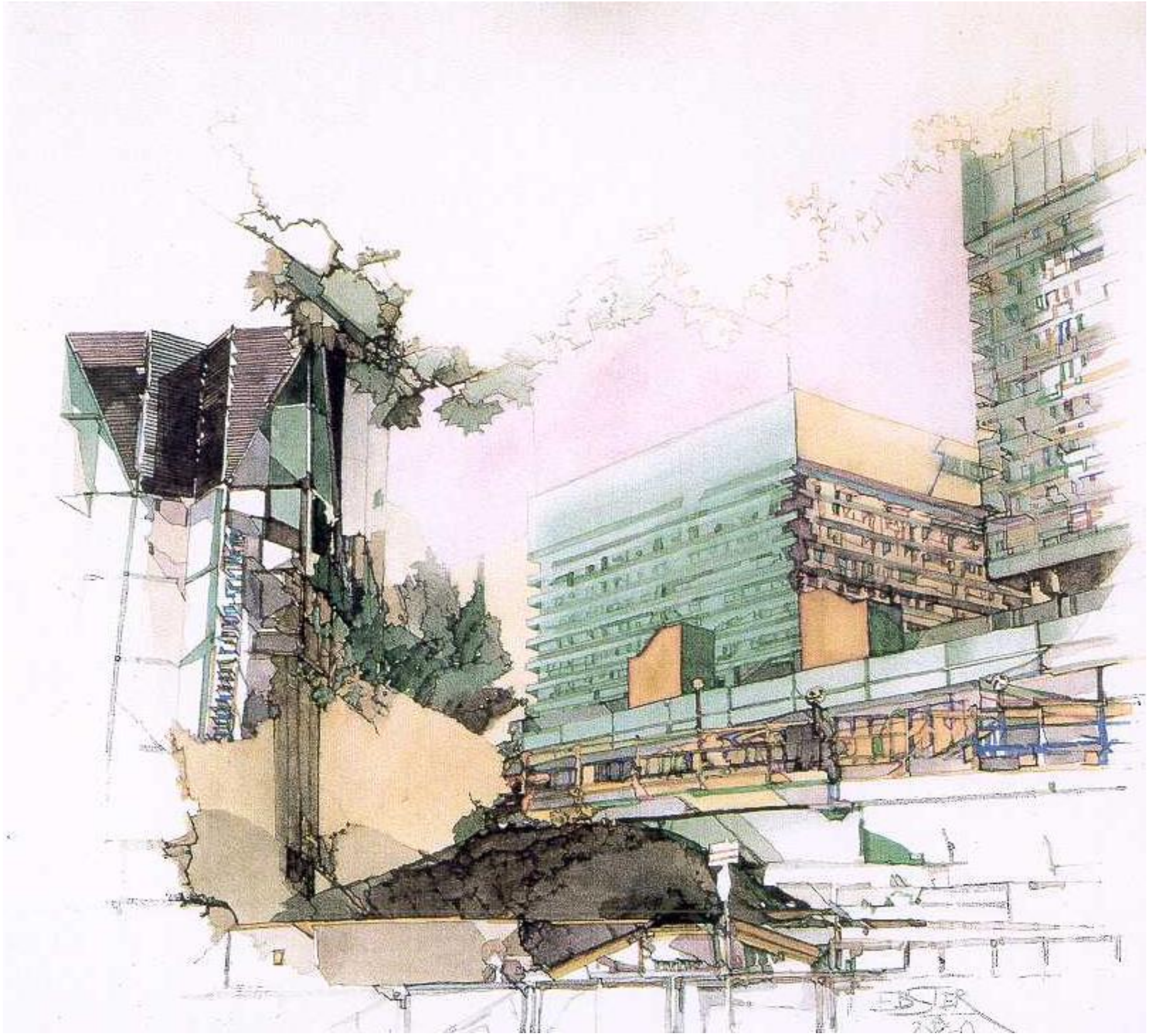
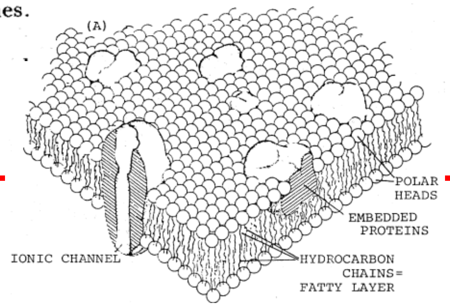
Workshop 8: FES in Rehabilitation – Practical Aspects

