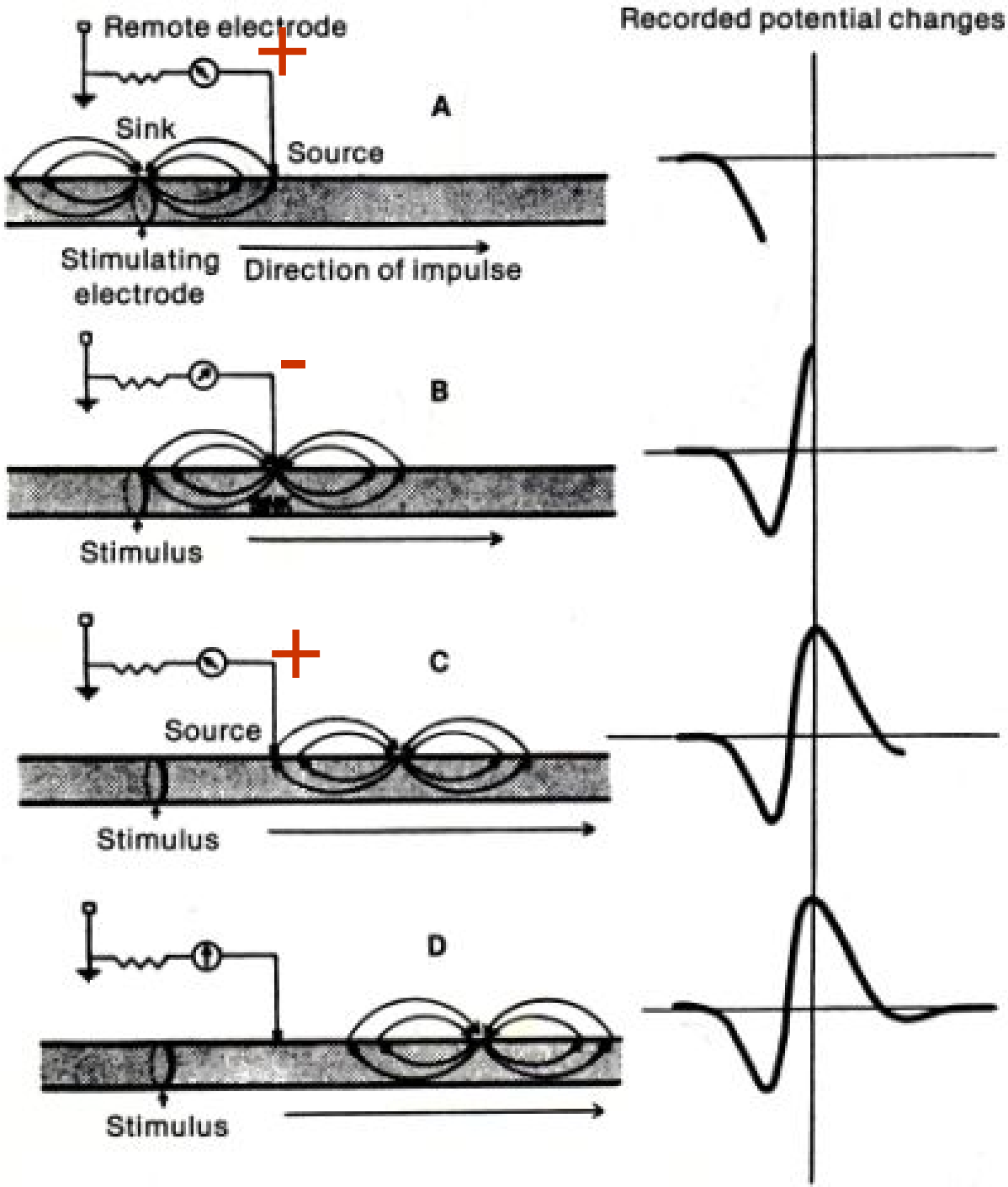


FIGURE 2-4. Local current circuits during the propagation of an action potential in a myelinated nerve fiber. The direction of propagation is from left to right, and the arrows indicate the direction of current flow between active and inactive nodes: **A,** nerve fiber at rest; **B,** impulse at node in center; and **C,** impulse at node on right.


Remote electrode
+
A
Sink
Source
Stimulating electrode
Direction of impulse
Recorded potential changes
-
B
Stimulus
+
C
Source
Stimulus
D
Stimulus

Compound Action Potential (CAP)

- ***Sum of electrical events after a stimulus***
- various fibres (with different CV's) have different thresholds for AP, so increasing stim. intensity changes form of CAP
- fibres with longest internode length have lowest threshold

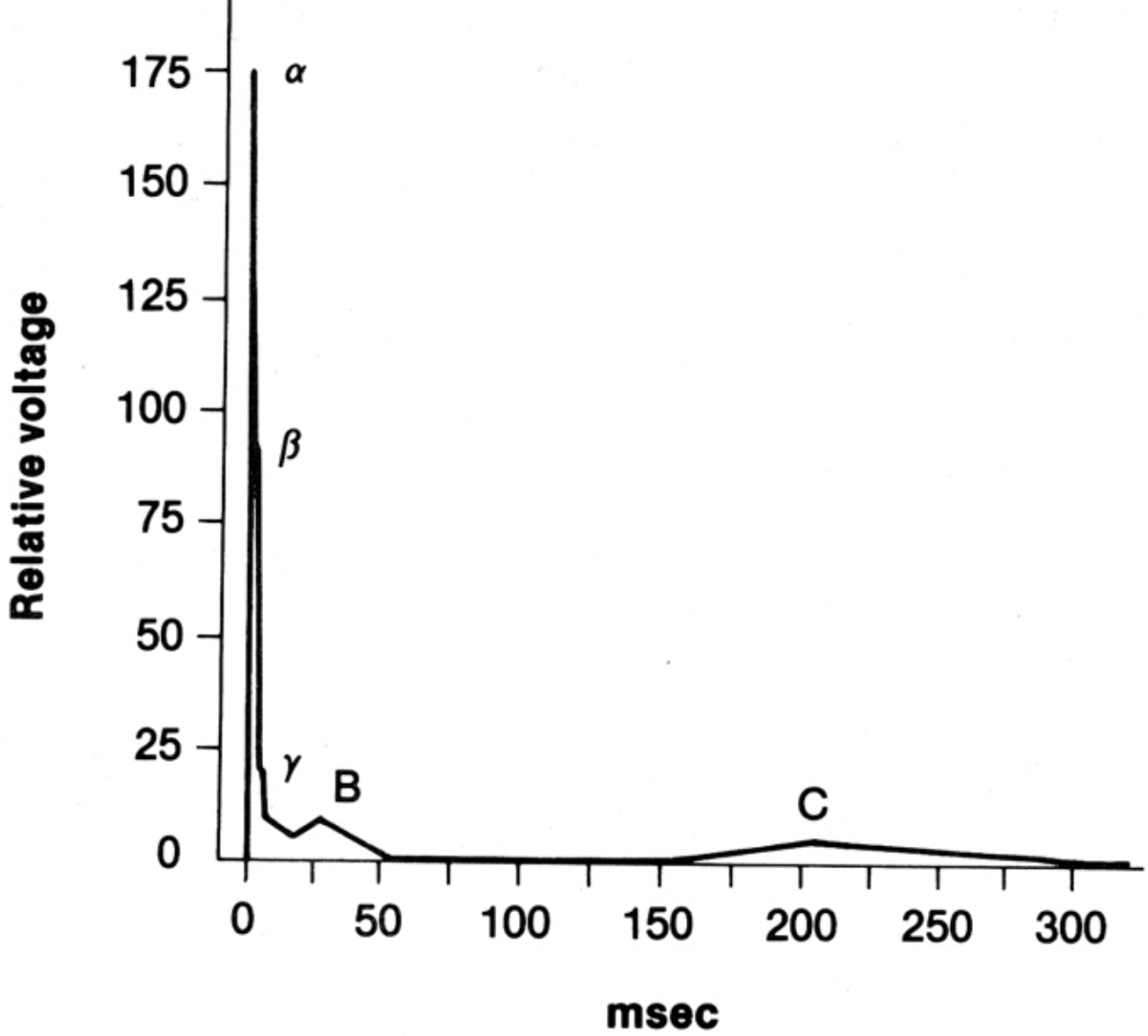


FIGURE 2-5. Compound action potential of a peripheral nerve, showing the relative sizes and time relationships of its components. (Reproduced with permission from W.F. Ganong, *Review of medical physiology,* 7th ed., Los Altos, Calif.:Lange

TABLE 2-2. Classification of afferent nerve fibers

Group	Fiber diameter (μ)	Conduction velocity (m/sec)	Source of fiber	Electrophysiologic equivalent
Ia	12–22	70–120	Spindle annulospiral endings	Aα
Ib	12–22	70–120	Golgi tendon receptors	Aα
II	5–12	30–70	Flower-spray spindle endings	A α and ? β
			Touch and pressure receptors	
III	2–5	12–30	Pain and temperature receptors	A δ
			Unidentified muscle receptors	
IV	0.5–1	0.5–2	Pain and temperature receptors	C
			Unidentified muscle receptors	

Conduction Velocity (CV)

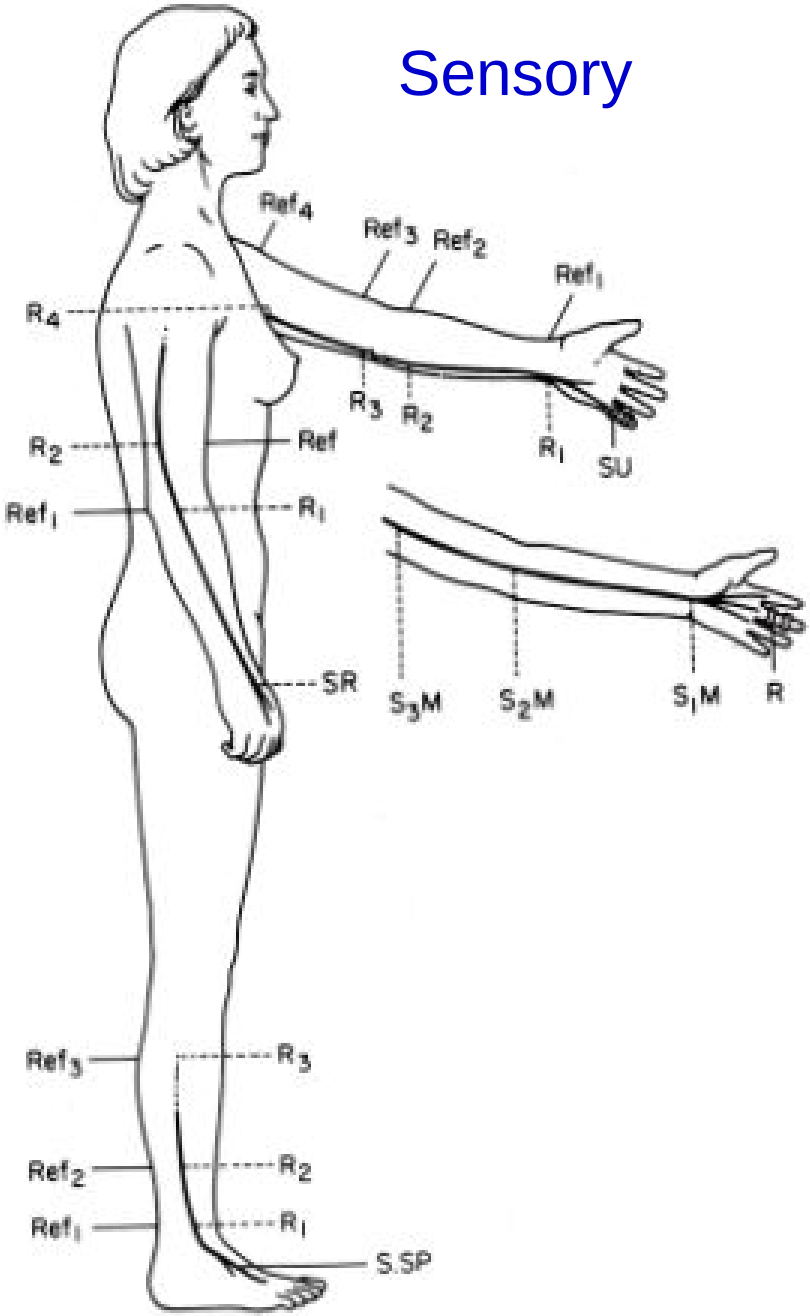
Fast conduction velocity related to :

a) ***larger fibre diameter***; decreases internal resistance

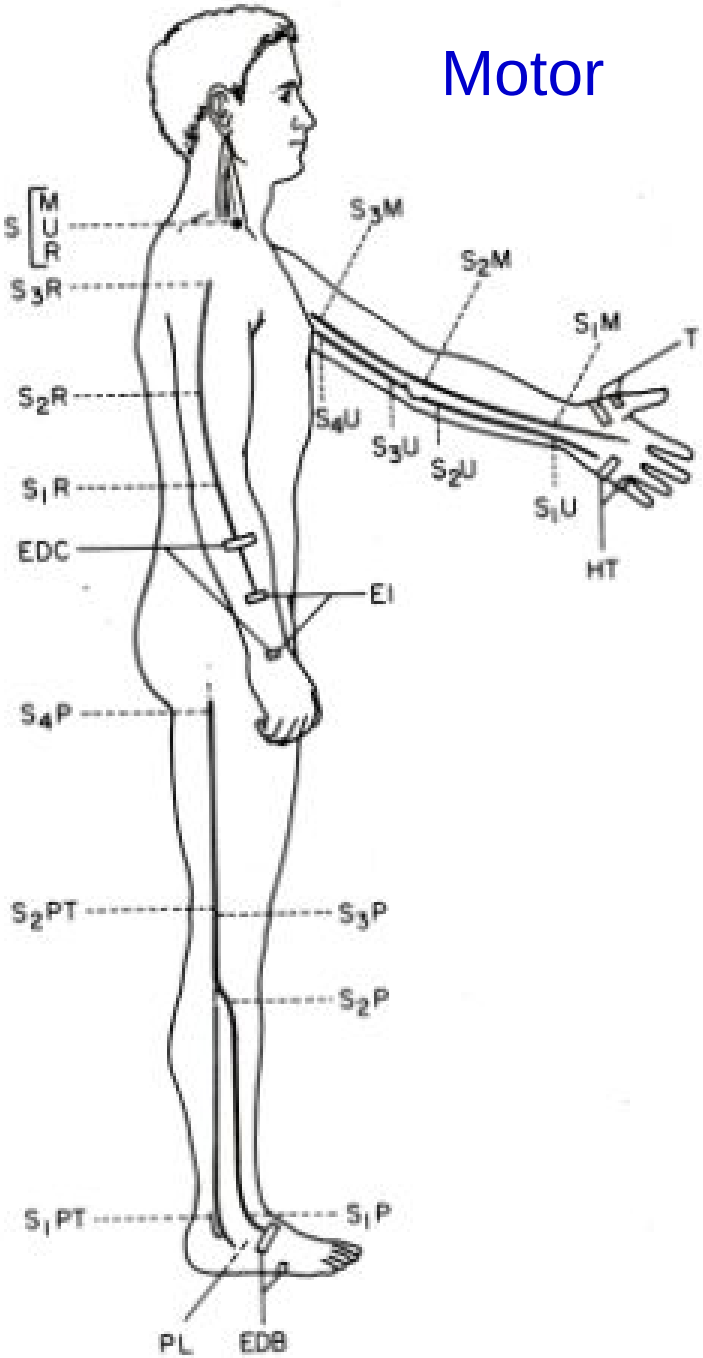
b) ***longer internode distance*** = longer to jump

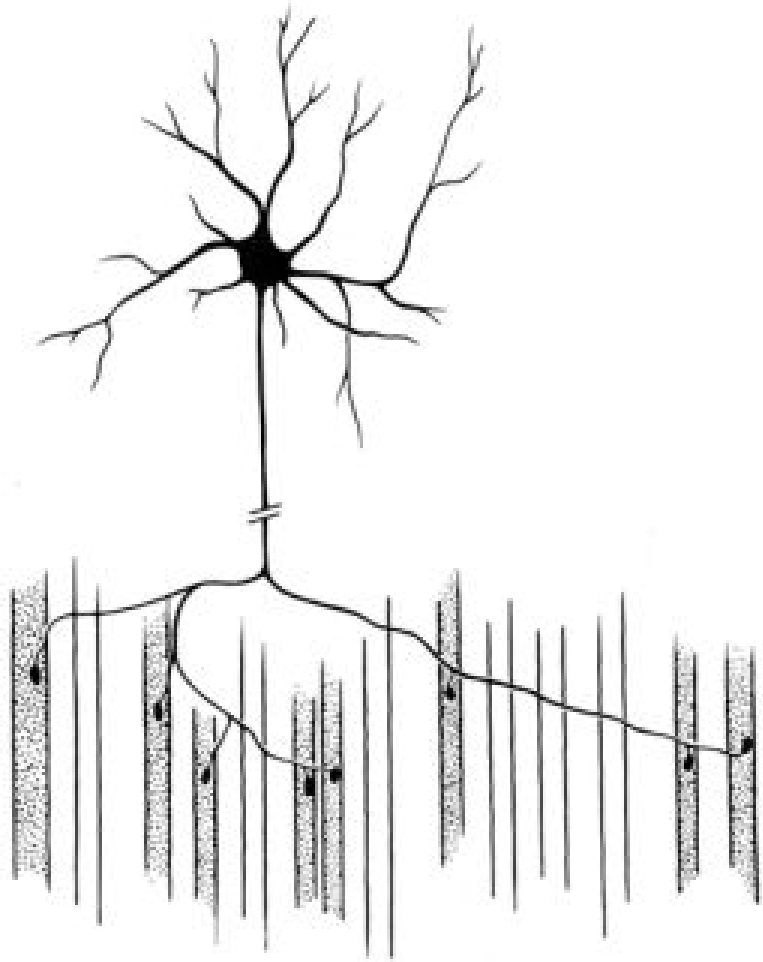
c) ***thicker myelin***

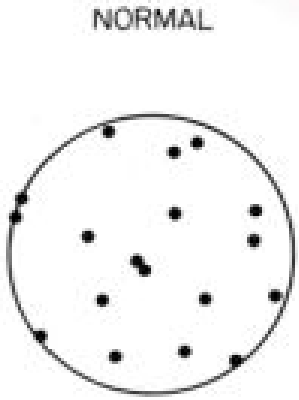
Sensory

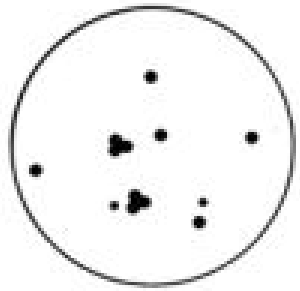


Motor









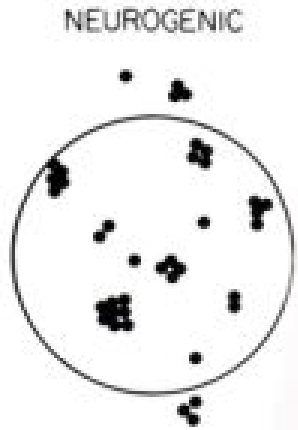


FIGURE 5.1. Major components of the motor unit, which include the motoneuron cell body and its dendritic tree, the axon, and the whole complement of muscle fibers innervated by the motoneuron.

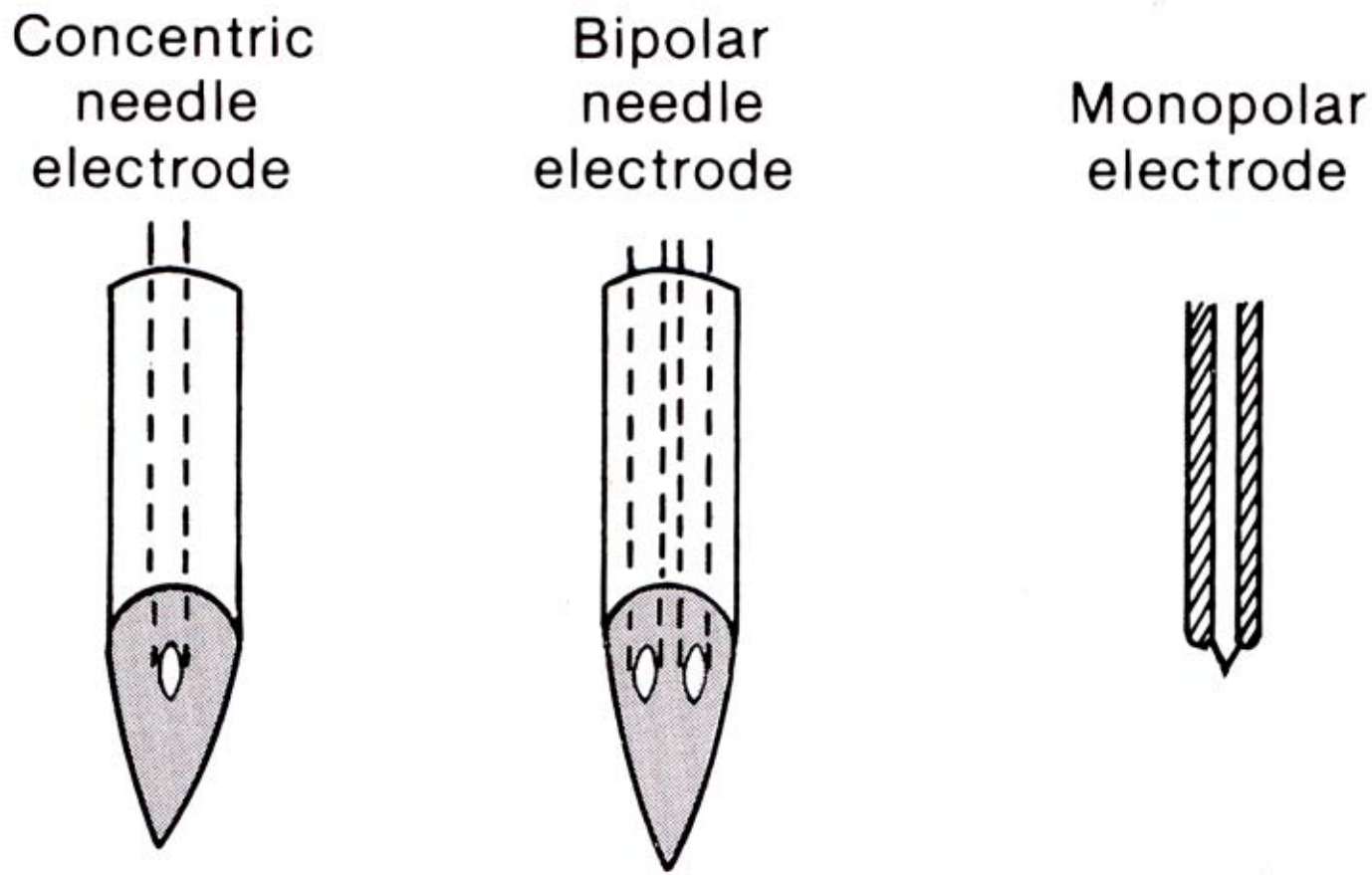


FIGURE 4-2. Needle electrodes used in clinical practice.