Role of Electrical Parameters



Bretscher M.S. and Raff M.C. 1975. Mammalian plasma membranes. Nature 258, 43-49



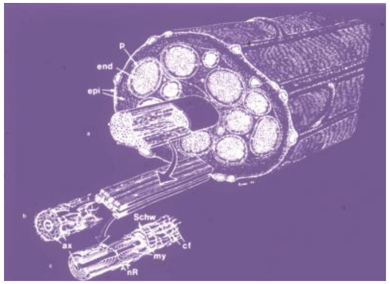
Functional Electrical Stimulation - FES

Induction of electrical fields in biological tissue -
- to influence voltage across excitable cell membranes
(mostly cylindrical surface of nerve or muscle fibers)

TOOL for
inducing action potentials in
- Afferent neurons
- Efferent neurons
- Muscle fibers

or shifting
resting potential / altering excitability

Limitations in
- Spatial resolution
- Selective recruiting
- Temporal selectivity
- Bidirectional firing



Systemic effects:

- NOT systemic eMedication !
- (rather alternative to systemic medication)
- NOT direct repair of neural damage
- BUT powerful tool for
- Support of recovery
- Support of tissue maintenance
- Prevention of secondary complications
- Augmentation or substitution of impaired functions (prosthesis)

INTERFACING NEURONS AND MUSCLES

with Functional Electrical Stimulation / Neuromodulation

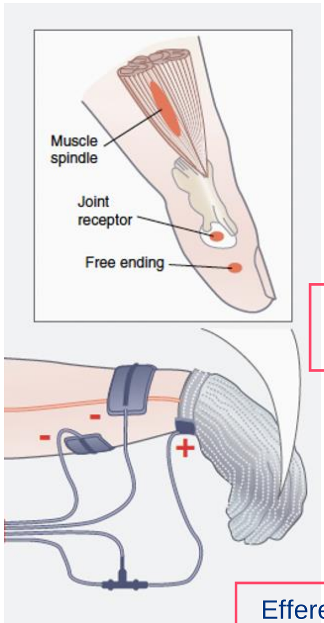
Afferent Nerves

Efferent Nerves

Muscle Fibers

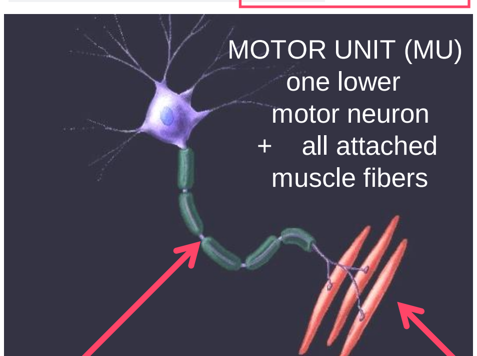
Sensory Functions

Motor Functions

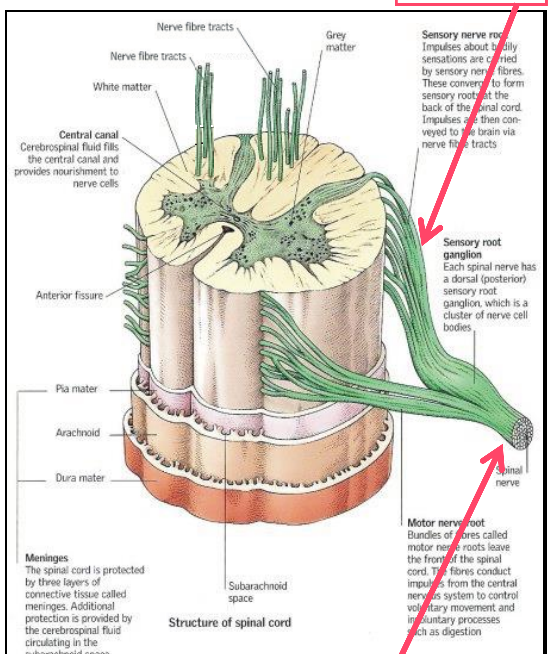


Afferent nerves

Efferent nerves



Afferent nerves



Neuromuscular - motor nerve

Denervated muscle fibers
(in absence of nerve **only !**)

Mixed Nerve

Conditioning, Training

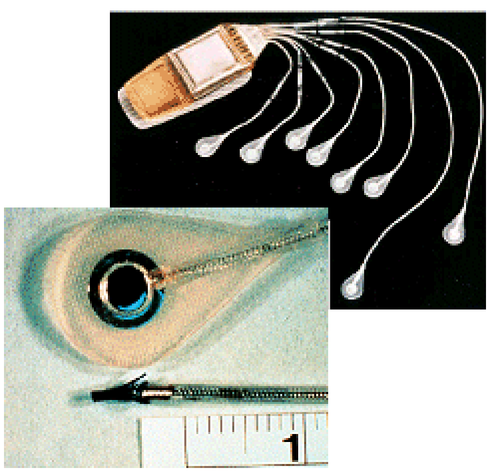
Tissue Preservation

Spasticity / Stiffness / Pain

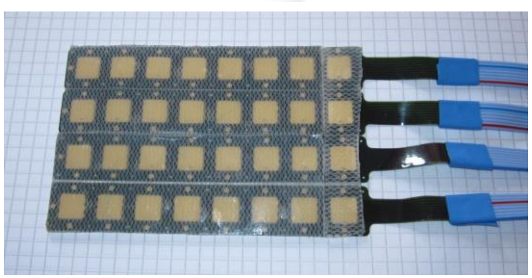
Motor Control

Substitution of Functions

Non-invasive and invasive tools



Electrode-tissue interface - Shape and size of stimuli



noninvasive

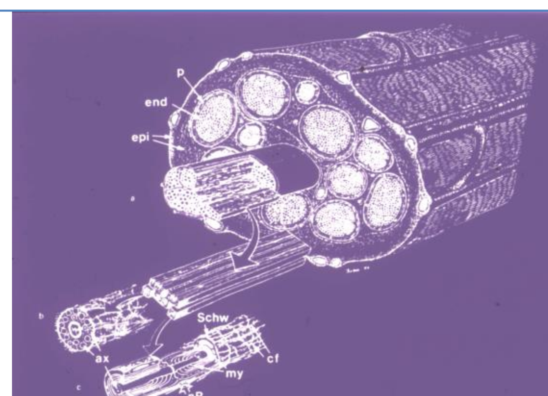
Decisive and limiting compromise on selectivity and safety

*

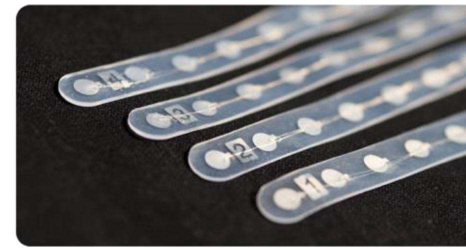
Generally coarse tool to activate tiny structures

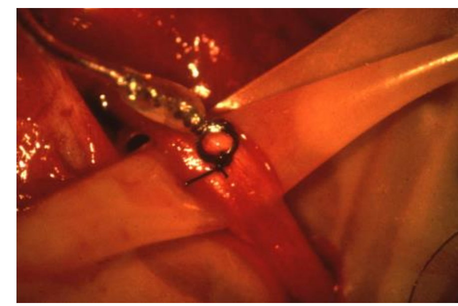
*

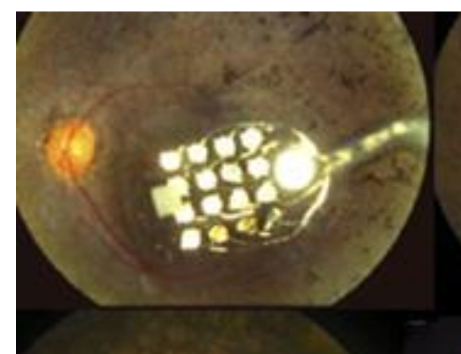
Integration of medical, physiological and engineering expertise