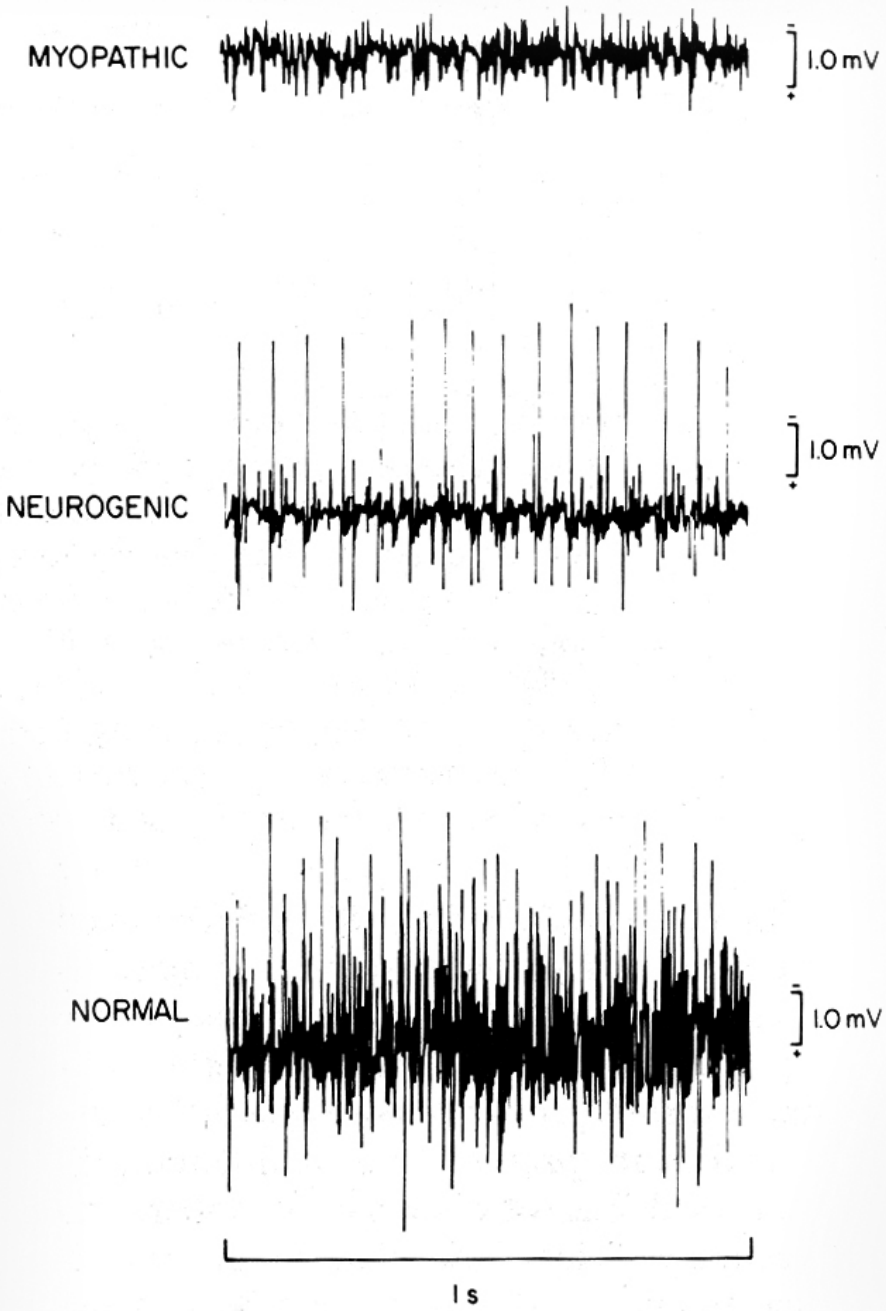

MYOPATHIC
1.0 mV
NEUROGENIC
1.0 mV
NORMAL
1.0 mV
1 s

TABLE 3.18. Correlation of Nerve Biopsy and Electrophysiological and Clinical Tests

Morphological Features in the Biopsy	*Electrophysiological Correlates*	*Clinical Correlates*	
		Motor	*Sensory*
Loss of nerve fibers			
Larger myelinated	↓ Amplitudes sensory nerve action	Weakness	↓ 2 point discrimination
	↓ Amplitudes M-potentials	± Wasting	↓ Vibration
	↓ Motor unit recruitment patterns		
	EMG evidence of denervated muscle fibers and neurogenic MUPs	± Fasciculation	↓ Touch
Smaller myelinated	No changes	—	
Unmyelinated			
Demyelination (± remyelination)	↓ Maximum sensory and motor sensory conduction velocities	—	↓ Pinprick sensation ↓ Temperature sensation ↓ Tickle appreciation
	↑ Temporal dispersion of nerve action potentials and maximum M-potentials		↓ Tendon reflex ↓ Vibration sense
	± Conduction block	Weakness ± Neurogenic tremor	

Neuromonitoring is used for….

- ***Detection*** **of neurological deterioration**
- ***Identification*** of neural structures (direct spinal cord recordings, direct nerve stimulation)
- ***Prediction*** of outcome

Risk factors associated with iatrogenic spinal cord injury during spine surgery

- Pre-operative myelopathy
- use of instrumentation
- number of levels of surgery
- level of spinal surgery (higher is worse)

May et al, J Neurosurg, 1996

Other periods of Risk

Before and after intubation (C-spine), and positioning

myelopathy

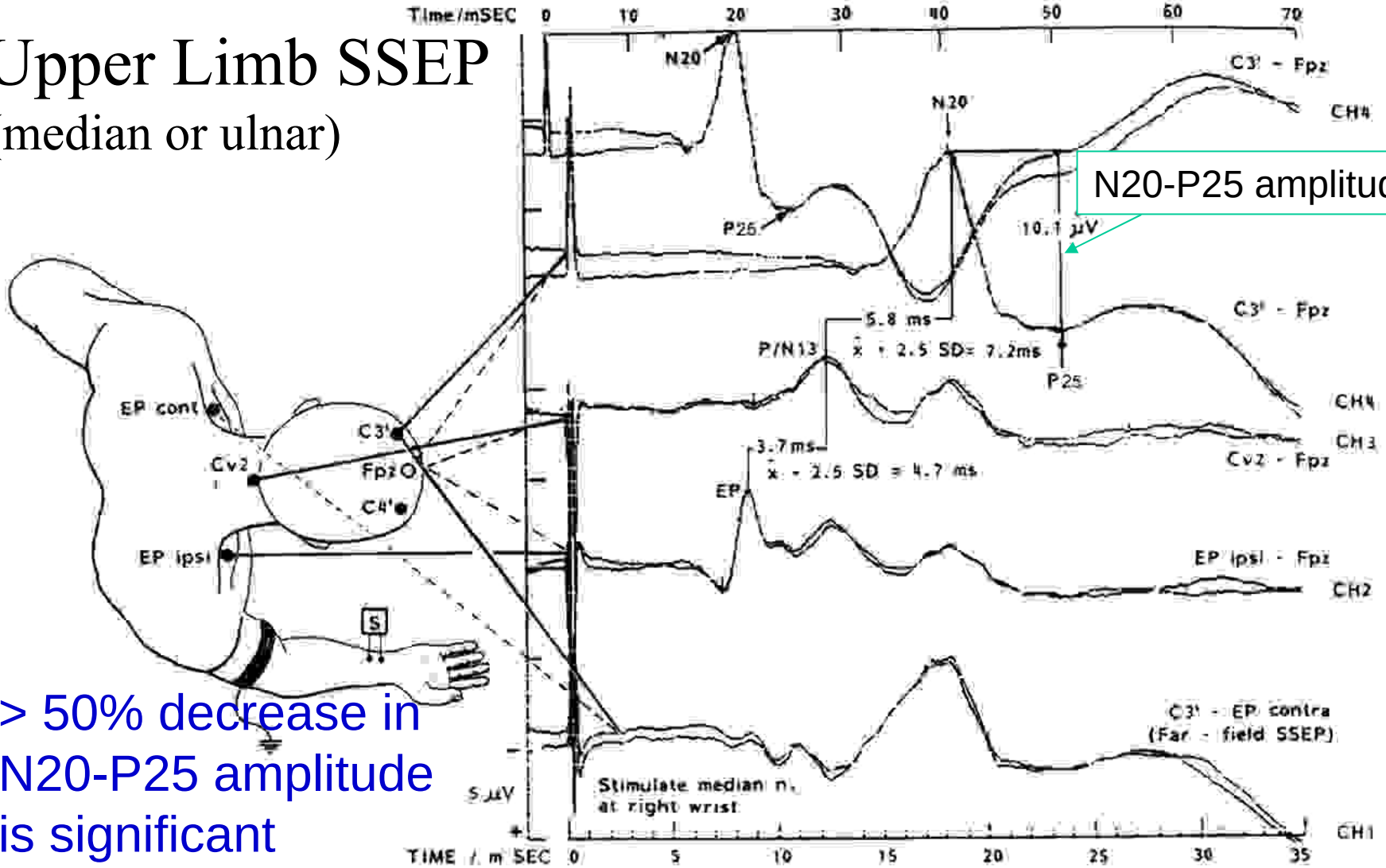
unstable spinal fractures

spinal stenosis

3 Neuromonitoring Modalities

- Somatosensory Evoked Potentials (SSEPs)
- Motor Evoked Potentials (MEPs)
- Electromyography (triggered and mechanically evoked EMG)

Upper Limb SSEP
(median or ulnar)



> 50% decrease in N20-P25 amplitude is significant

Median n.: C6-7 cutaneous, C8-T1 muscle

Ulnar n.: C8 cutaneous, C8-T1 muscle

TABLE 4.4. Electrogenic Origins of Various Subcortical Potentials (Median Nerve Stimulation at Wrist)

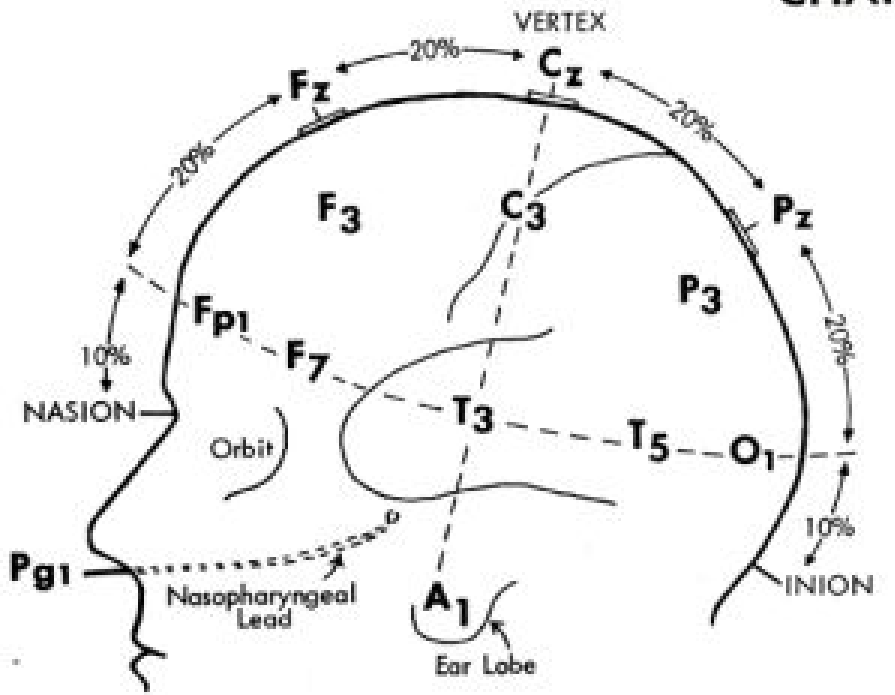
	Potential	*Probable Electrogenic Source*
Far Field		
G_1 Cephalic and	P8–9	Brachial plexus
G_2 Opposite hand, knee, or foot	P15	Ascending medial lemniscus
Nearer Field		
G_1 Posterior neck and	P8–9	Brachial plexus
G_2 Opposite hand	N11	Ascending dorsal column activity
	N13–14	Postsynaptic activity in dorsal horn (C3–T2)
G_1 Posterior neck and	P8–9	Brachial plexus
G_2 Cephalic (F_z)	N11	? ascending tract or postsynaptic activity in spinal cord
	N13–14	Postsynaptic activity dorsal in horn (C3–T2)
		+
G_1 Contralateral scalp (C3/4) and	N15–20	Ascending medial lemniscus
G_2 Ipsilateral scalp (C3/4)		Thalamocortical activity

TABLE 4.5. Electrogenic Origins of Cortical Potentials

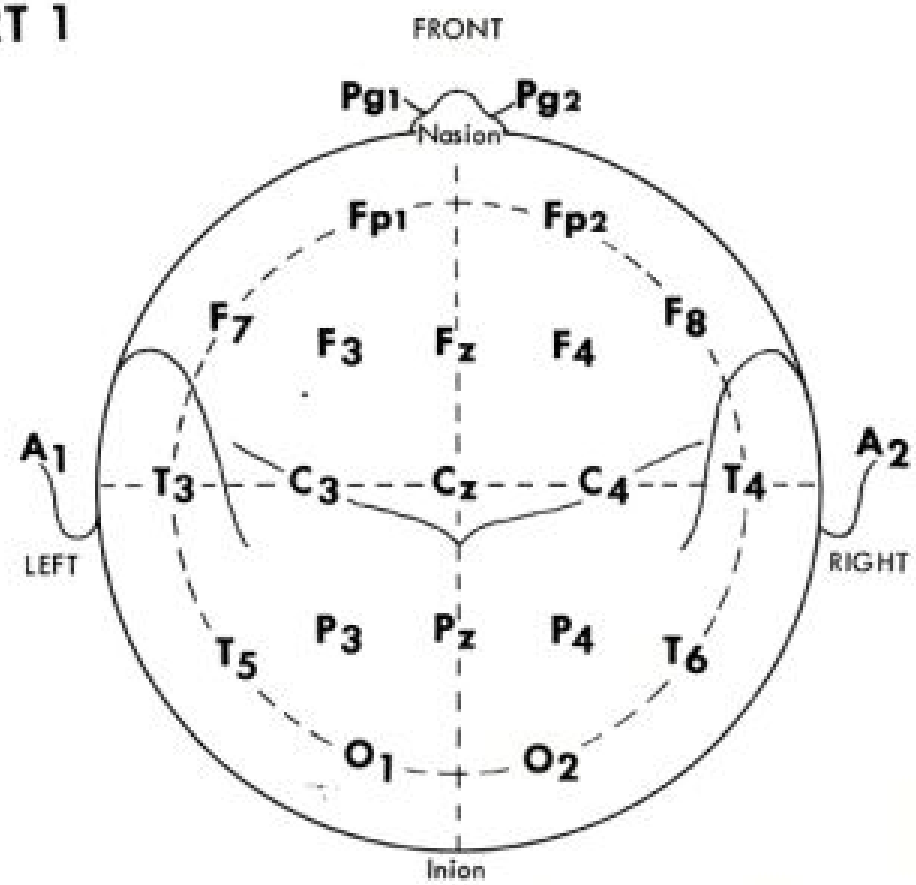
Postcentral recordings	N20–22	Earliest activity in postcentral cortex or thalamocortical
Postcentral recordings	N20 to P30	Primary sensory cortical activity
Precentral	P22	?Precentral cortical activity

INTERNATIONAL (10-20) ELECTRODE PLACEMENT

CHART 1



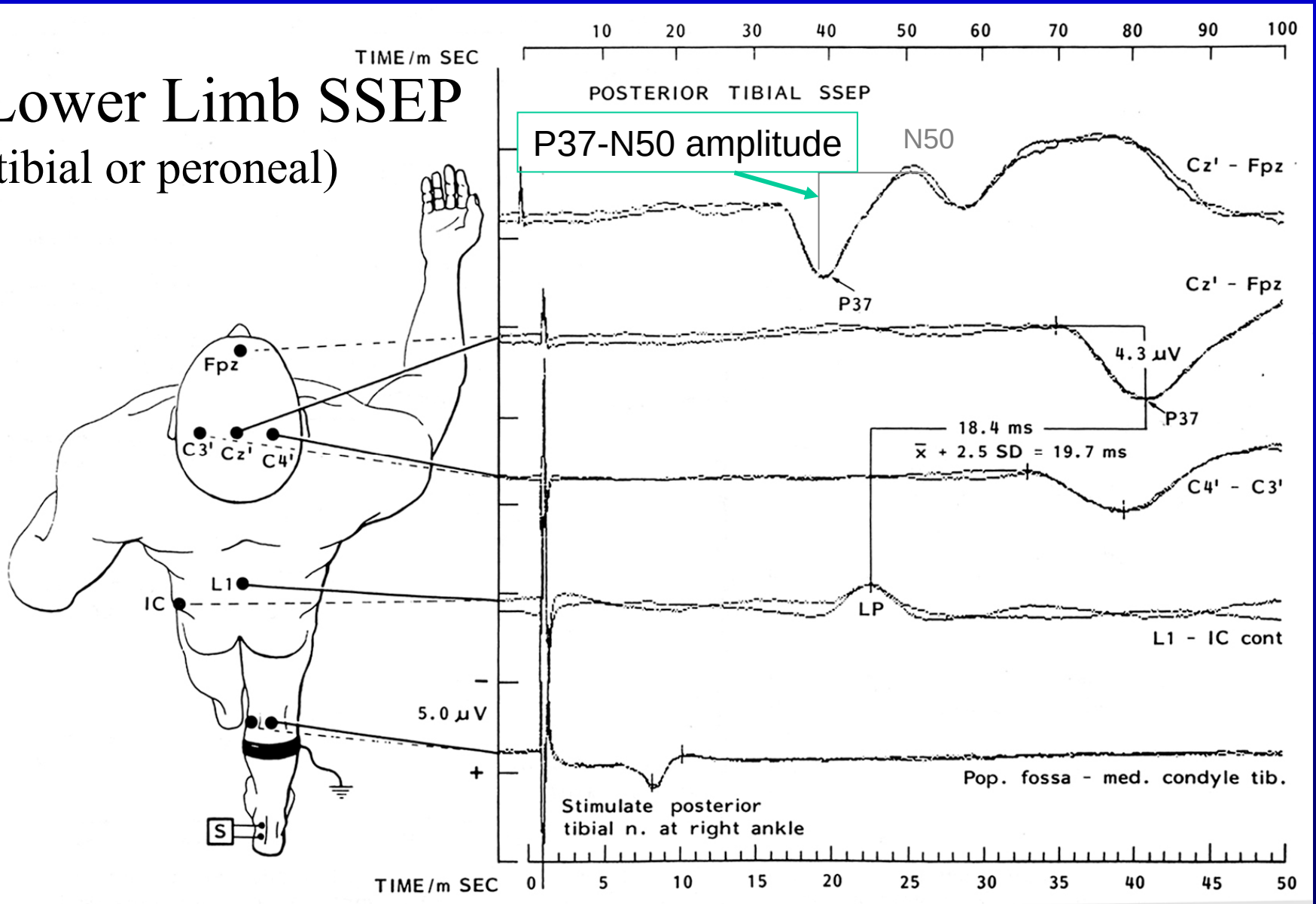
LEFT SIDE OF HEAD



TOP OF HEAD

Lower Limb SSEP

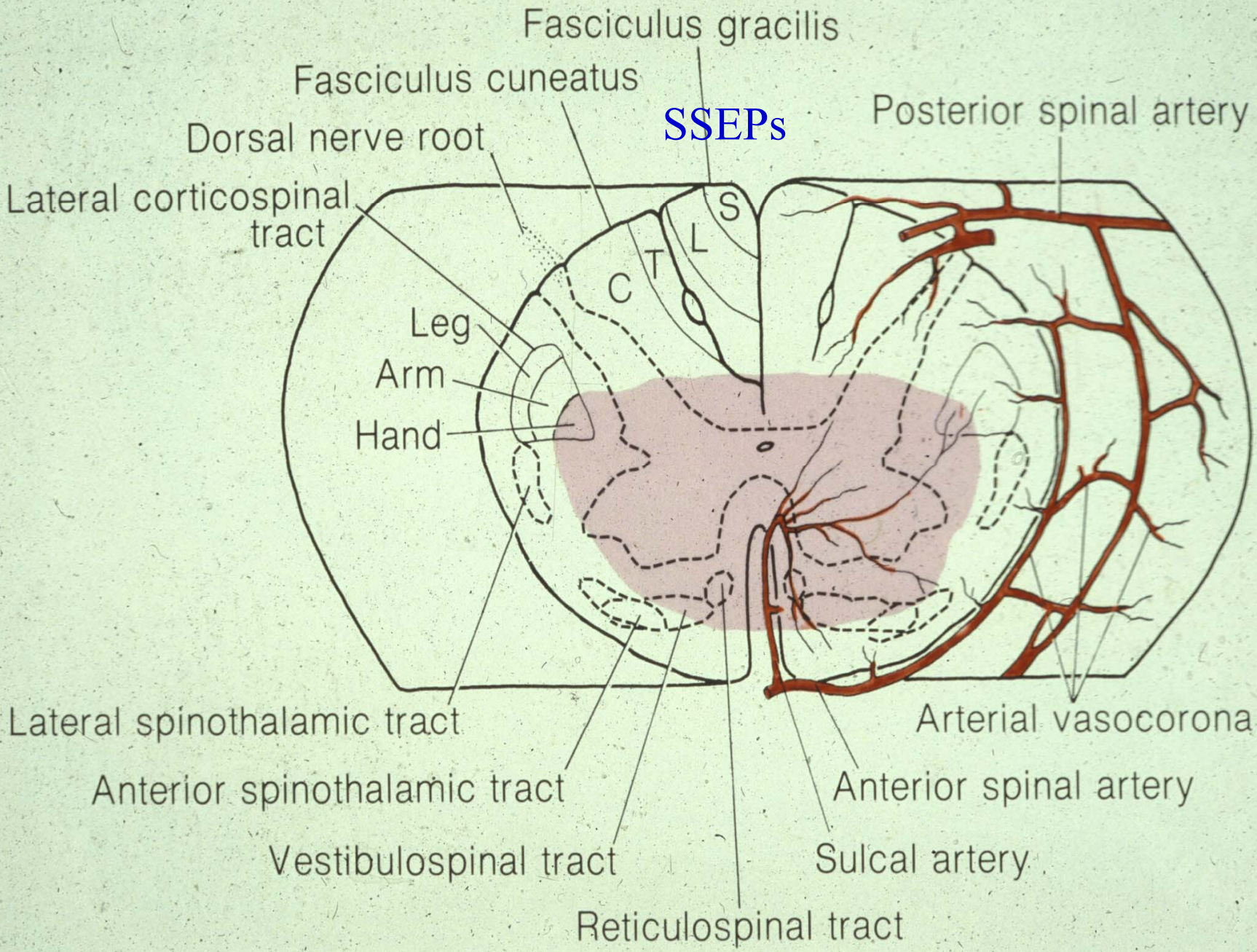
(tibial or peroneal)



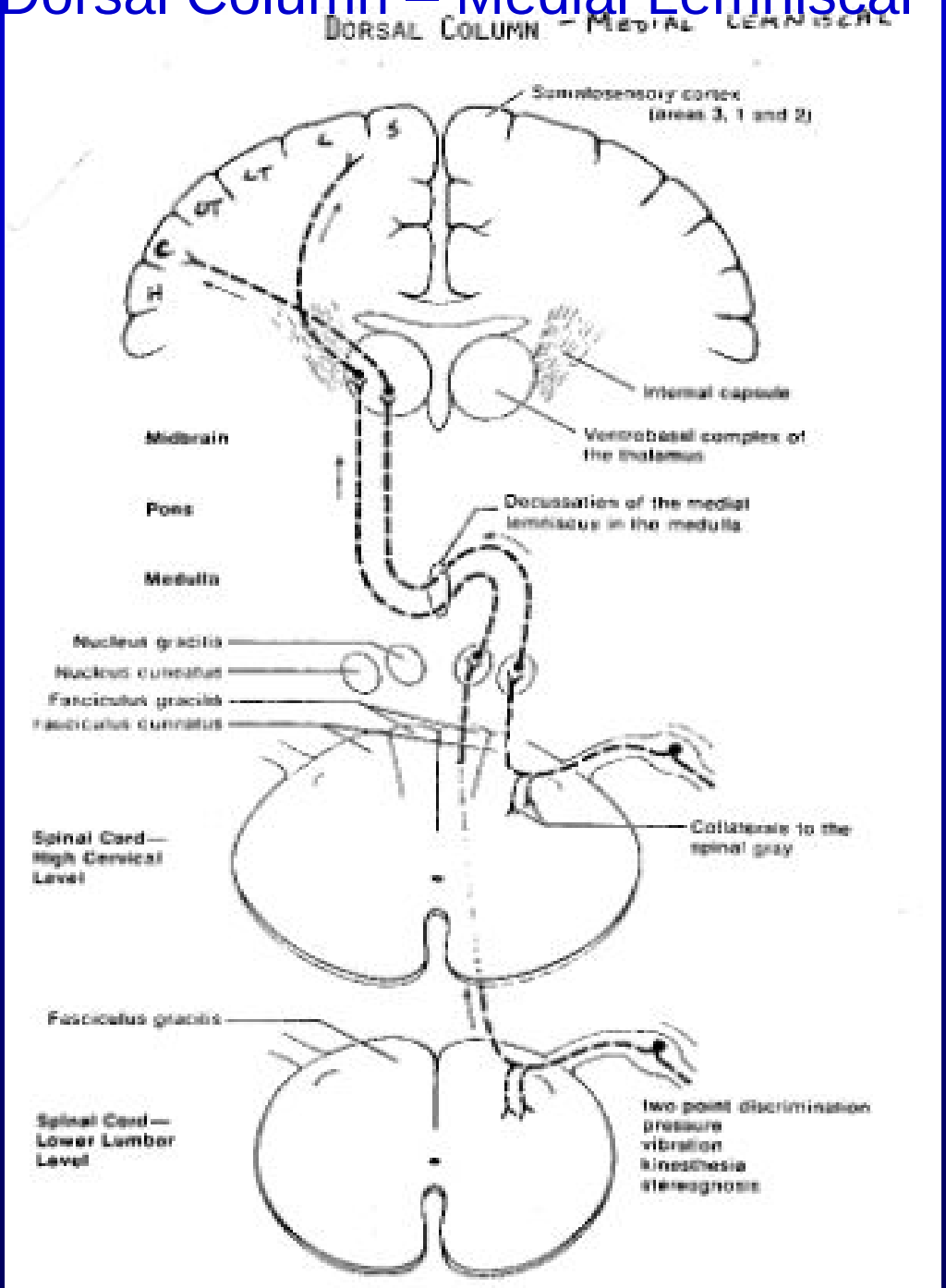
Tibial n. (ankle): L4-S2 cutaneous, S1-2 muscle

TABLE 10-3 Anesthetic Effects on Somatosensory Evoked Potential

	Amplitude	**Latency**
Thiopental	Small or no change	Increase
Etomidate	Increase	Increase
Fentanyl	Modest or no decrease	Modest or no increase
Diazepam	Decrease	Increase
Midazolam	Decrease	Increase
Ketamine	Increase	Increase
Propofol	No change	Increase
Nitrous oxide	Decrease	No change
Halothane	Decrease	Increase
Enflurane	Decrease	Increase
Isoflurane	Decrease	Increase


Fasciculus gracilis
Fasciculus cuneatus
SSEPs
Posterior spinal artery
Dorsal nerve root
Lateral corticospinal tract
S
L
T
C
Leg
Arm
Hand
Lateral spinothalamic tract
Arterial vasocorona
Anterior spinothalamic tract
Anterior spinal artery
Vestibulospinal tract
Sulcal artery
Reticulospinal tract

Dorsal Column – Medial Lemniscal

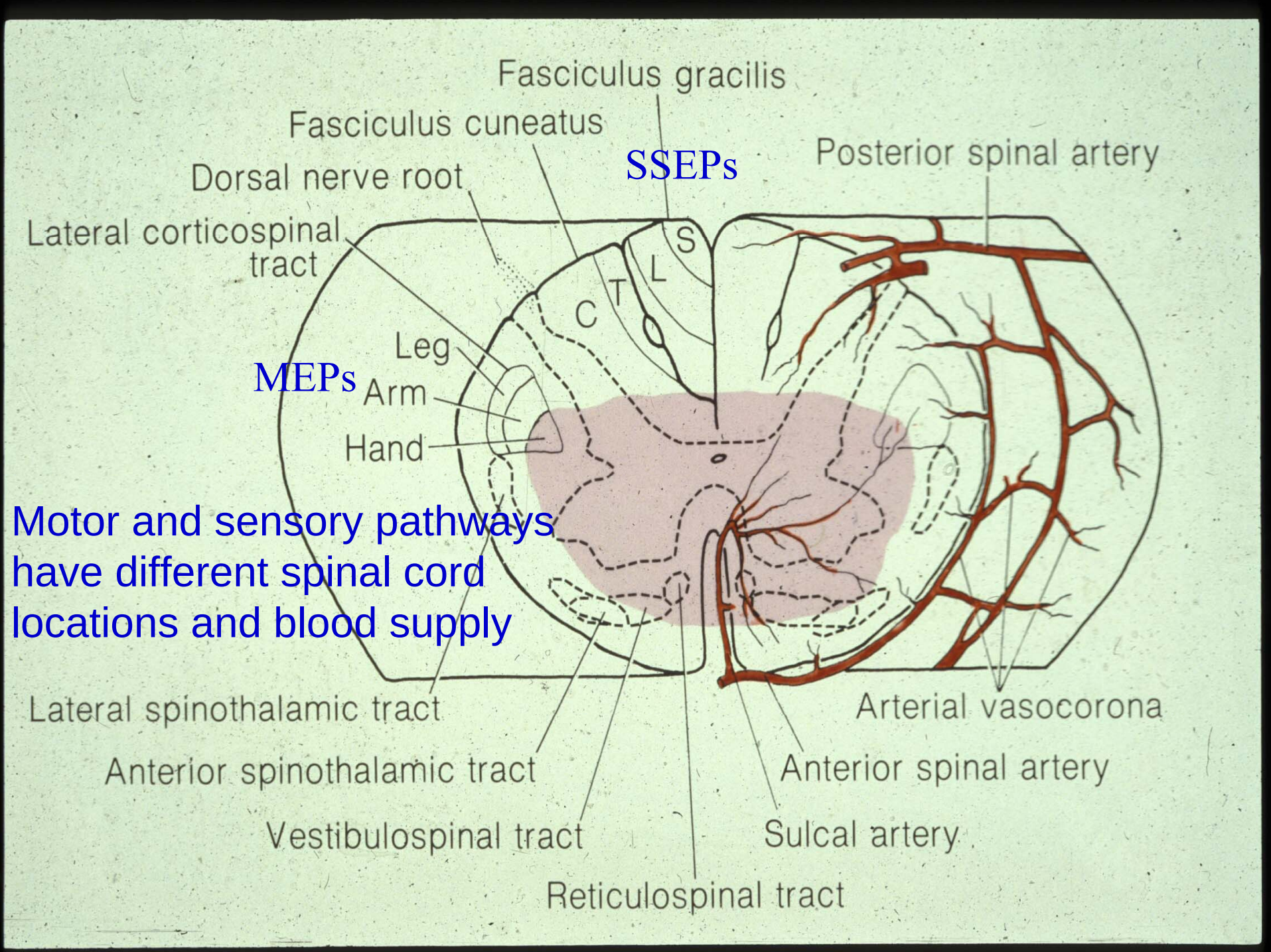


Utility of SSEP

- ***Experienced*** SSEP monitoring teams had lower incidence of iatrogenic SCI
  - Nuwer MR et al., 1995 (52,263 patients monitored, mainly for correction of spinal deformity
- Useful for alerting surgeons to risky surgical maneuvers
- This has ***not*** been proven for MEP monitoring but evidence likely to come

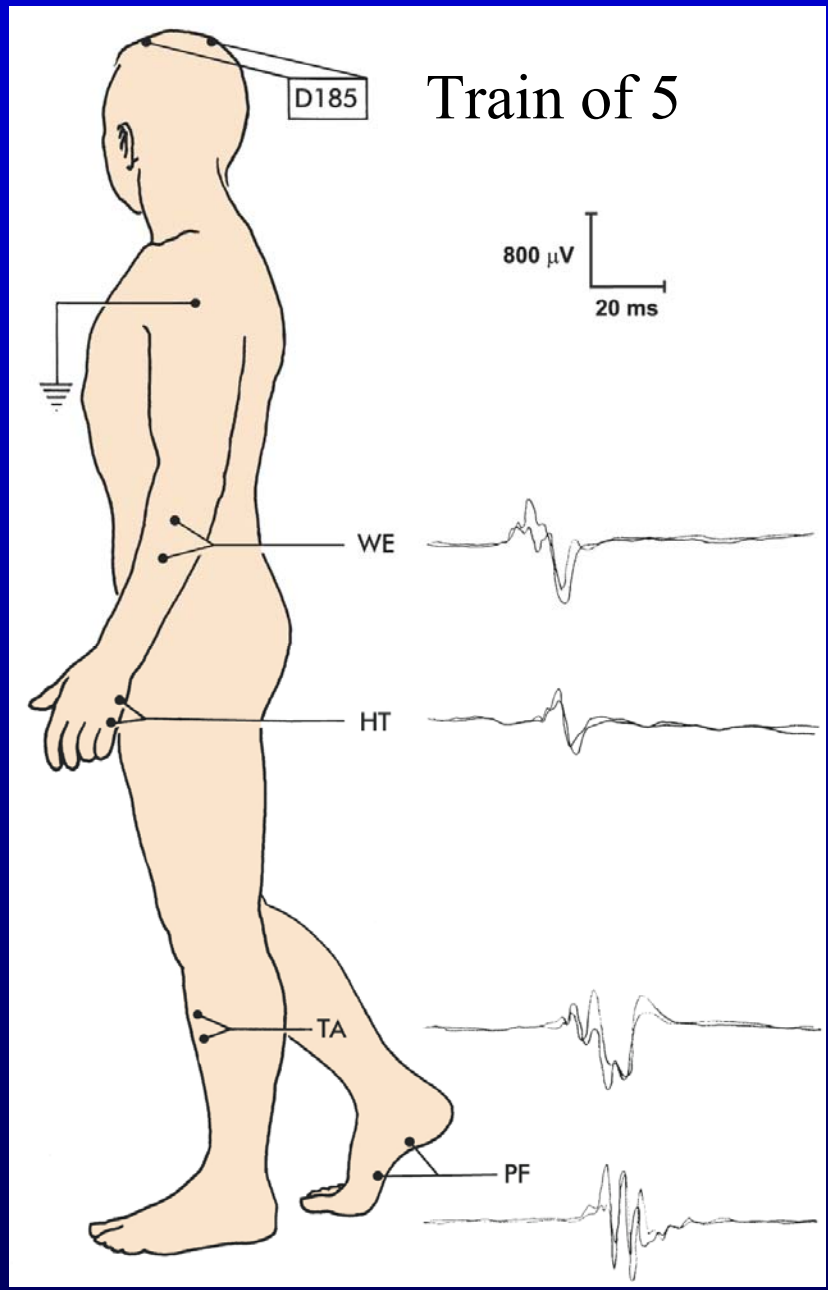
IF THERE IS A CHANGE

- Check SSEP neck potential and the second SSEP scalp recording to corroborate
- Check anaesthesia (it should be stable)
- Check BP. If hypotensive then correct
- Do Motor Evoked Potentials (MEPs)


Fasciculus gracilis
Fasciculus cuneatus
SSEPs
Posterior spinal artery
Dorsal nerve root
Lateral corticospinal tract
S
L
T
C
Leg
MEPs
Arm
Hand
Motor and sensory pathways have different spinal cord locations and blood supply
Lateral spinothalamic tract
Arterial vasocorona
Anterior spinothalamic tract
Anterior spinal artery
Vestibulospinal tract
Sulcal artery
Reticulospinal tract

Transcranial Electric (TCES) Motor Evoked Potentials

Repetitive scalp stimulation, muscle recording (bilateral, pure motor test)

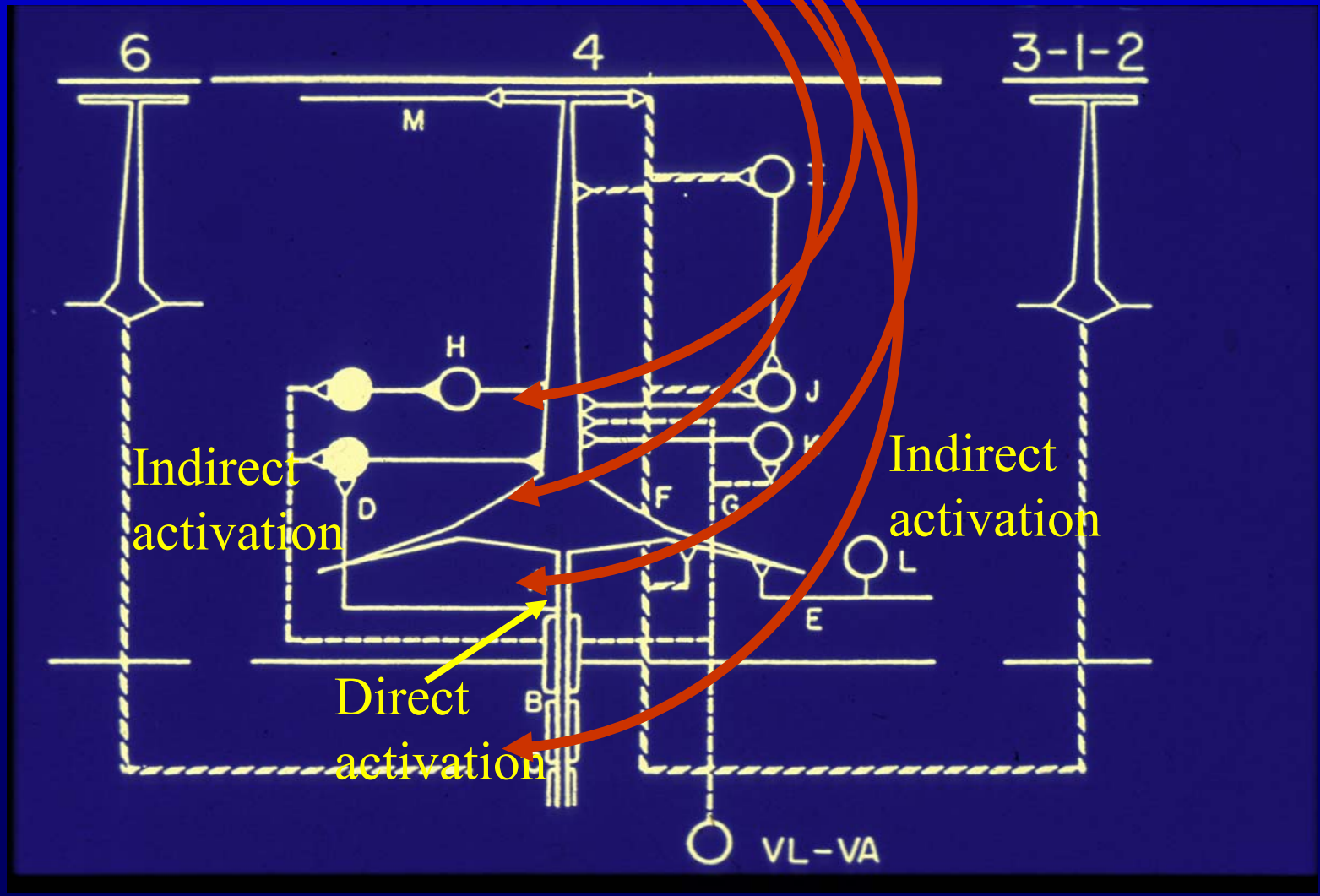


anode

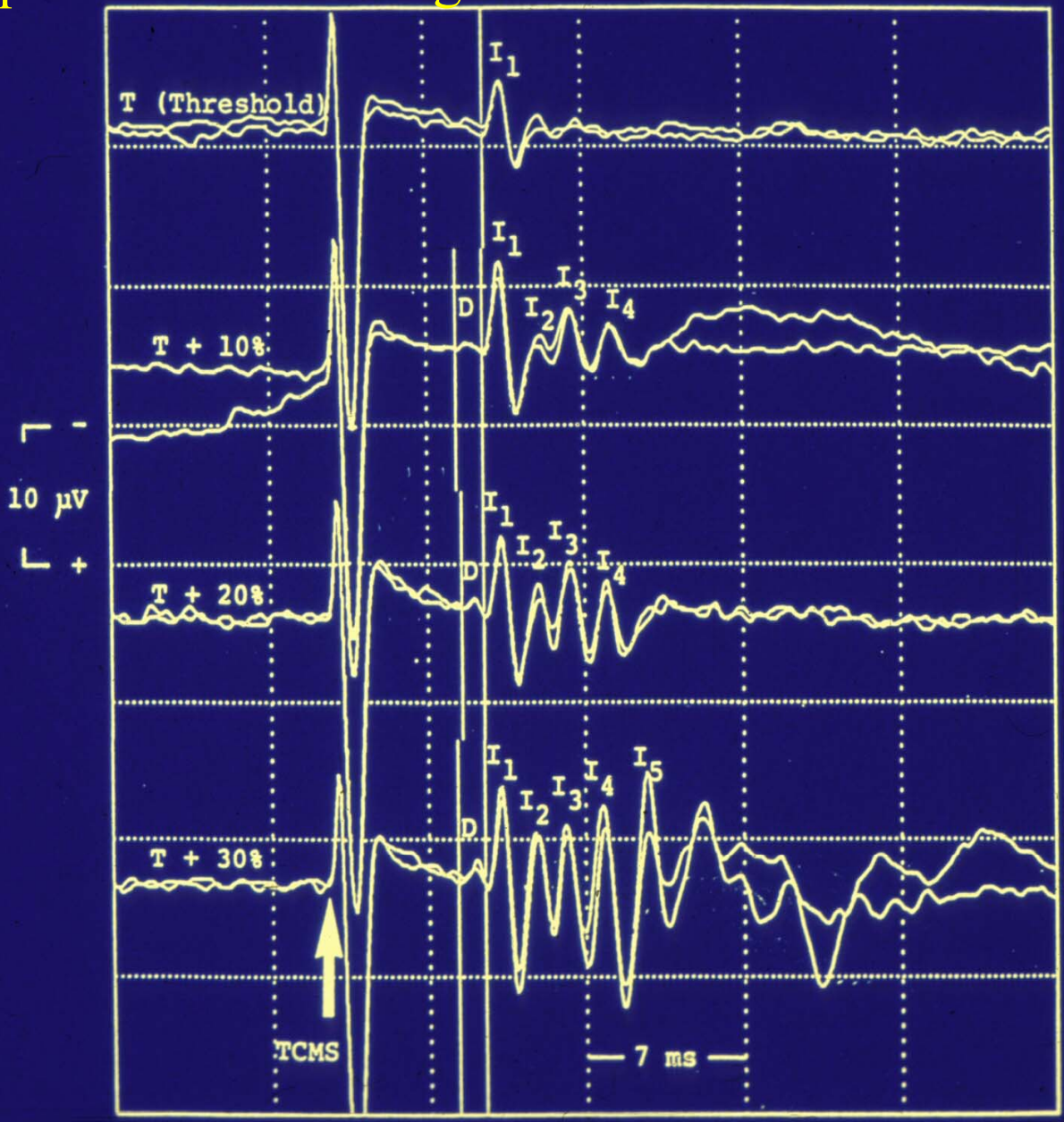
Pre -motor cortex

Motor cortex

Sensory cortex

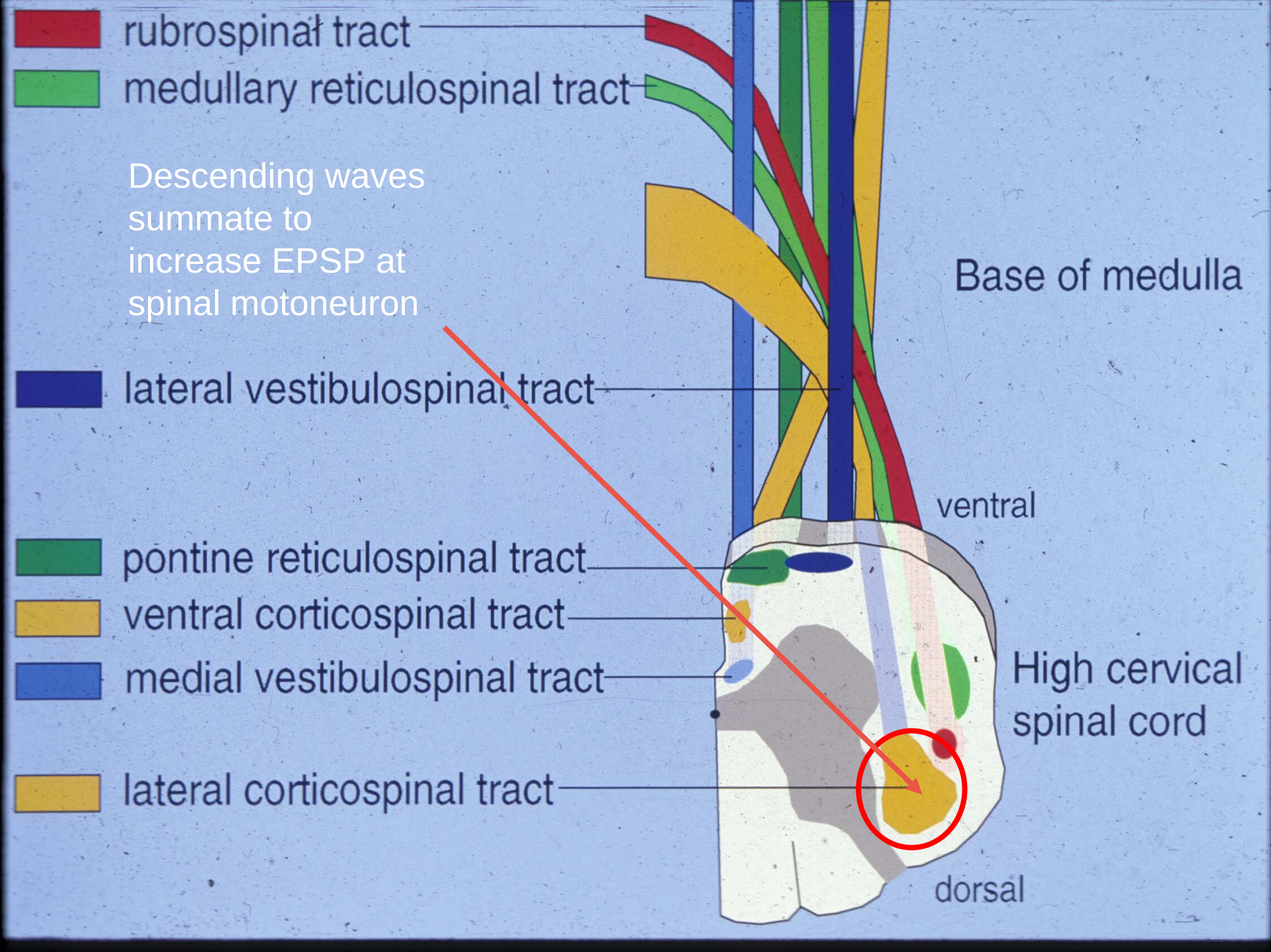


Spinal cord recording after transcranial brain stimulation



Threshold stimulus intensity

Threshold stimulus intensity + 30%


rubrospinal tract
medullary reticulospinal tract
Descending waves summate to increase EPSP at spinal motoneuron
Base of medulla
lateral vestibulospinal tract
ventral
pontine reticulospinal tract
ventral corticospinal tract
medial vestibulospinal tract
High cervical spinal cord
lateral corticospinal tract
dorsal