implanted

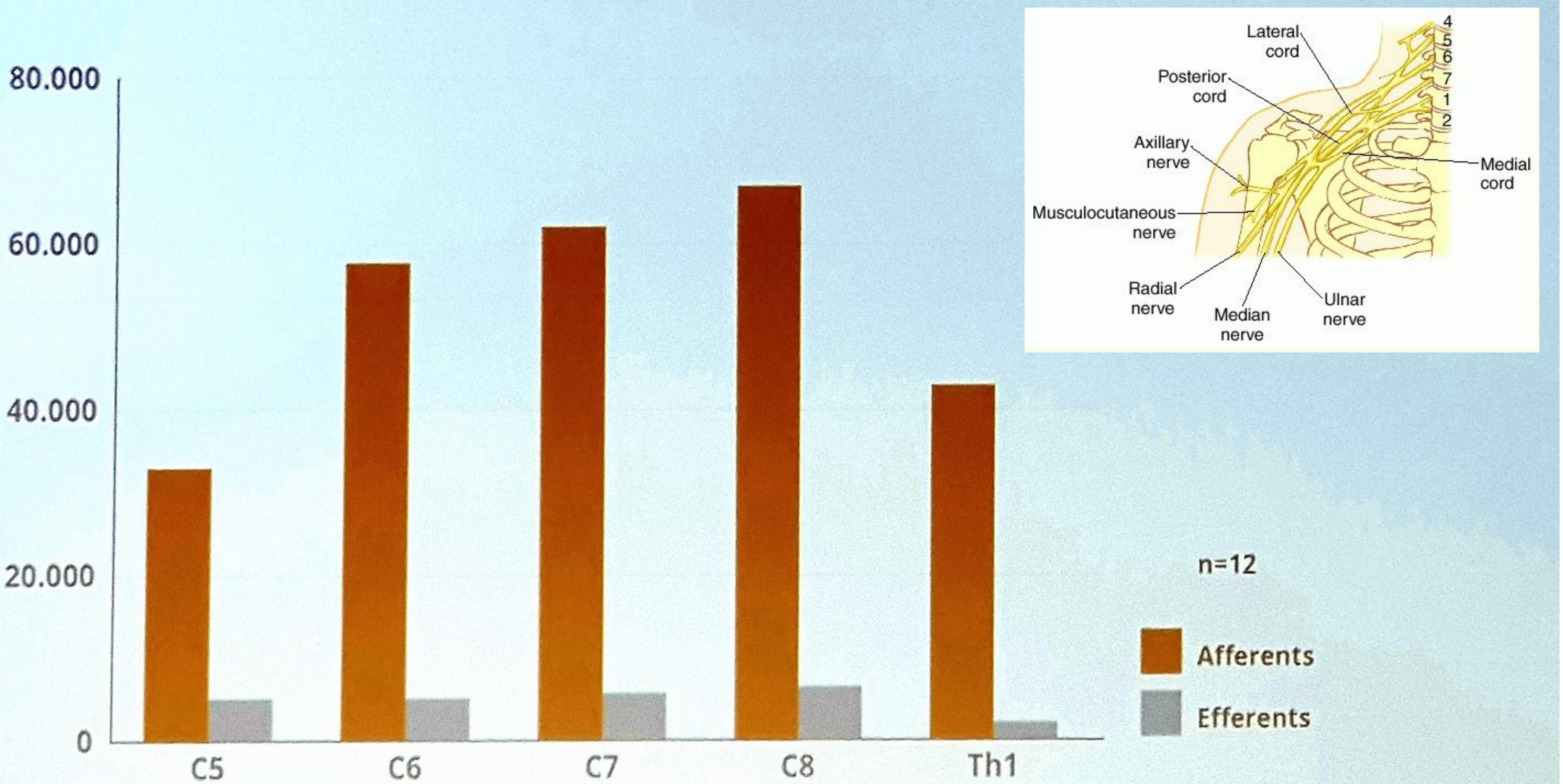






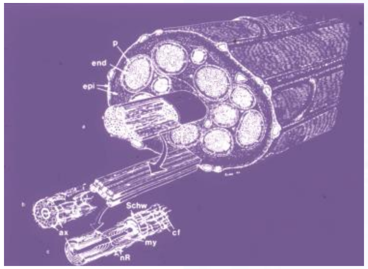
Neuron Recruitment

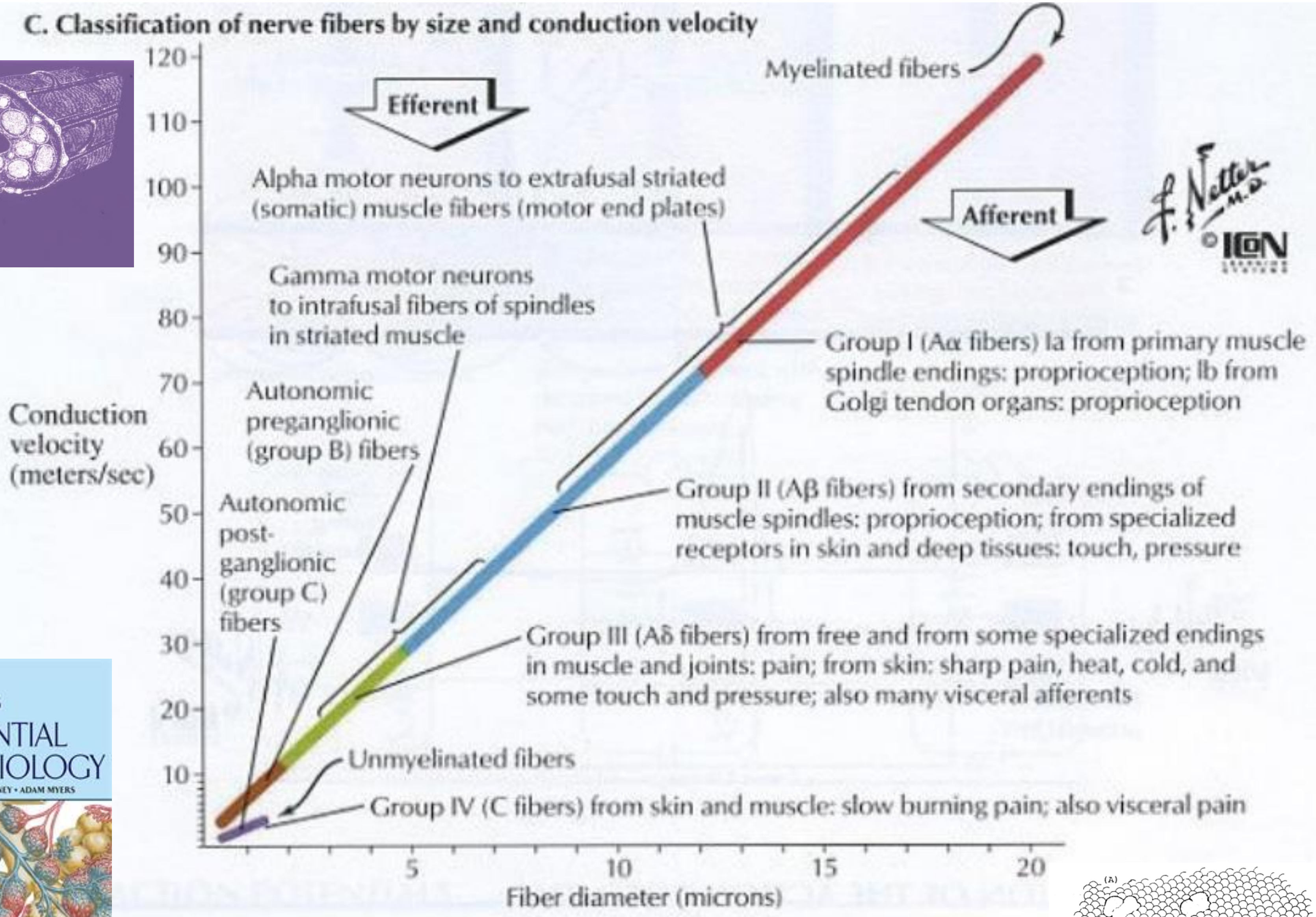
FIRST QUANTITATIVE **DATA ON HUMAN BP**

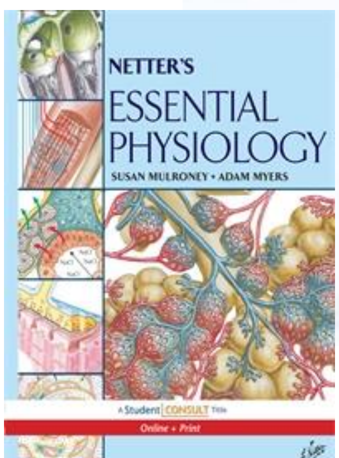


afferent – efferent
9 : 1

Gesslbauer B, et al.
Axonal components of nerves innervating the human arm.
Ann Neurol. 2017 Sep;82(3):396-408