Corticospinal Pathway

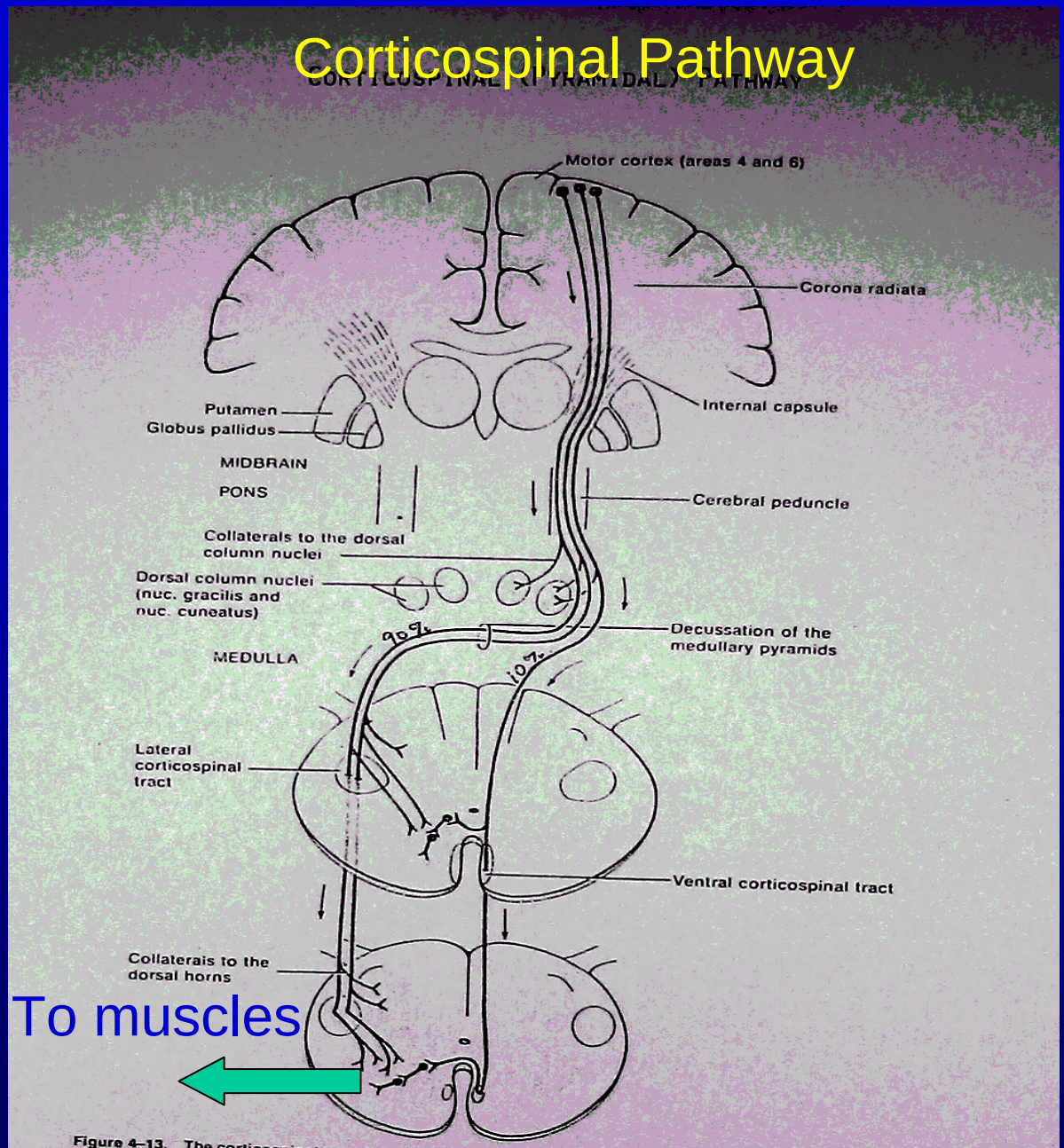
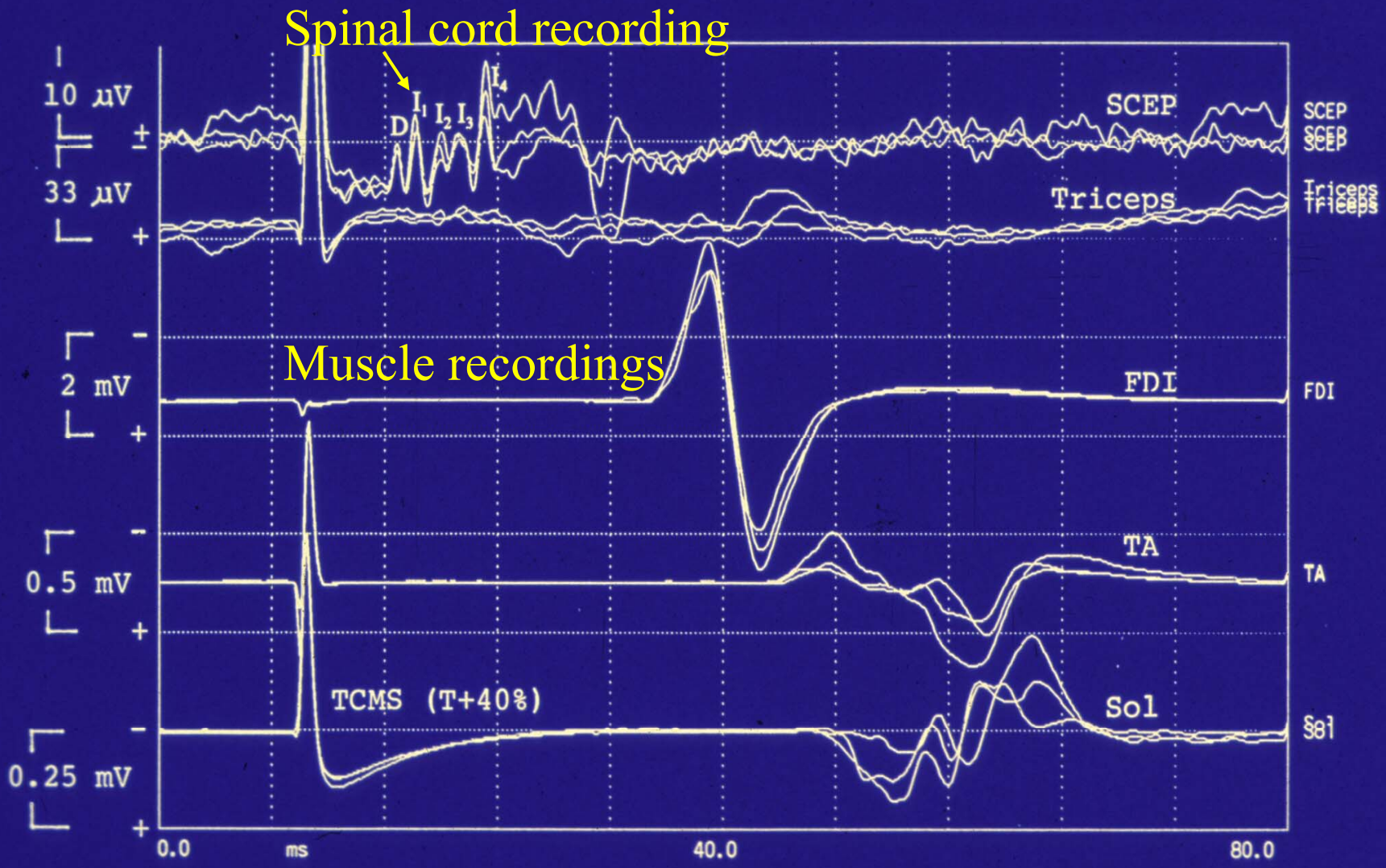
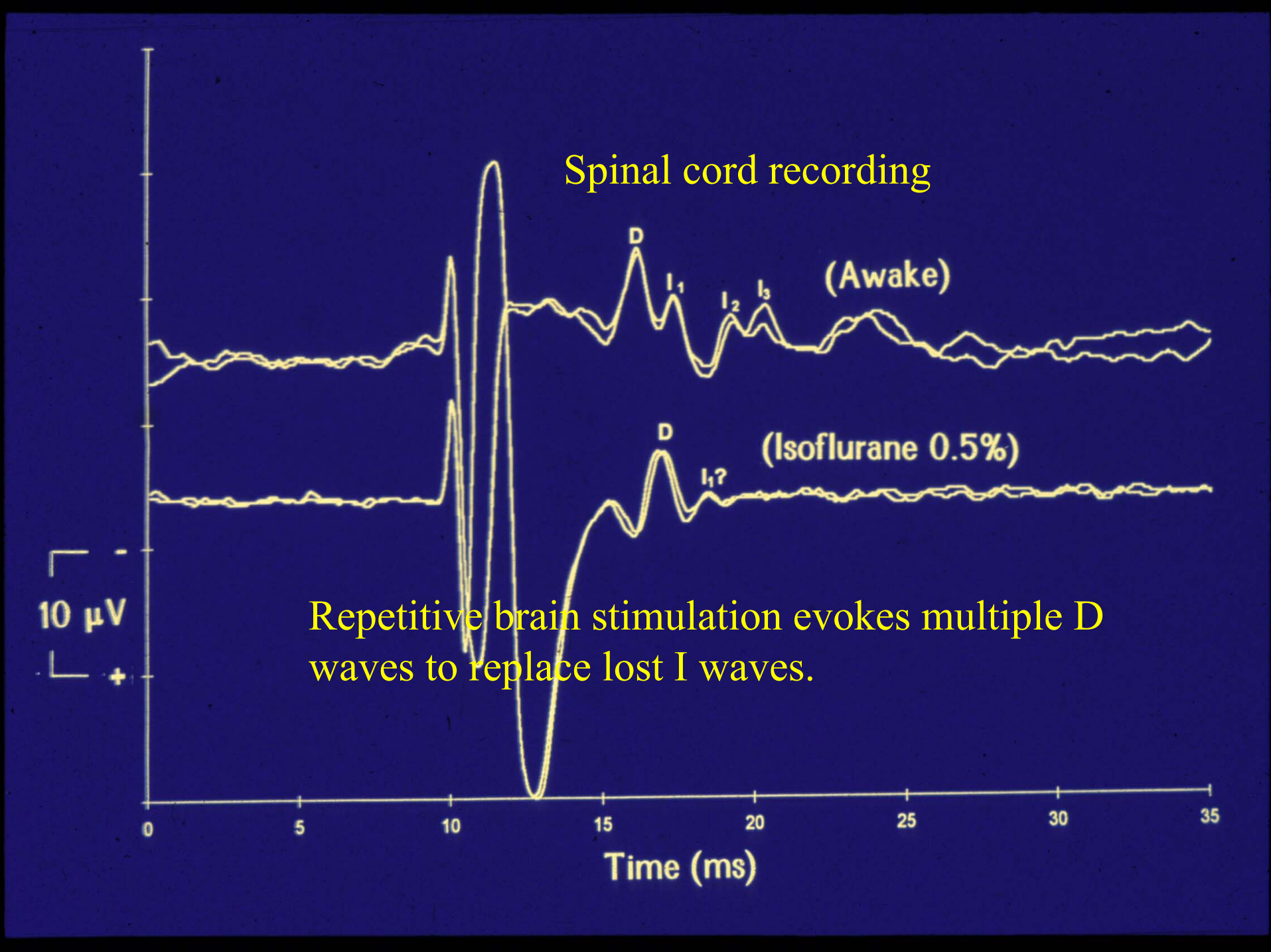
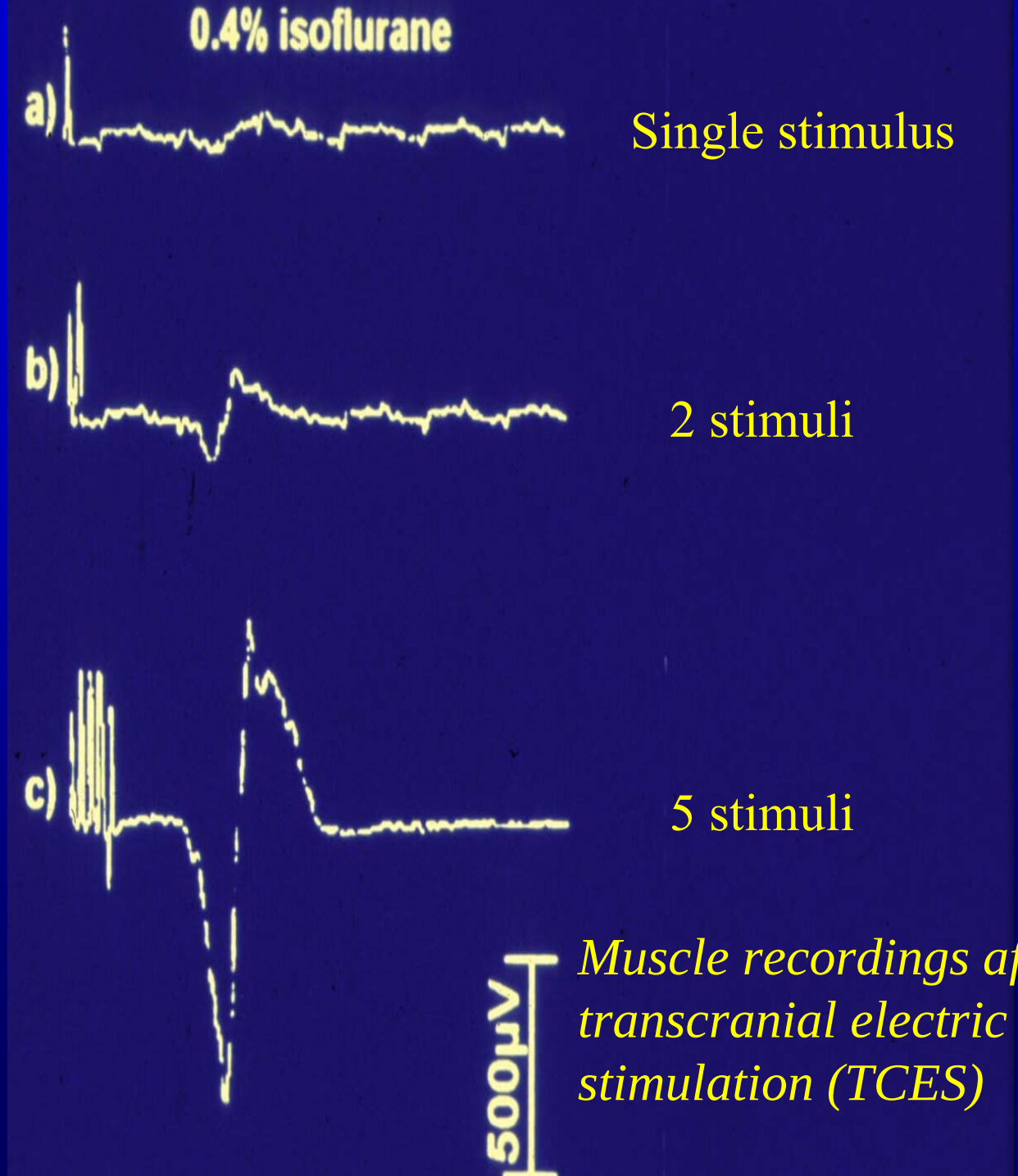


Figure 4–13. The corticospinal tracts. In this illustration only those neurons that originate in the motor cortex are included.



4 waves necessary for muscle response after transcranial magnetic stimulation; temporal summation of EPSPs at spinal motoneuron


Spinal cord recording
D
I1
I2
I3
(Awake)
D
I1?
(Isoflurane 0.5%)
10 µV
Repetitive brain stimulation evokes multiple D waves to replace lost I waves.
0
5
10
15
20
25
30
35
Time (ms)



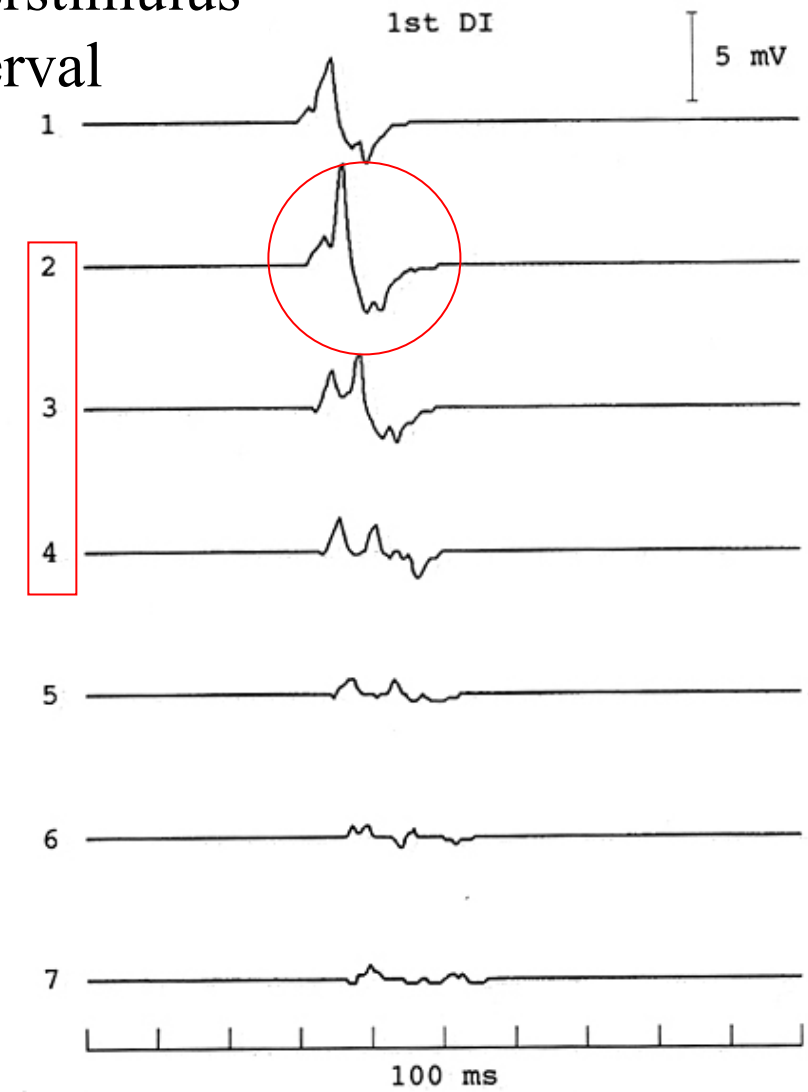
Single stimulus

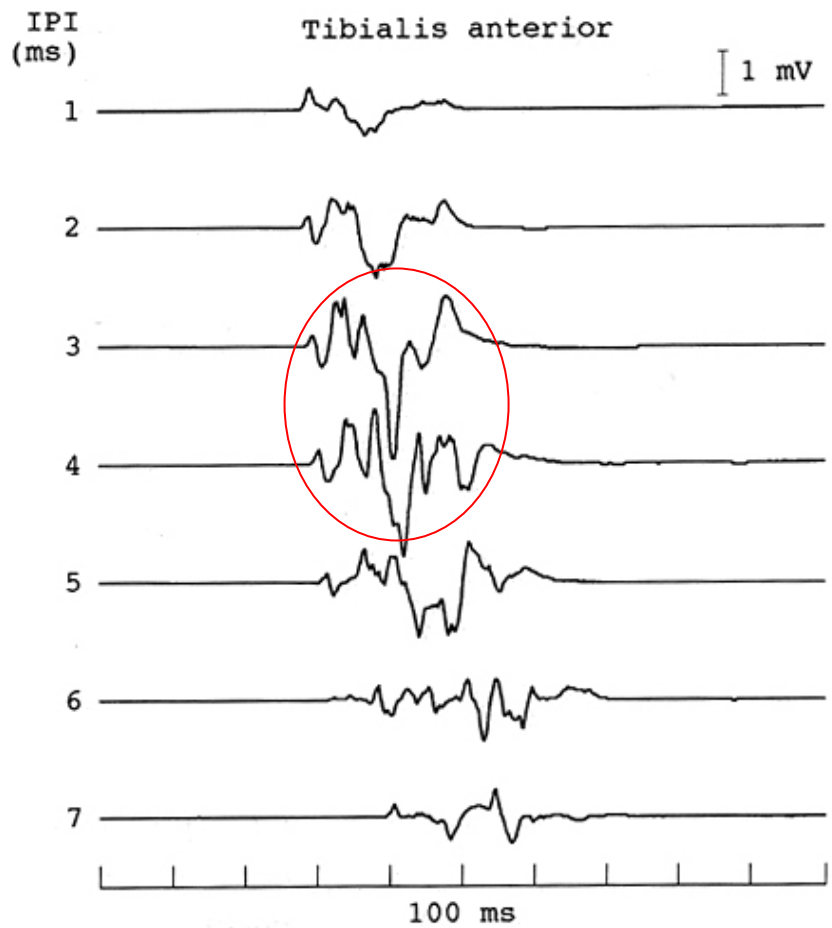
2 stimuli

5 stimuli

Muscle recordings after transcranial electric stimulation (TCES)

Interstimulus Interval





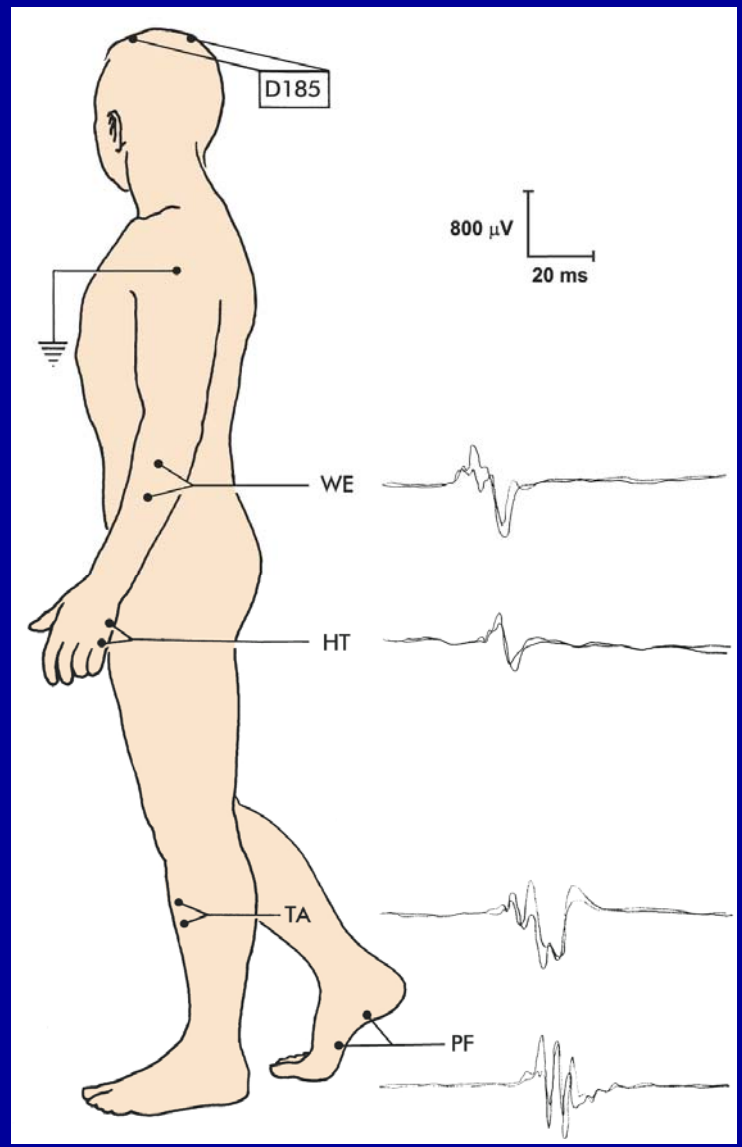
Train of 3 Train of 5

Muscle recording after TCES

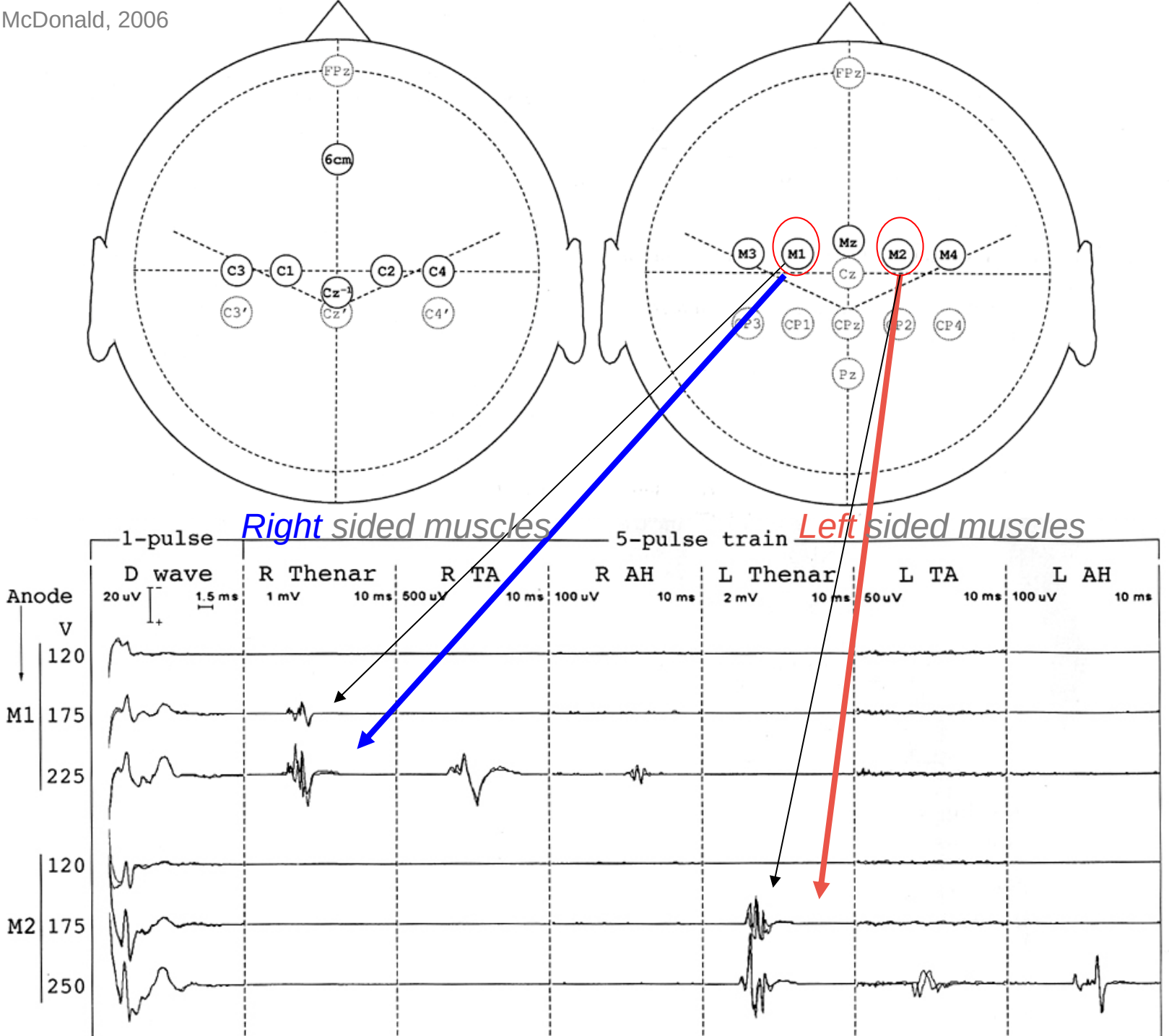
Transcranial Electric Stimulation (TCES)

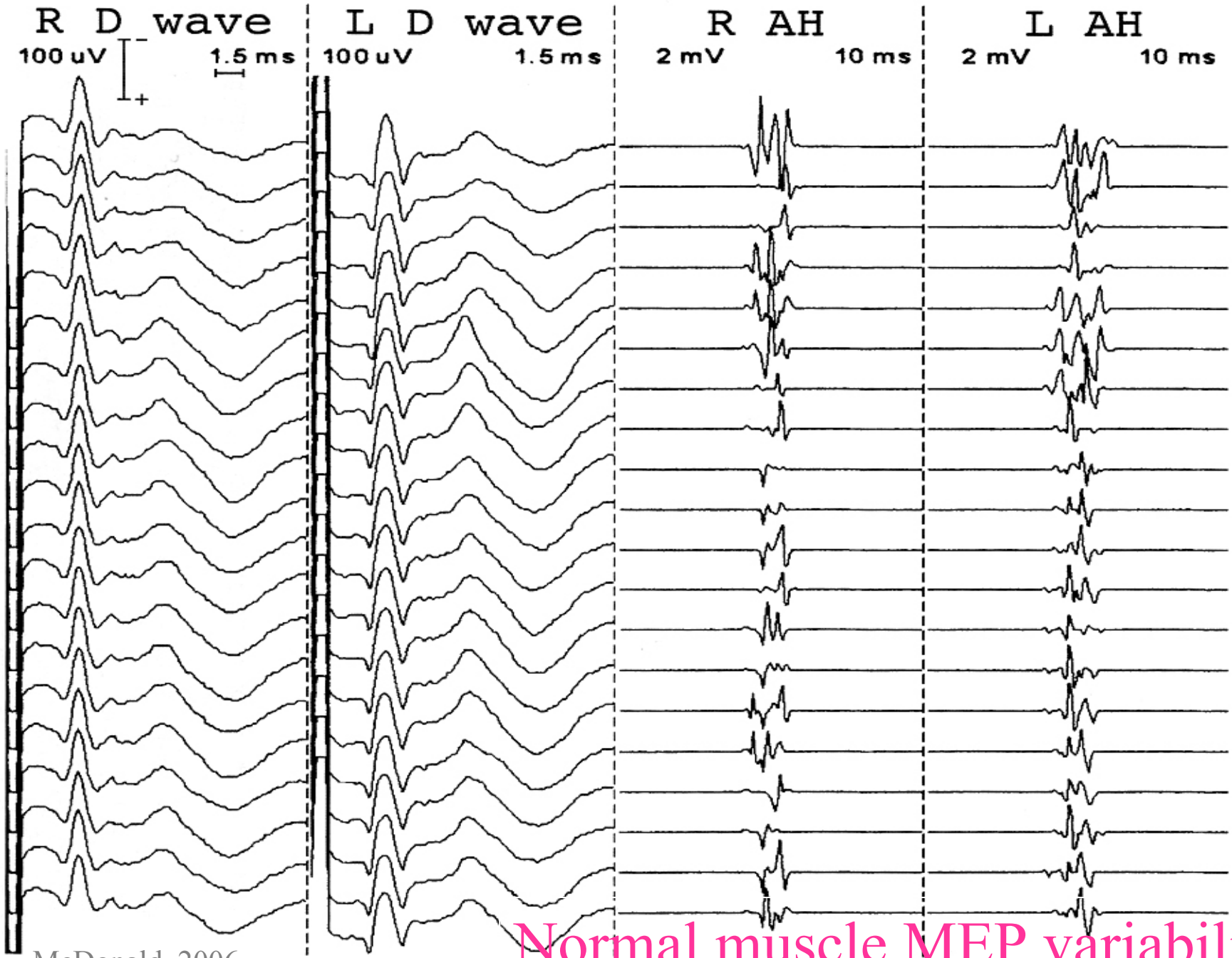
When anode is on left scalp, MEPs on right side are recruited first

... and vice versa



McDonald, 2006





McDonald, 2006

Normal muscle MEP variability

What is significant MEP change?

- **We use** > 80% decrease in amplitude (baseline MEP must be > 100μV)

- **Others use…**

  - total loss of MEP (due to complexity, non-linearity, instability – fade)

  - > 100 V stimulus increase in MEP threshold (Calancie et al., 1998)

Anaesthesia

Best:

TIVA (Propofol, narcotic)

Acceptable:

Propofol, narcotic ± 0.5 MAC single gas

No neuromuscular blockade

MEP Problems

(scalp stimulation, muscle recording)

- Tongue lacerations (27/10,000)
  - Use soft bite block
- Very low but not negligible association with seizures (5/15,000; ? > spontaneous seizures)

Inform surgeon before stimulation due to patient movement

MEP (problems cont'd) (scalp stimulation, muscle recording)

- Anaesthesia decreases CNS excitability (especially in α motoneuron)
- Normal "fade" of MEP amplitude over time (increase 23V/hr in myelopathy)
- *Only ~ 10% of total muscle membrane current is activated*

Muscle MEP (TCES) Method
Our "starting" stimulation parameters

- Transverse scalp stimulation (C3 - C4; less patient neck and trunk movement than Cz - Fpz)
- Train of 5 stimuli; 50μsec pulse width; 2 msec interstimulus interval; 300-500V
- Clear supra threshold in all targeted muscles (up to 500V)

Exclusion Criteria for TCES
(no good evidence that these matter)

- history of seizures (or proconvulsant medications)
- skull fractures
- intracranial electrodes, clips or shunts
- cardiac pacemakers or other implanted biomedical devices
- cardiac arrhythmias

Clinical Applications for MEP

Spinal cord tumours

Spinal deformity and Spinal decompression

Aortic aneurysm

Brachial plexus repair

Posterior fossa surgery

Intracranial aneurysm

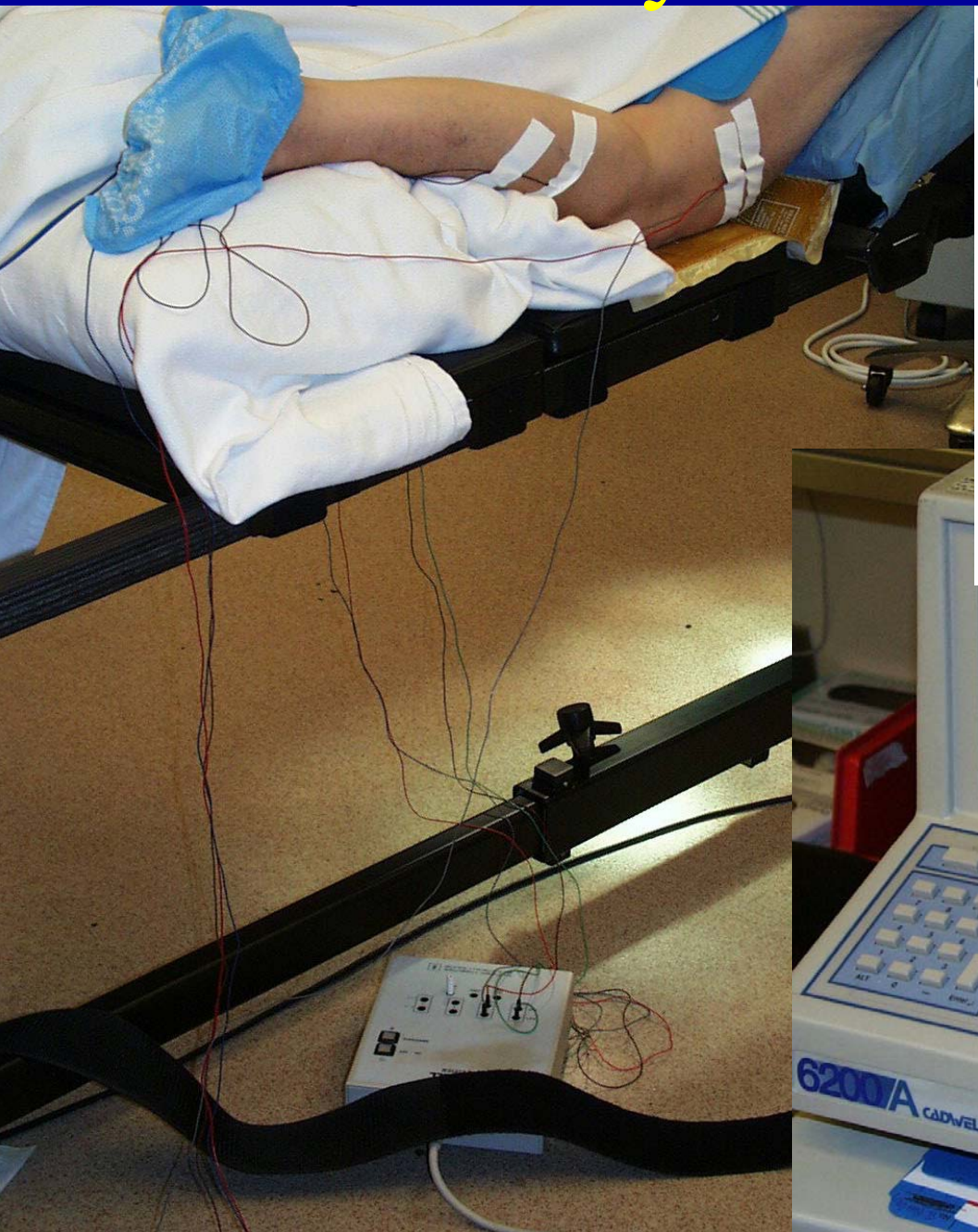
Peri-rolandic brain tumour

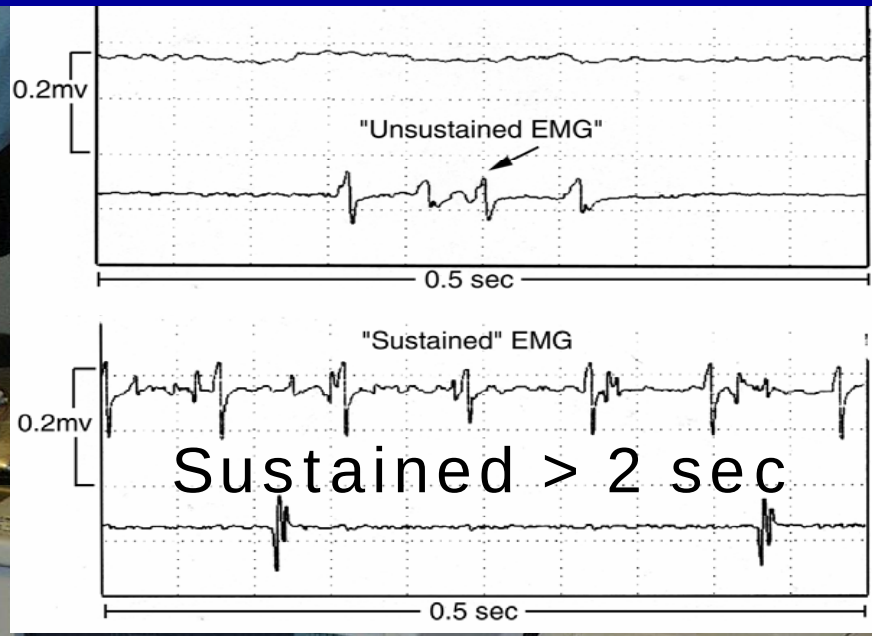
Limitations

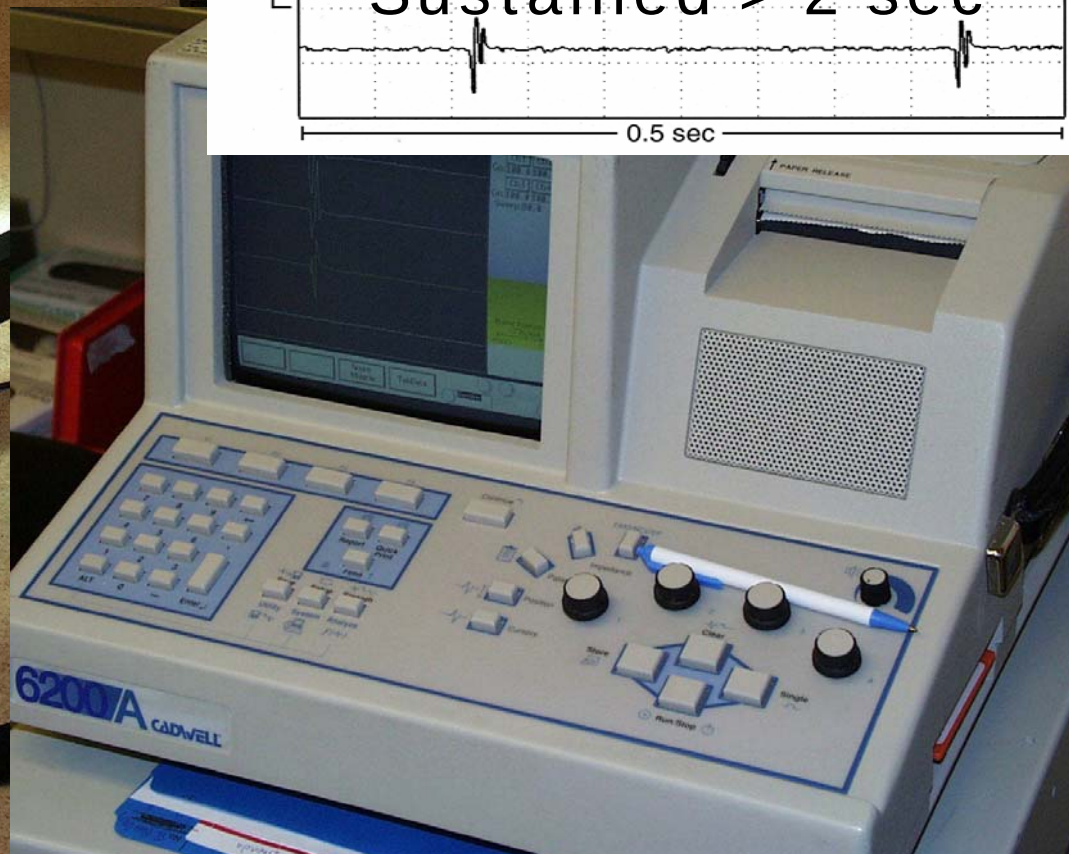
- SSEP/MEP do not detect single nerve root injury (SSEP/MEP traverse multiple roots) ….so

- ***Do continuous EMG when nerve root is at risk***

Mechanically Evoked EMG







Advantages

- Immediate feedback (**auditory** and visual) about motor nerve function.
- Simultaneous monitoring of multiple nerves.
- Unaffected by anaesthetic

EMG monitoring

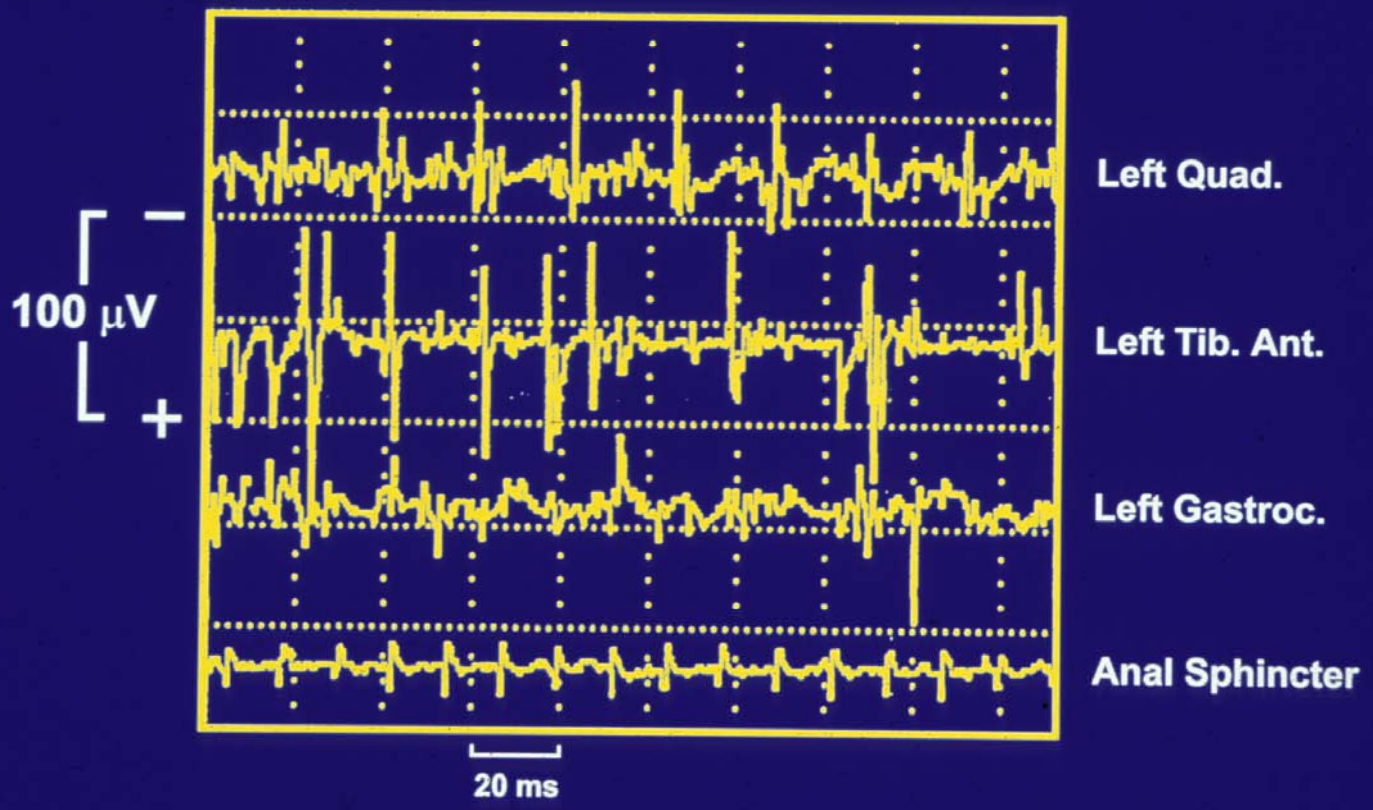
For cervical spine surgery, select muscles at risk. For example:

For operations at C5 - monitor deltoid

For operations at C6 - monitor biceps

For operations at C7 - monitor anconeus or triceps

EMG During Tumour Resection



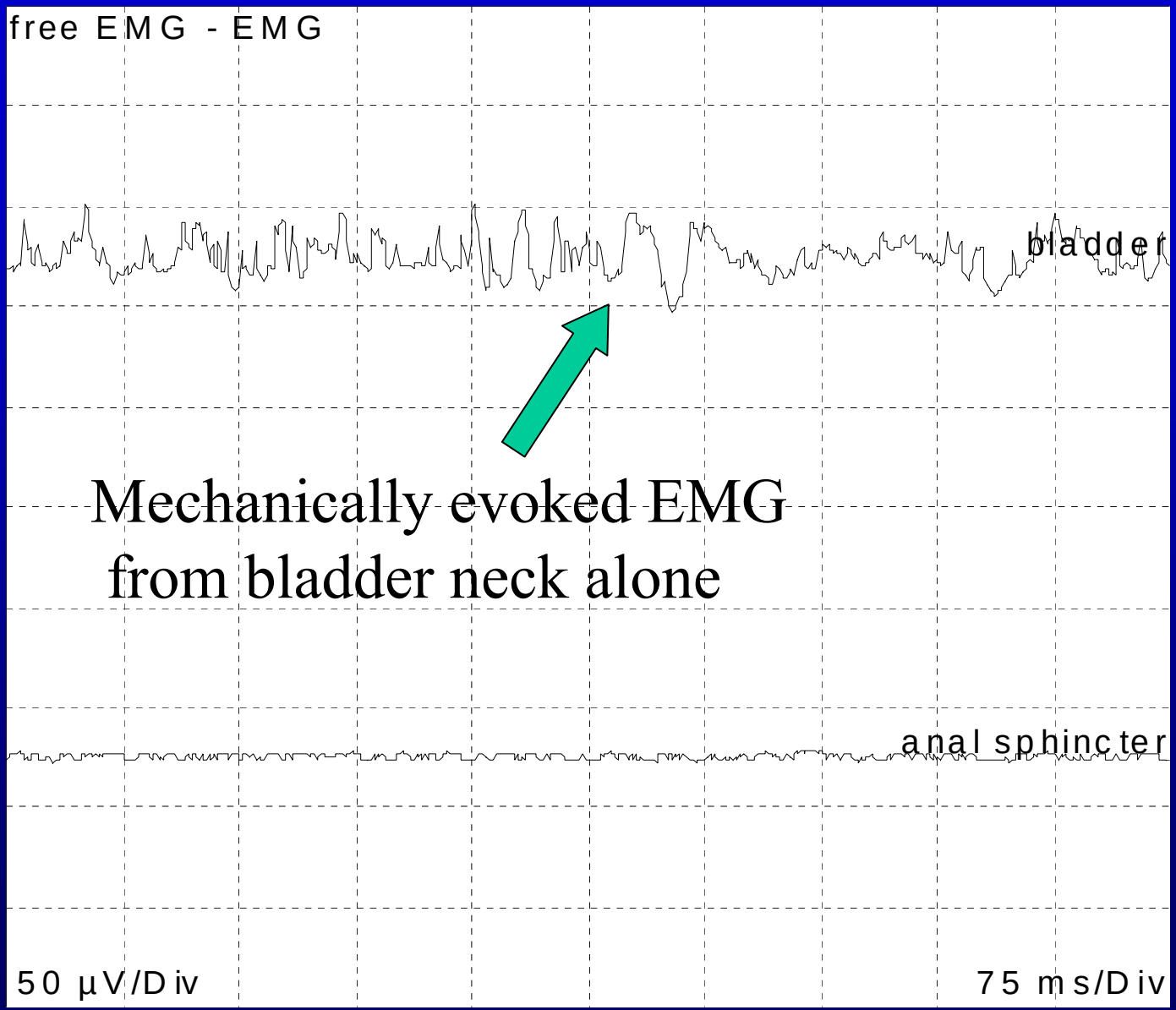
Lumbar Spine Surgery

Gunnarsson et al., Spine, 2004

EMG

- Sensitivity - 1.0 (no false -'ves)
- Specificity - 0.24 (many false +'ves)

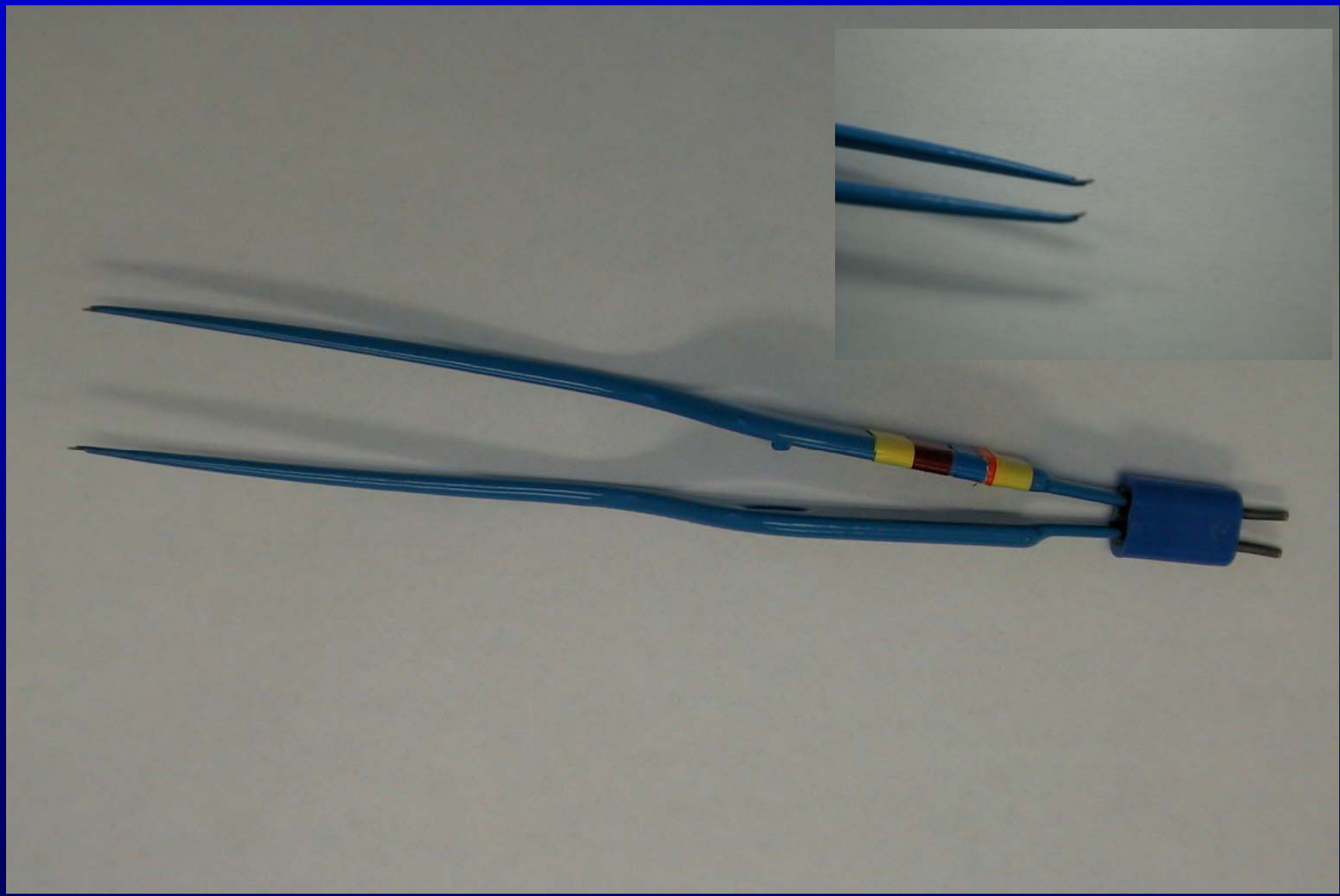
**All surgery was below spinal cord, so sensitivity and specificity is for iatrogenic nerve injury


free EMG - EMG
bladder
Mechanically evoked EMG
from bladder neck alone
anal sphincter
50 µV/Div
75 ms/Div

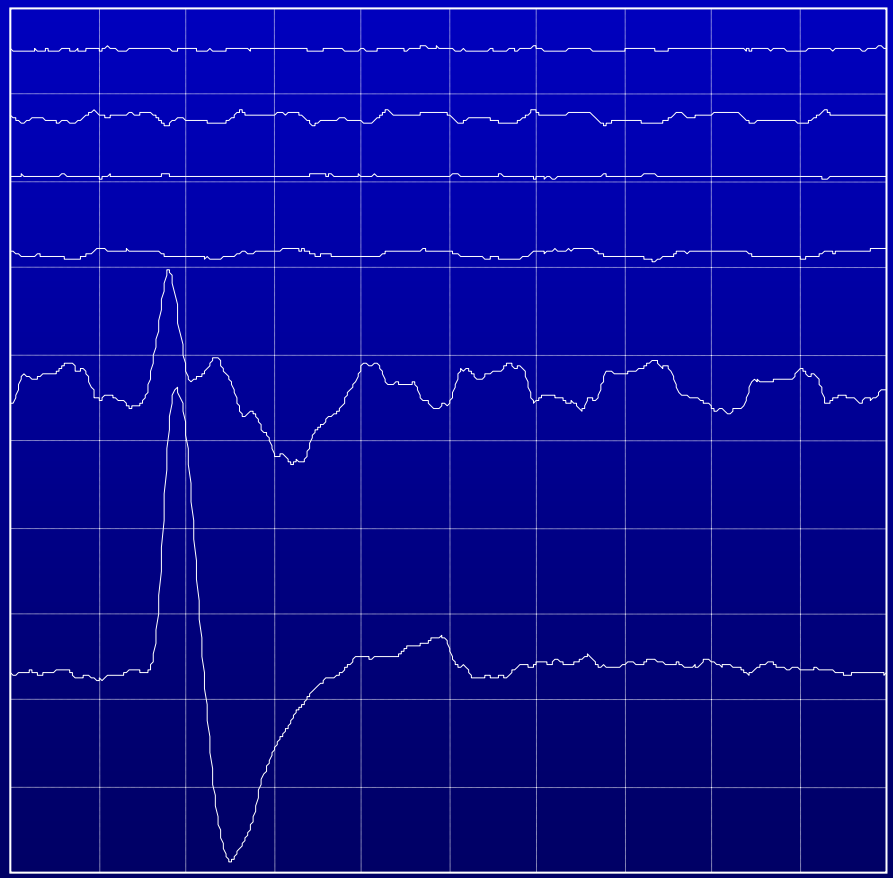
Free Running EMG
Pitfalls

- Damaged nerves less responsive to irritation than undamaged ones
- Sharp transection may be silent or a brief burst followed by silence)
- Unclear relationship with neuronal injury
- spontaneous muscle activity may be related to lightening of anaesthetic
- Limits use of neuromuscular blockade

Bipolar Stimulator (insulated except tips) for neural ID



Triggered EMG



Reducing false positives and negatives (EMG)

- If unexpected result then use positive control
- choose appropriate muscles

Stimulus Thresholds: ma (range)

Normal nerve: 2.2 (0.2 - 5.7)

Chronically compressed nerve: (6.3 - 20)

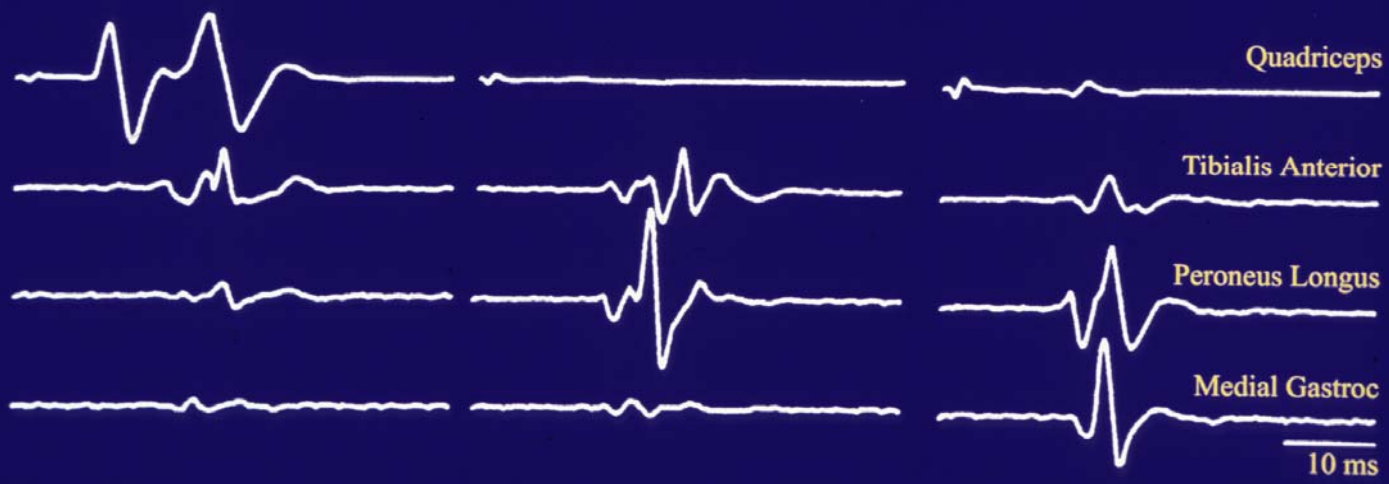
(McGuire et al, 1995; Holland et al, 1998)

EMG monitoring

Spinal Nerve	**Muscle**
C5	Deltoid
C6	Biceps
C7	**Anconeus**, Triceps
C8-T1	Hand intrinsics (T, HT)
L2	**Iliapsoas**, Vastus Lateralis, Rectus Femoris
L3	**Vastus Medialis**, rectus femoris
L4	**Tibialis anterior**, Vastus Medialis
L5	Peroneii, tibialis anterior
S1-S2	Gastrocnemius, Soleus
S3-S4	Anal and bladder sphincters

*For thoracic spinal nerves use intercostal m. or abdominal m.(if below T8)

EMG Responses to Pedicle Stimulation



Stimulus Thresholds: ma (range)

Normal pedicle hole: 30.4 (16.5 - 44.3)

Normal pedicle screw: 24 (12.1 - 35.9)

Misplaced pedicle hole: 3.4 (1 - 6)

Misplaced pedicle screw: 3.5 (1 - 6)

(McGuire et al, 1995; Holland et al, 1998)

Scoliosis Society SSEP Monitoring Survey, 1995

(Nuwer et al, EEG clin Neurophysiol, 1995)

0.063 false negative

0.98% false positive

92% sensitivity, 98.9% specificity

51,263 procedures

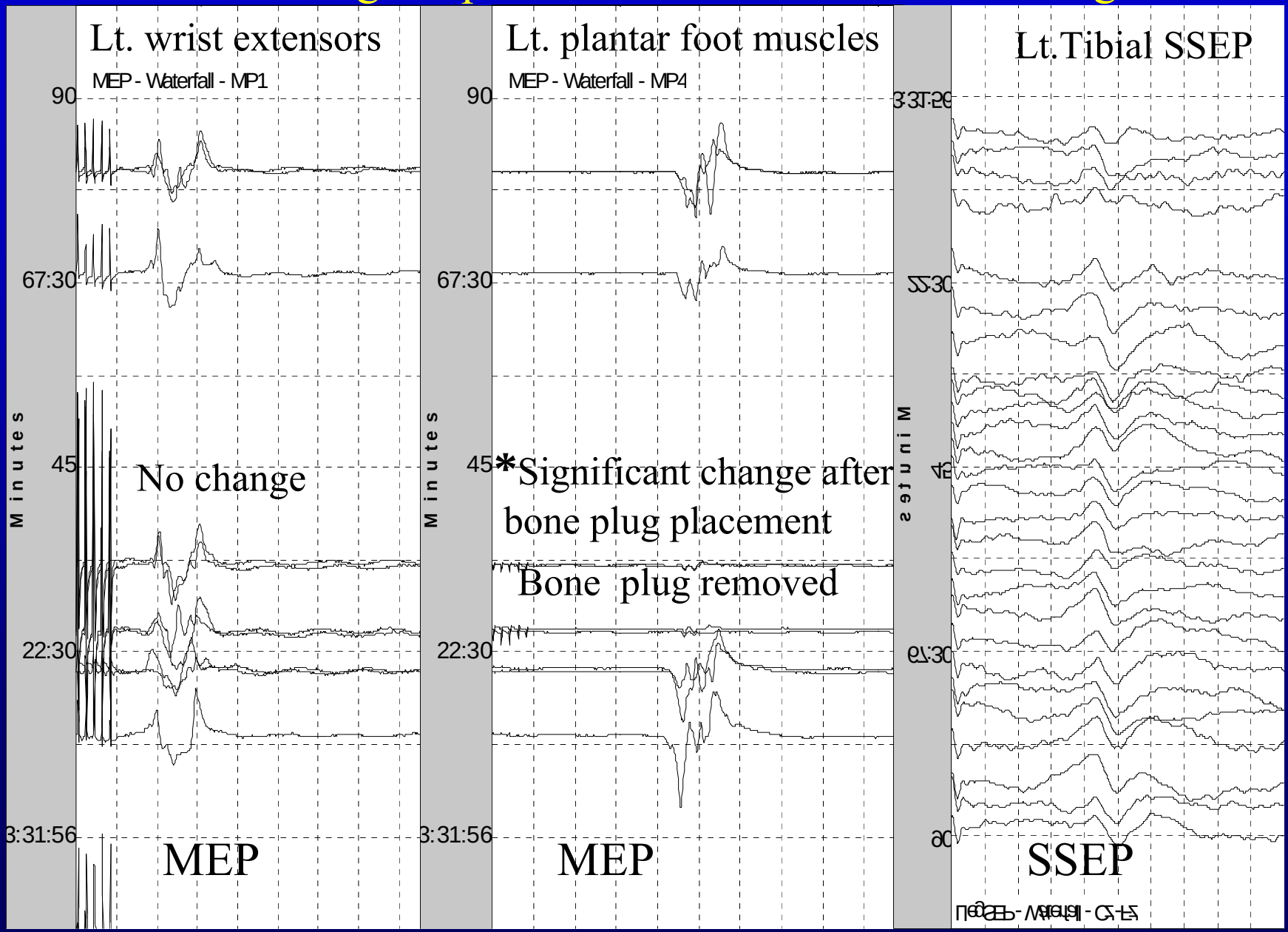
SSEP problems

- Some patients are not monitorable by SSEP
- Some complications go undetected by SSEP

MEP
(scalp stimulation, muscle recording)

- non-invasive
- real time
- more motor specific
- less bulky and less costly than magnetic stimulation

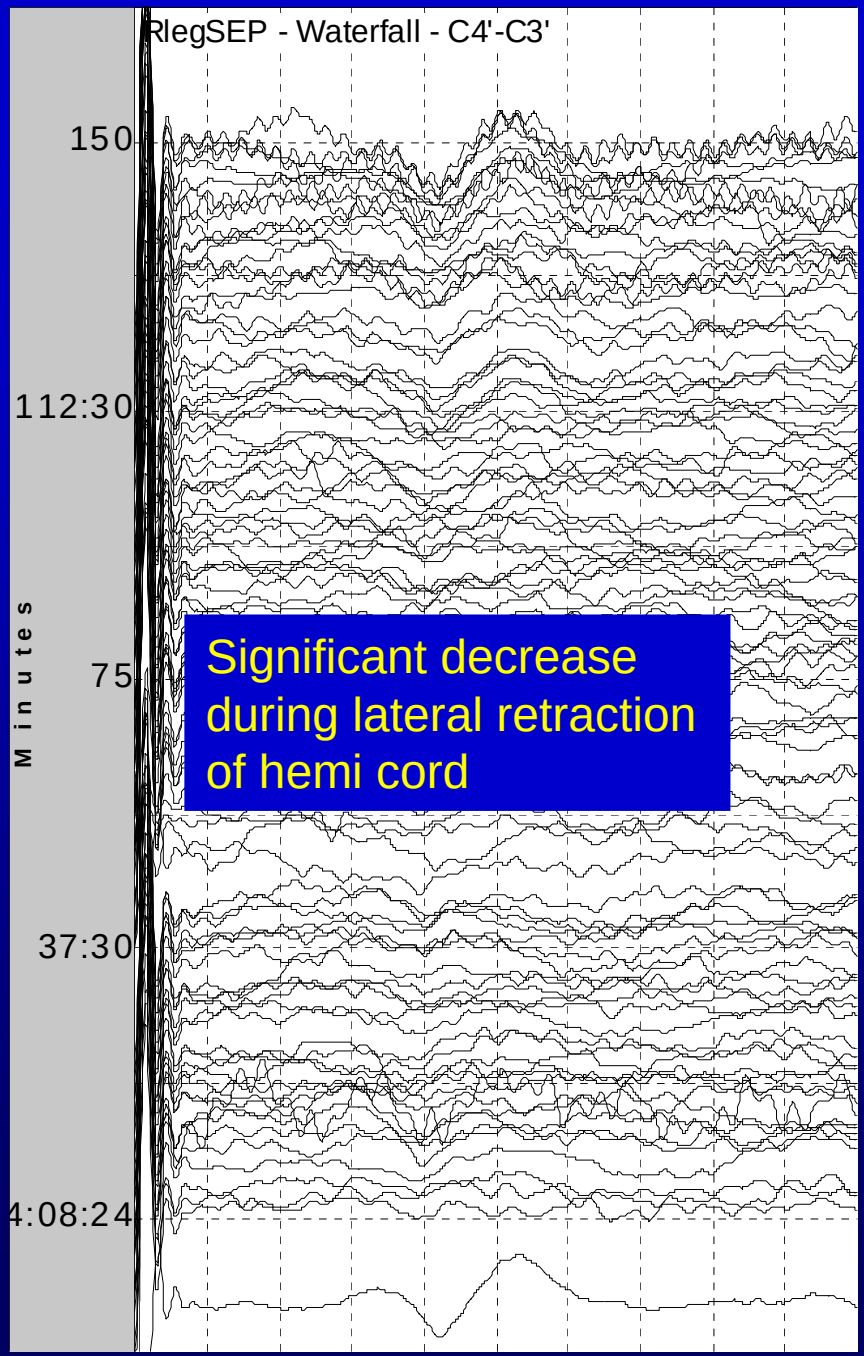
Transient change in plantar foot MEP w/o SSEP change