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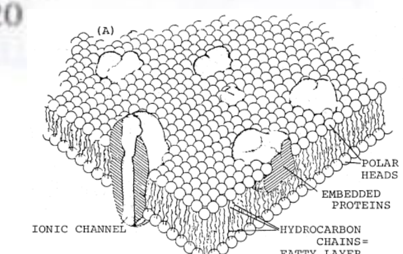
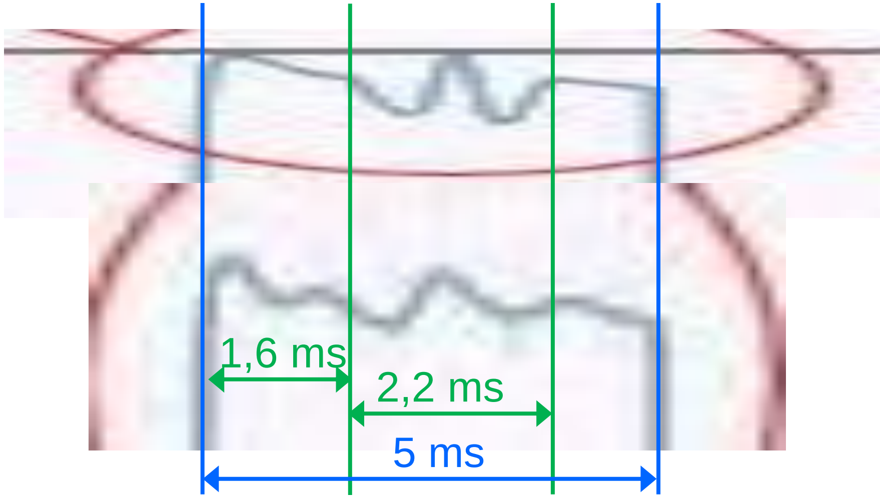
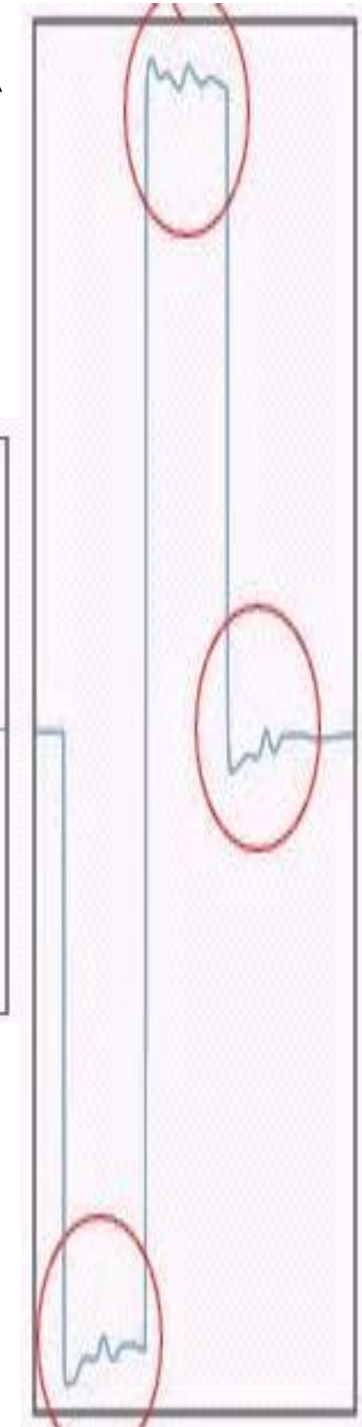
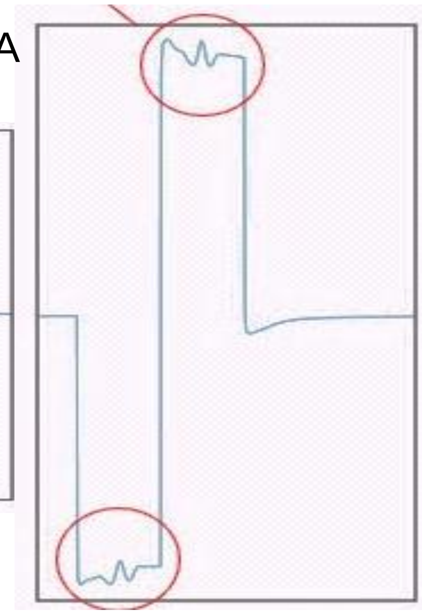