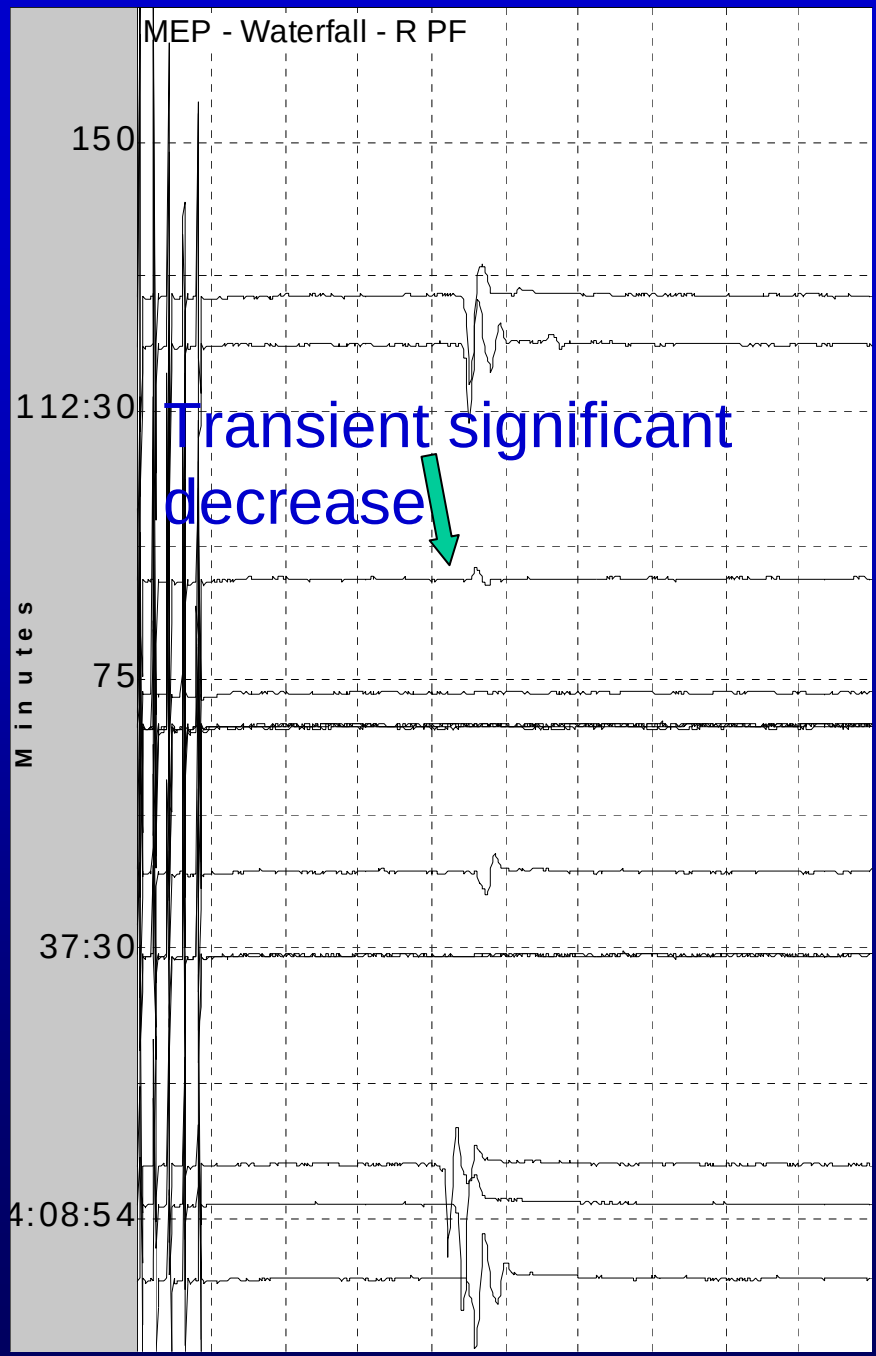


Neurological Examination

- *Pre-op:* Fibromyalgia. Progressive weakness in UE's. O/E: No deficits

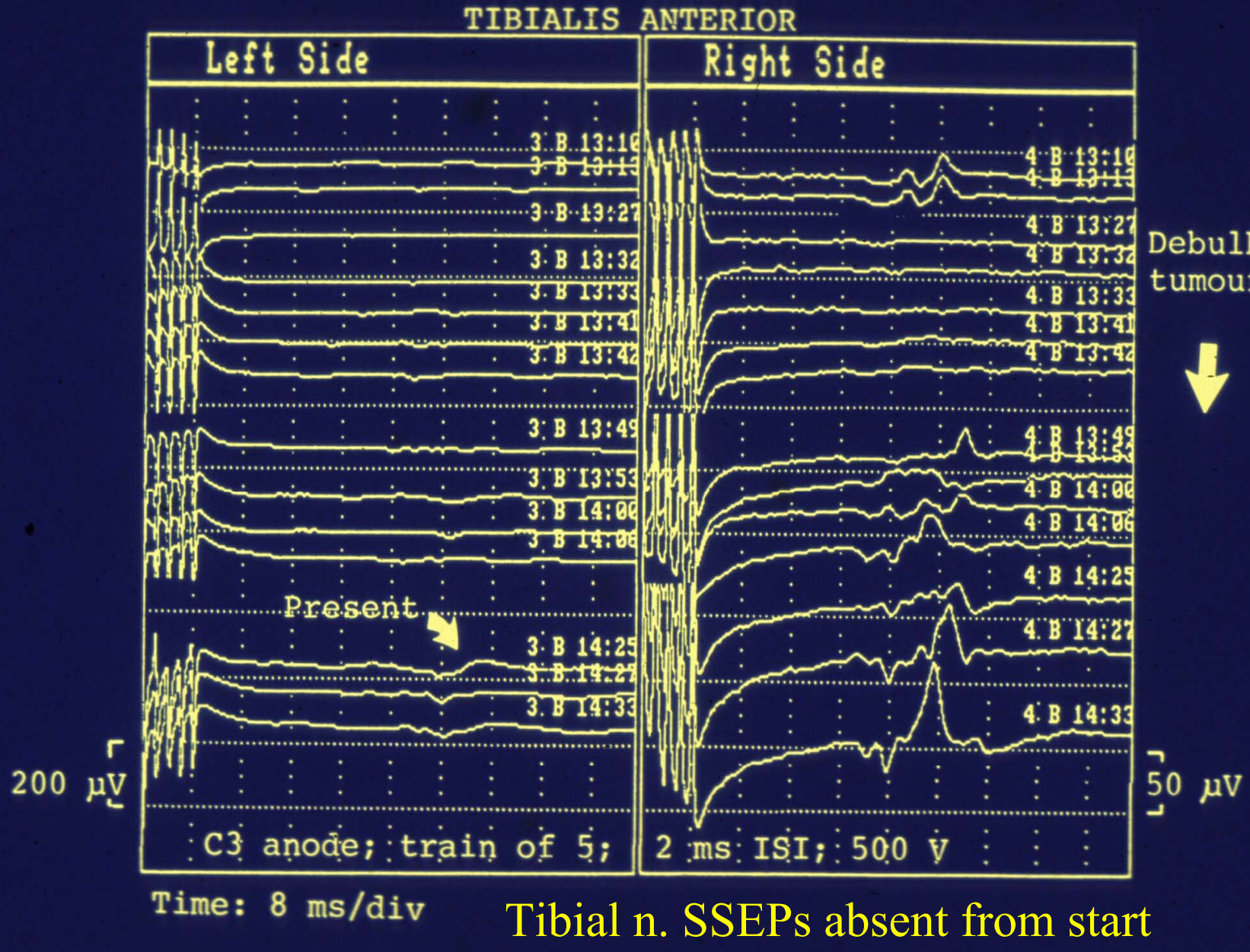
- *MRI:* 1.2 x 0.7 cm T3/4 intramedullary lesion (ependymoma)


RlegSEP - Waterfall - C4'-C3'
150
112:30
75
37:30
4:08:24
Minutes
Significant decrease during lateral retraction of hemi cord

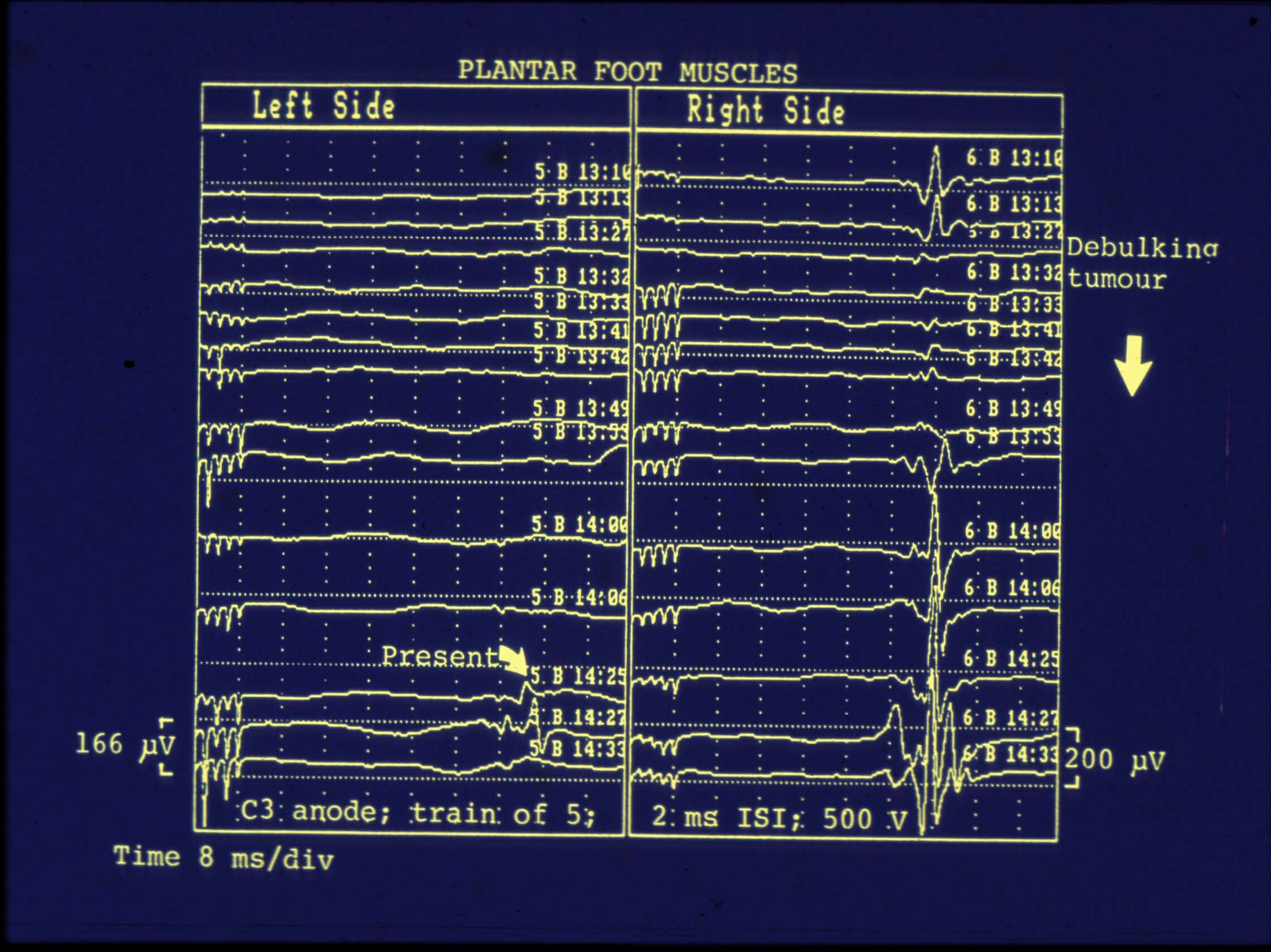

MEP - Waterfall - R PF
150
112:30
75
37:30
4:08:54
Minutes
Transient significant decrease

Post-op. Neurological Examination

- c/o numbness from just below umbilicus down. O/E: Absent vibration sense in LE's, absent R great toe position sense, MRC 4/5 L ankle PF. Normal LT and PP sensation.



Tibial n. SSEPs absent from start


PLANTAR FOOT MUSCLES
Left Side
Right Side
5 B 13:19
5 B 13:13
5 B 13:27
5 B 13:32
5 B 13:33
5 B 13:41
5 B 13:42
5 B 13:49
5 B 13:55
5 B 14:00
5 B 14:06
Present
5 B 14:25
5 B 14:27
5 B 14:33
6 B 13:19
6 B 13:13
6 B 13:27
6 B 13:32
6 B 13:33
6 B 13:41
6 B 13:42
6 B 13:49
6 B 13:53
6 B 14:00
6 B 14:06
6 B 14:25
6 B 14:27
6 B 14:33
Debulking tumour
166 µV
200 µV
C3 anode; train of 5;
2 ms ISI; 500 V
Time 8 ms/div

Survey on *Combined* Monitoring (ASNM and ACNS)

(n =8,763/yr; 6,000 from one center)

Legatt AD. Clin Neurophysiol, 2002

- SSEP and MEP unchanged 90.5%
- Unchanged SSEP, **MEP** change 3.5%
- **SSEP** change, MEP unchanged 2.0%
- **SSEP and MEP** change 4.0%

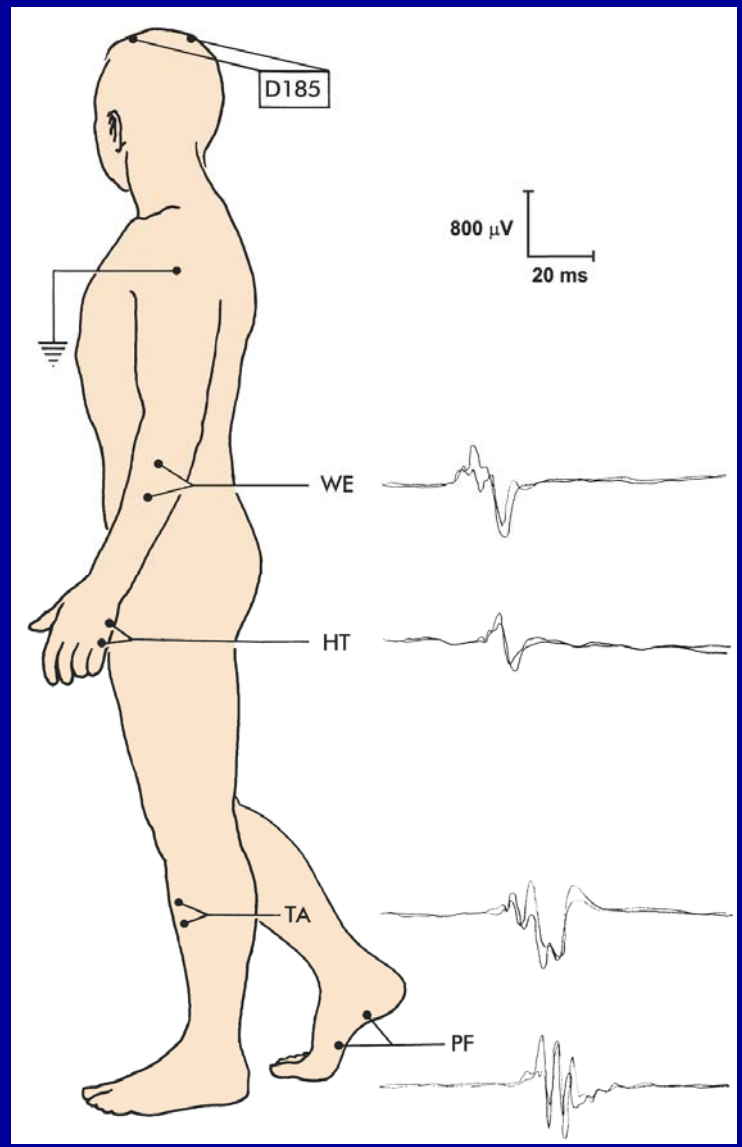
Problems: "Change" not defined, **neurological deficits not described,** all MEP techniques lumped together (13 of 39 centers used brain stim)

Houlden, Burkholder, Schwartz, Rowed, Midha, Fazl, Finkelstein

Hypothesis:

The sensitivity and specificity of combined SSEP/MEP is better than that of SSEP alone in predicting outcome after spinal surgery

<u>Persistent MEP and/or SSEP change</u>



What is significant MEP change

- > 80% decrease in amplitude (baseline MEP must be > 50μV)
- > 100 V stimulus increase in MEP threshold (Calancie et al., 1998)

Results:

193 spinal operations
MEP and SSEP recordable in 80%

Reliable MEP, SSEP and pre- & post-op neuro exams (blind to OR findings) in 118

81% (of 118) had pre-existing deficits

- 36% myelopathy
- 35% radiculopathy
- 10% radiculomyelopathy

10 patients had immediate post-op deficits

- ***2 myelopathy***
- (8 radiculopathy)

Sensitivity and Specificity

- ***Sensitivity*** *for myelopathy (only 2 patients had persistent MEP and SSEP change)*

  SSEP - 1.0 SSEP/MEP - 1.0

- ***Specificity*** *for myelopathy*

  SSEP - 0.99 SSEP/MEP - 0.97

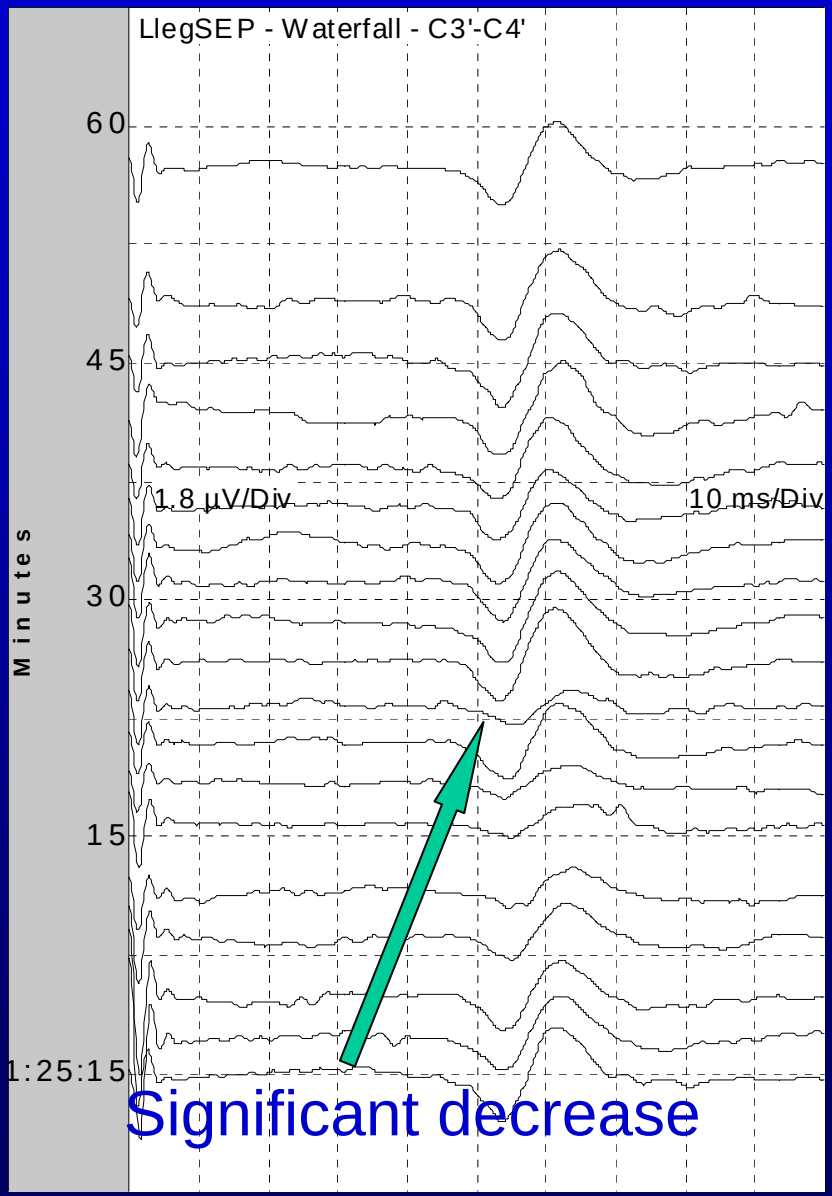
one patient had progressive spinal cord ischemia that went undetected by SSEP and MEP

Transient MEP and/or SSEP change (not explained by anaesthetic or systemic factors)

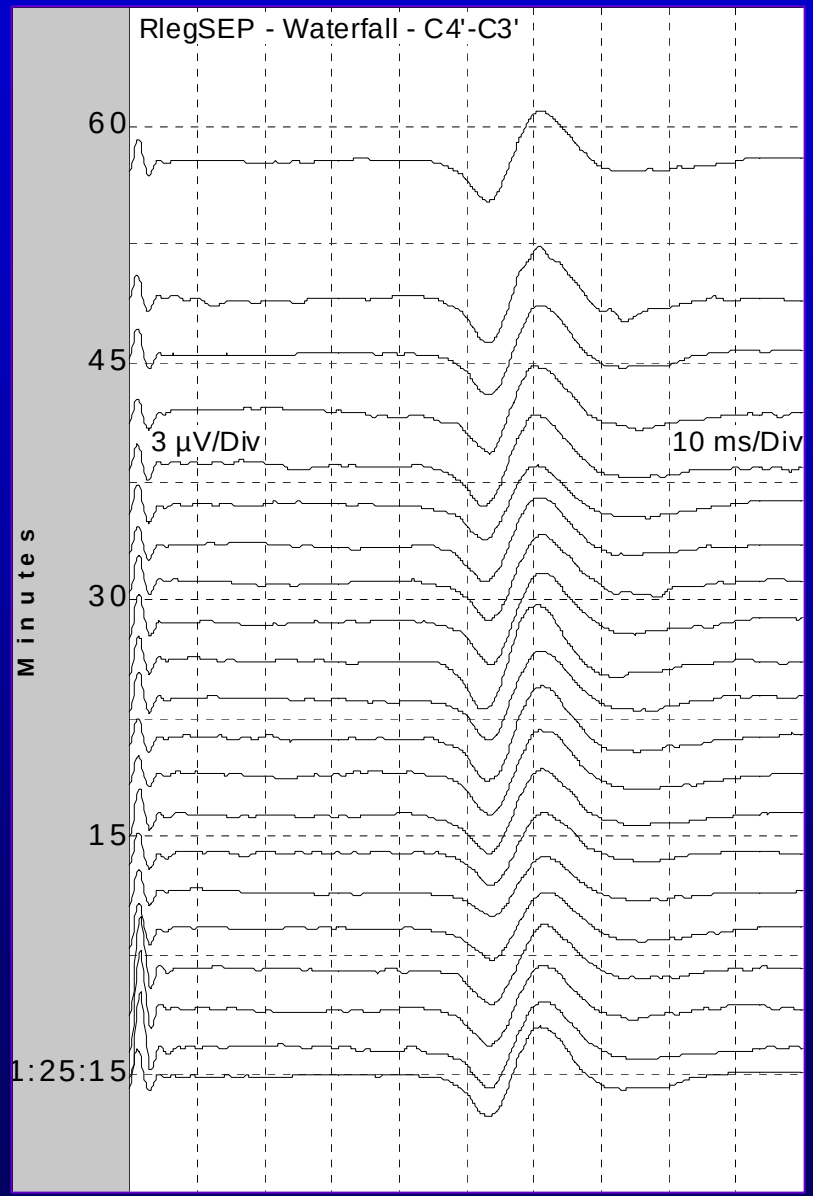
- 3/118 (2.5%) had transient MEP change (1 had new nerve root injury)
- 2/118 (1.7%) had transient SSEP change