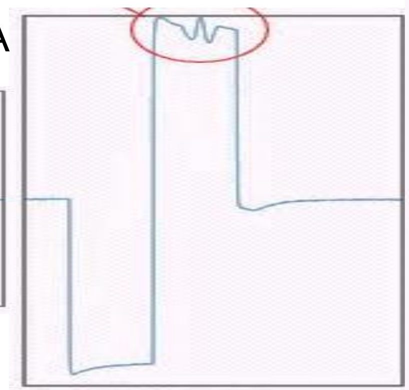
2 mA



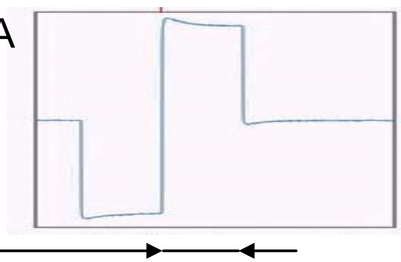
1 mA



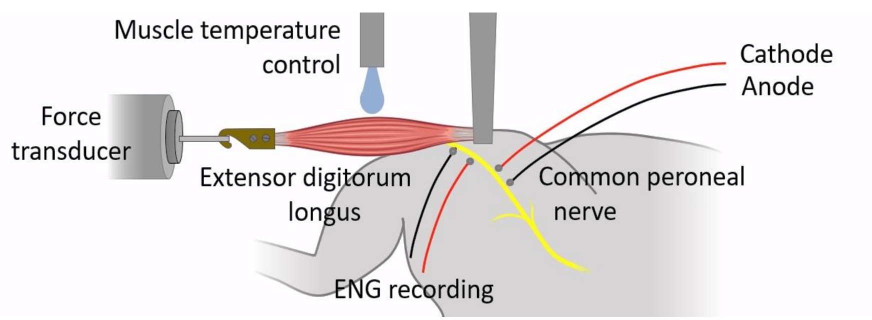
0,5 mA



0,2 mA



5 ms



Steffen Eickhoff, Jonathan Jarvis – John Moores University, Liverpool
UNPUBLISHED DATA