- Surgeon informed in all cases

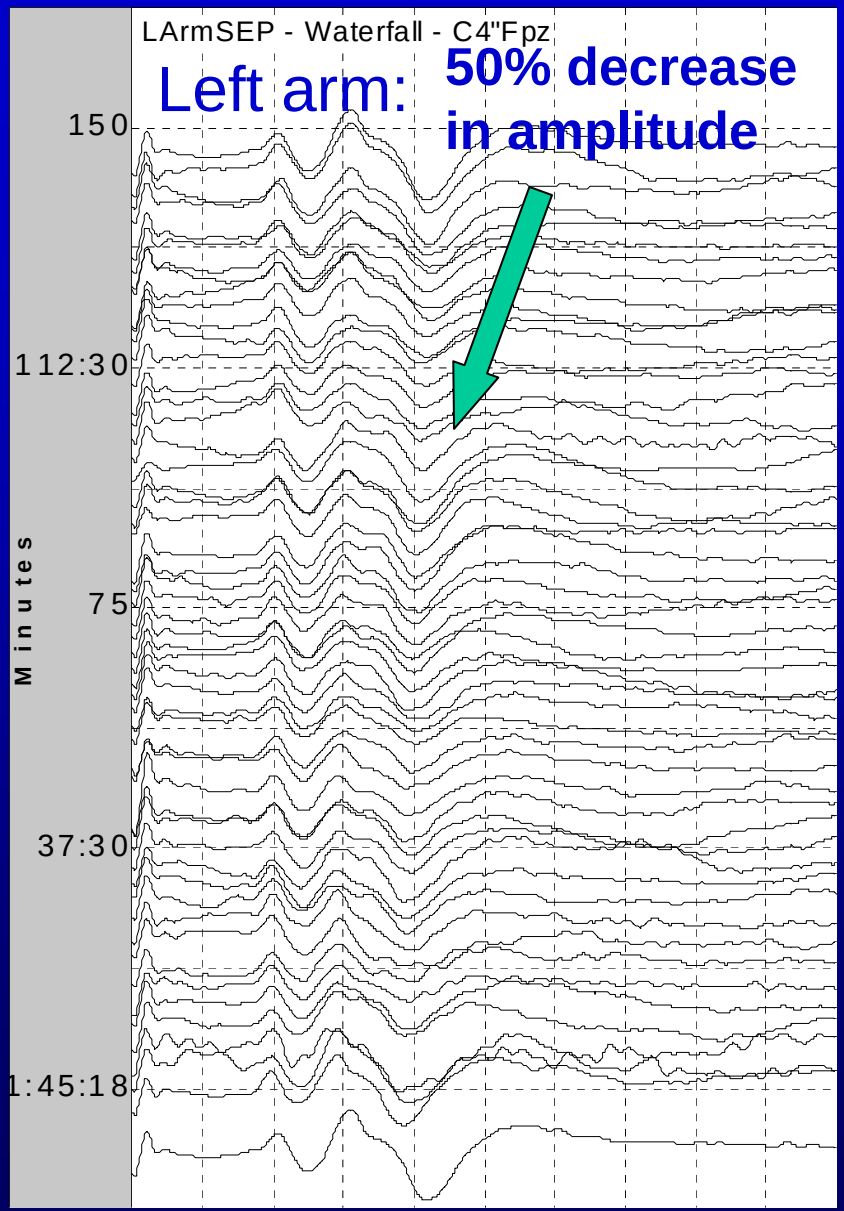
Unilateral transient significant change, C3-5 laminectomy

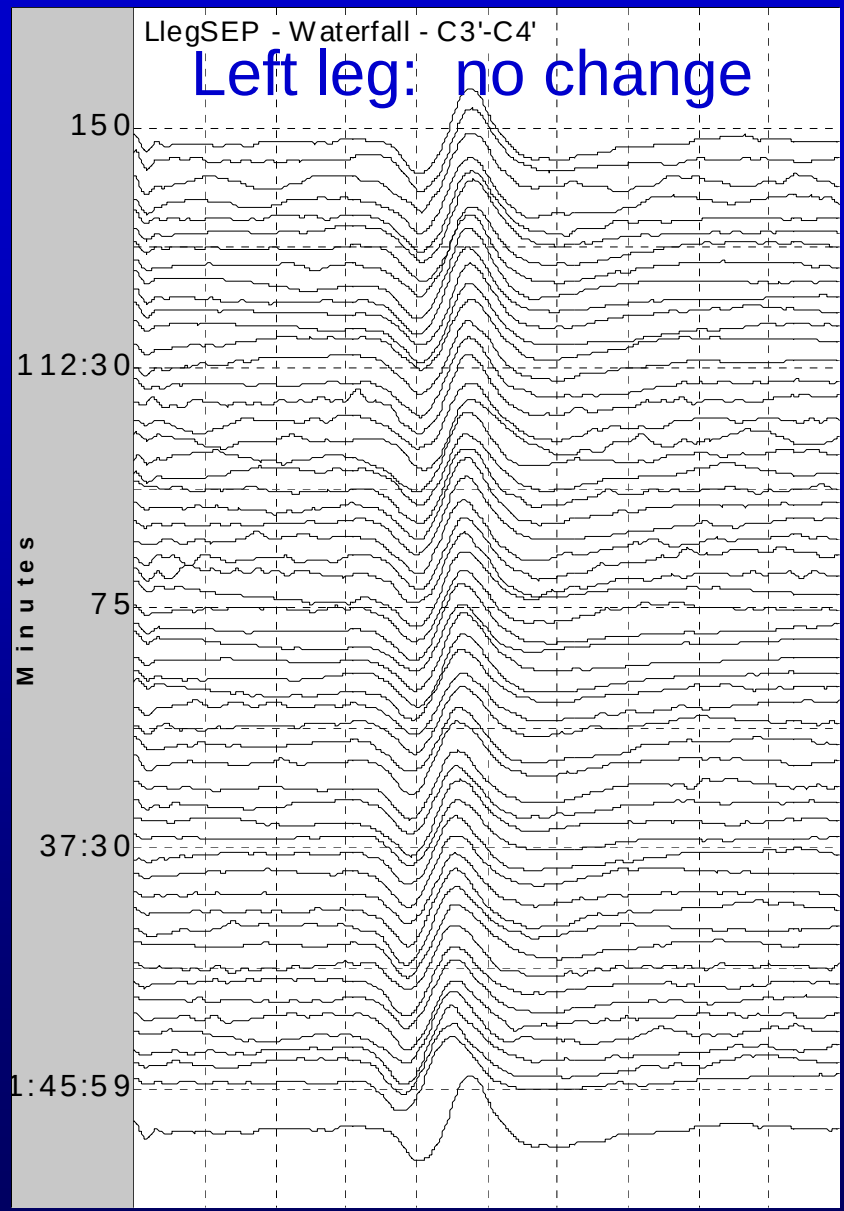


Significant decrease



Mild transient arm change w/o leg change





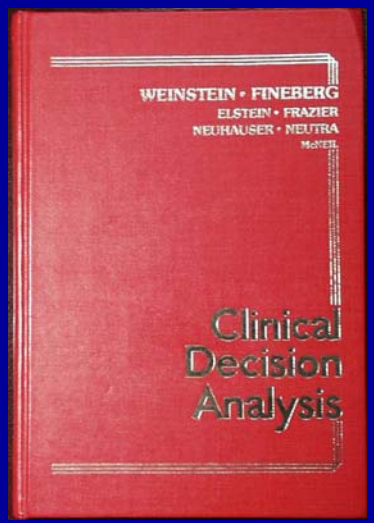
False positive and negatives

- SSEP false positive - 0.9% (0.98%, Nuwer)
- SSEP/MEP false positive - 2.5%

- SSEP false negative - 0% (0.063%, Nuwer)
- SSEP/MEP false negative - 0%

Sensitivity of SSEP/MEP for radiculopathy

	new deficit	no new deficit	totals
+ ve test	1	0	1
- ve test	7	110	117
totals	8	110	118



Sensitivity

(true +ve / total new deficits)

1/8 = 0.125

Conclusion

- Sensitivity/specificity of MEP/SSEP was similar to that of SSEP (more cases needed)
- SSEP and MEP do not detect nerve root injuries

- Association between MEP monitoring and reduction of iatrogenic spinal cord injury has ***not*** been established

- Experience: Familiarity with pitfalls and artifacts? Cogent communication? Trust?

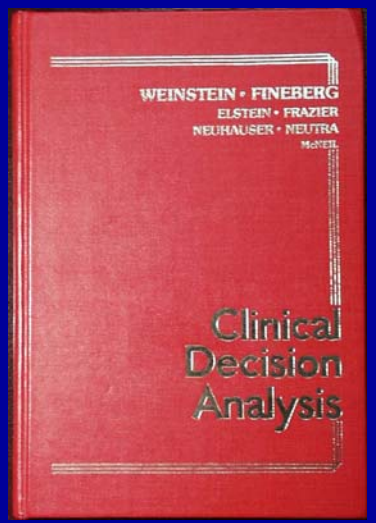
Why do MEP?

- Performing SSEP *and* MEP monitoring is useful for parallel redundancy or when one technique is not possible

- More salutary effects are likely forthcoming (Recent FDA approval for transcranial electric stimulation)

Sensitivity of EMG for radiculopathy

	new deficit	no new deficit	totals
+ ve test	6	10	16
- ve test	0	37	37
totals	6	47	53



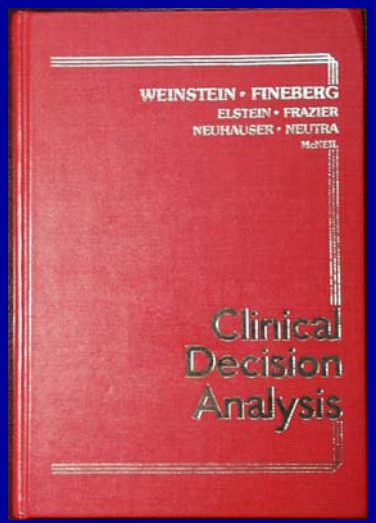
Sensitivity

(true +ve / total new deficits)

6/6 = 1.0

Specificity of EMG for radiculopathy

	new deficit	no new deficit	totals
+ ve test	6	10	16
- ve test	0	37	37
totals	6	47	53



Specificity

true –ve / total no change

37 / 47 = 0.79

SSEP/MEP is not sensitive to a single root injury (*SSEP/MEP* traverse multiple roots).

EMG is sensitive but not specific for nerve root injury.

Intraoperative Electrophysiological Techniques

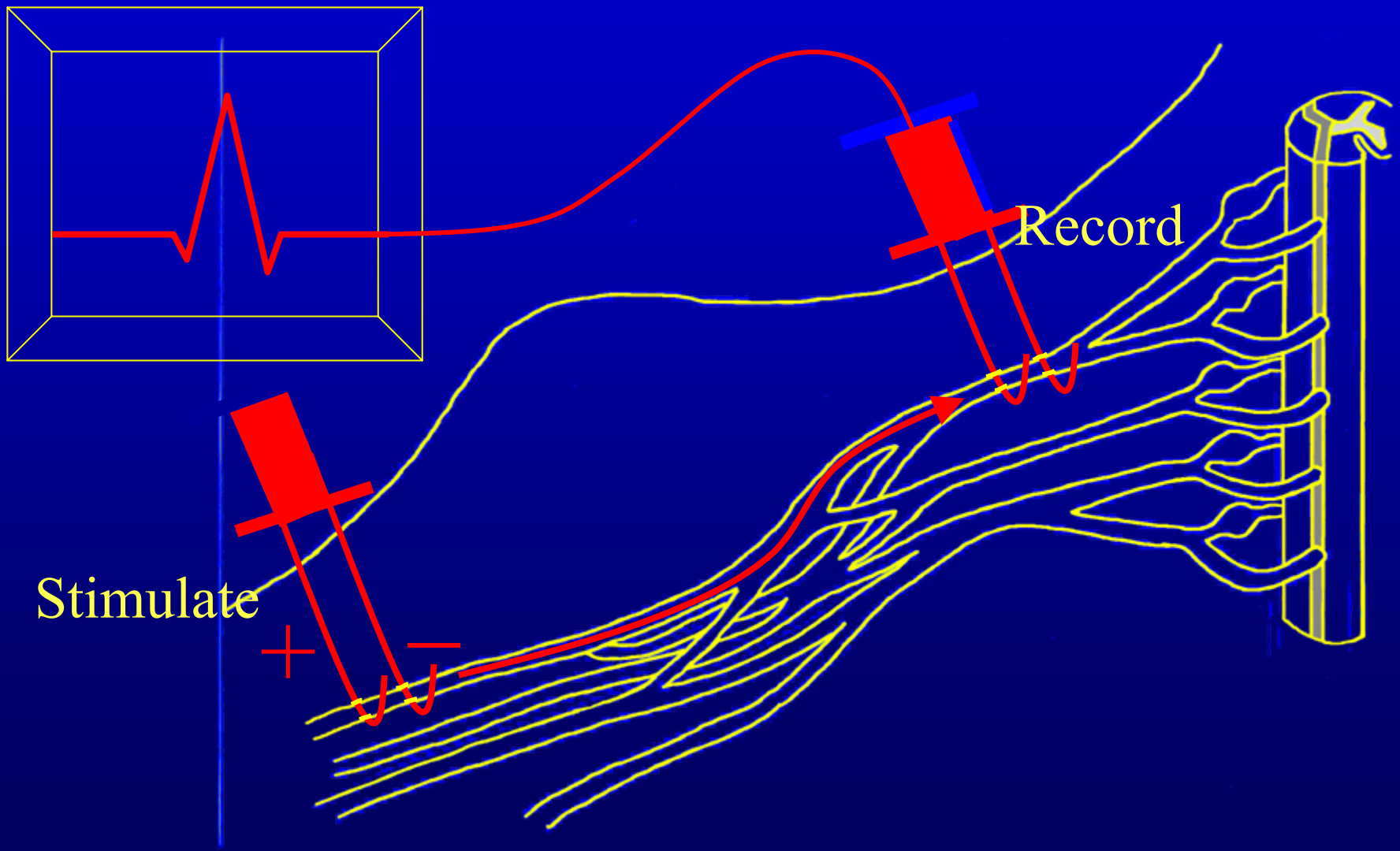
- ***Nerve Conduction Studies (NAPs, MCAPs)***
- Somatosensory Evoked Potentials (SSEPs)
- Motor Evoked Potentials (MEPs, MNAPs)
- Electromyography (triggered and mechanically evoked)

Confirms preoperative electrophysiological tests and observations

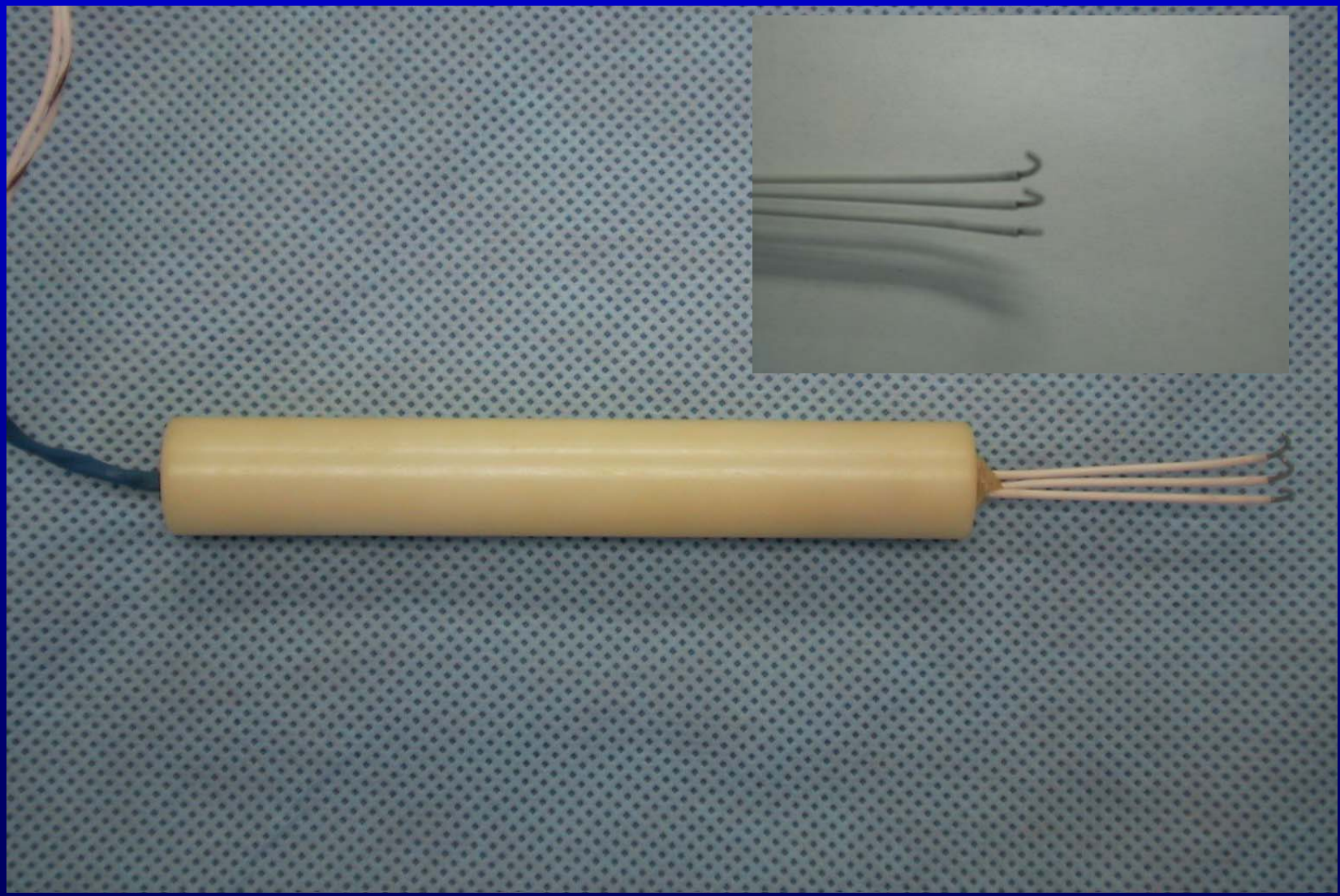
Goals of Electrophysiological Techniques

- Assess nerve function
  - functional vs. non-functional nerve (SSEPs, NAPs, MNAPs, MCAPs)
  - nerve regeneration (NAPs)
- Protect nerve during manipulation
  - mechanically evoked EMG, (SSEPs)
- Nerve identification
  - to guide dissection (triggered EMG, (NAPs))
  - to identify a specific nerve (triggered EMG)

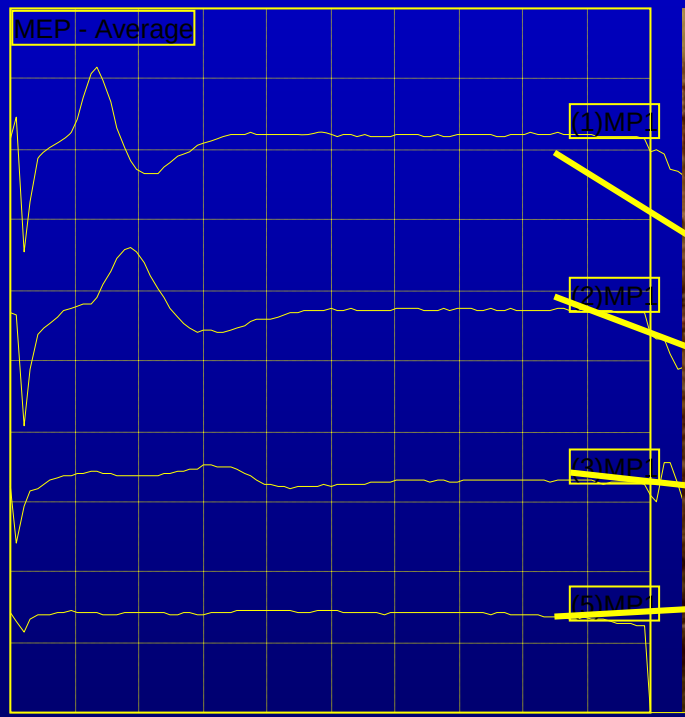
Nerve Action Potential (NAP)

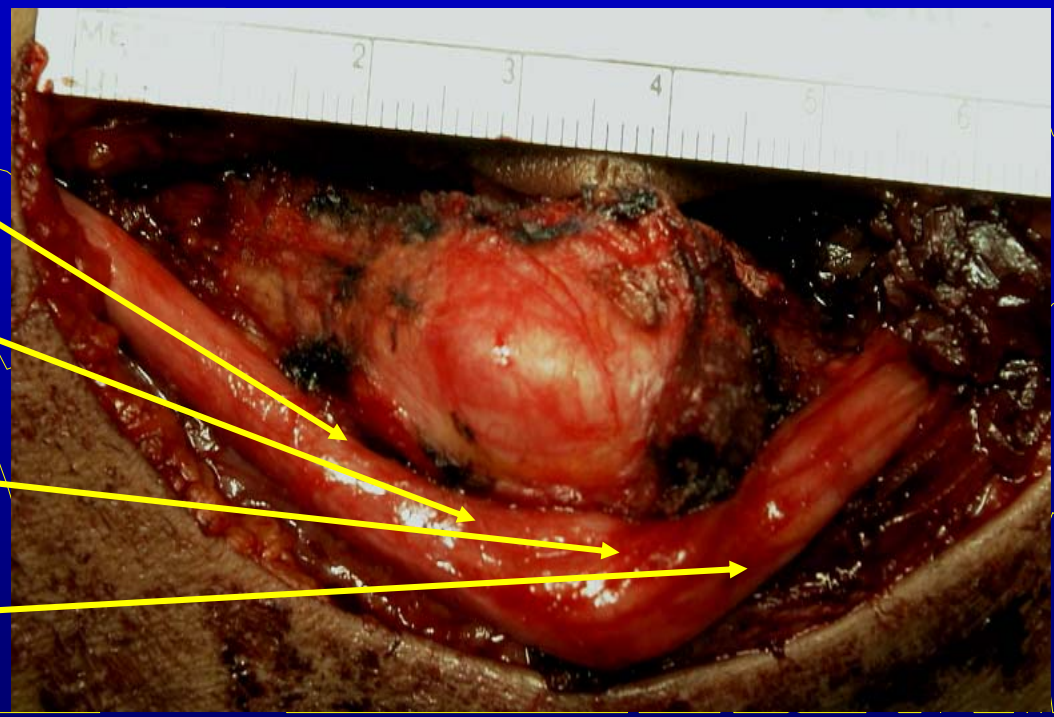


Tripolar Stimulator (Anode - Cathode - Anode)



Conduction Block (Ulnar n.)





1.5 ms/Div

100μV/Div

Complete Erbs Palsy