SELECTIVITY

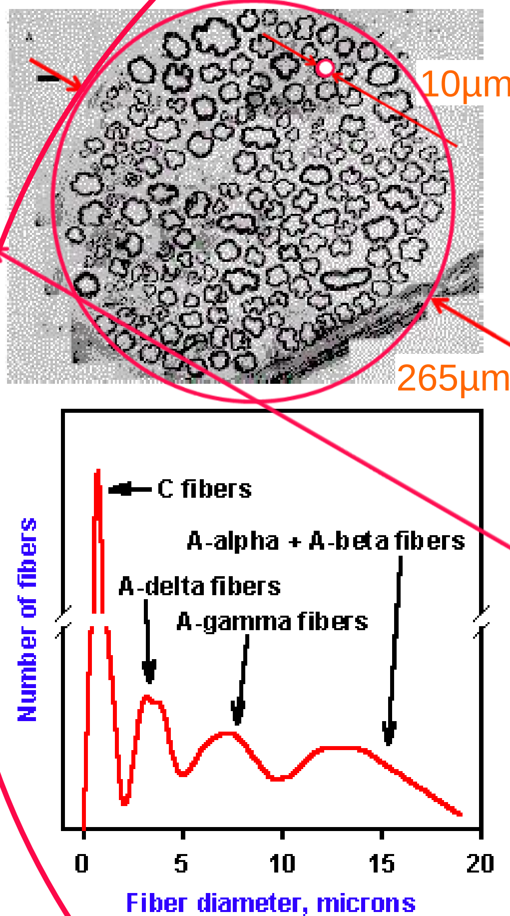
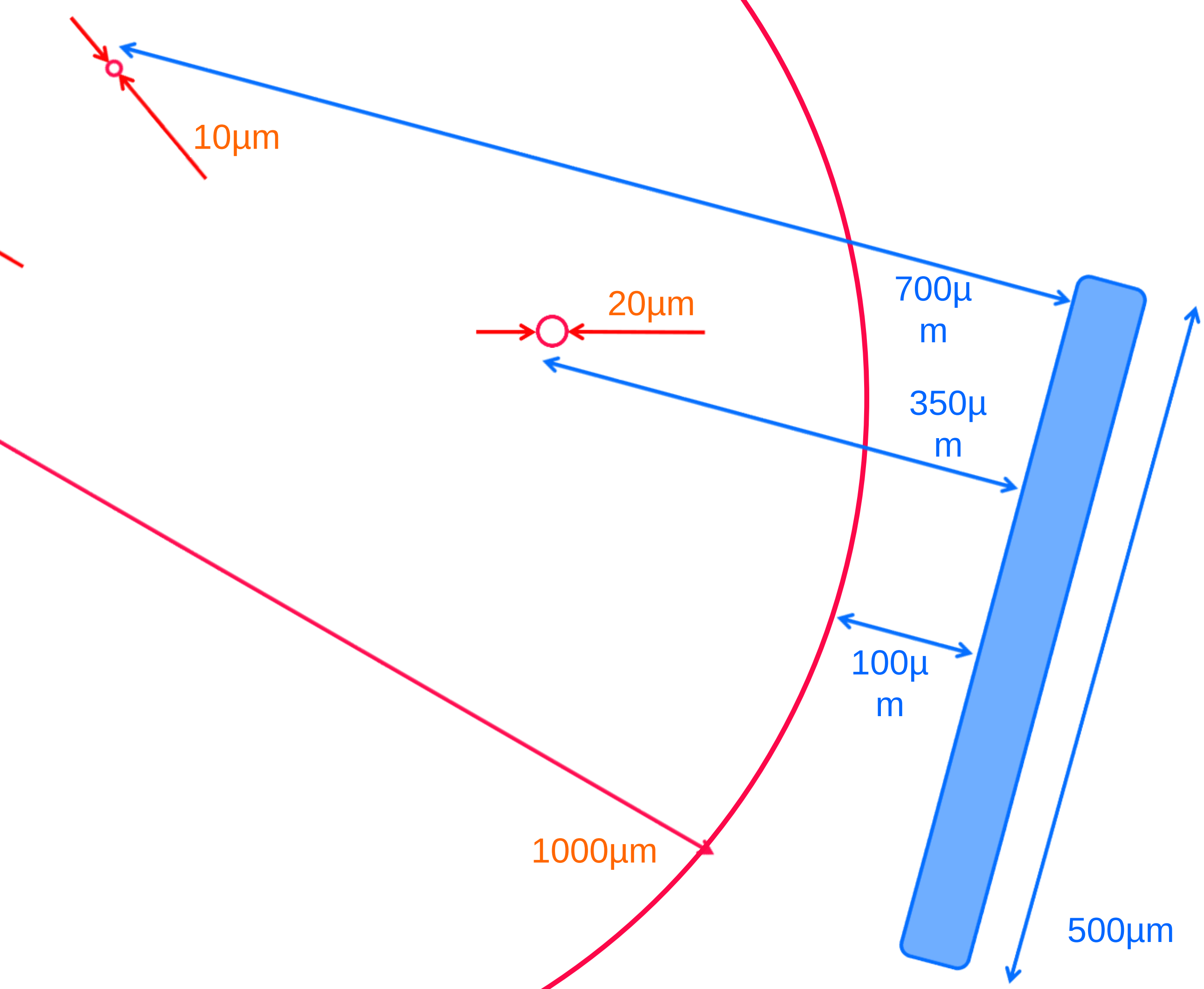
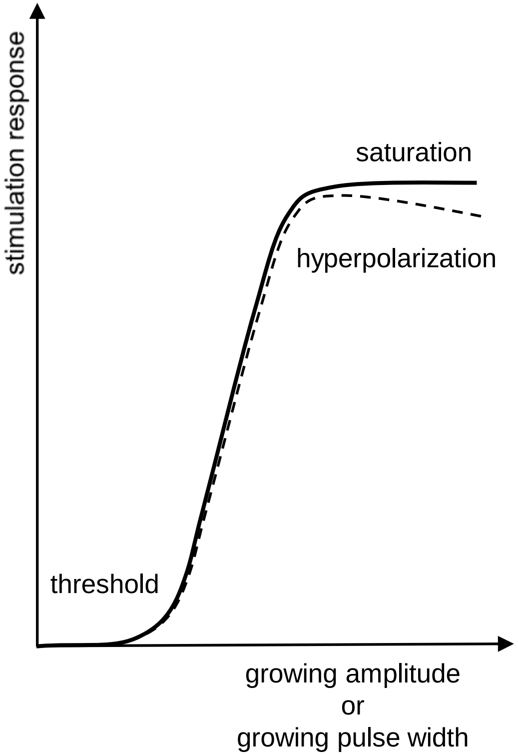


Fig. 5-13. Distribution of fibers within a peripheral nerve. Upper: A cross section of the posterior articular nerve of the cat showing fibers of different diameters. Calibration: 10 microns (Courtesy of F.J. Clark). Lower: A plot of the number of fibers of different diameters in a peripheral nerve. Note the predominance of fibers less than 2 microns in diameter.



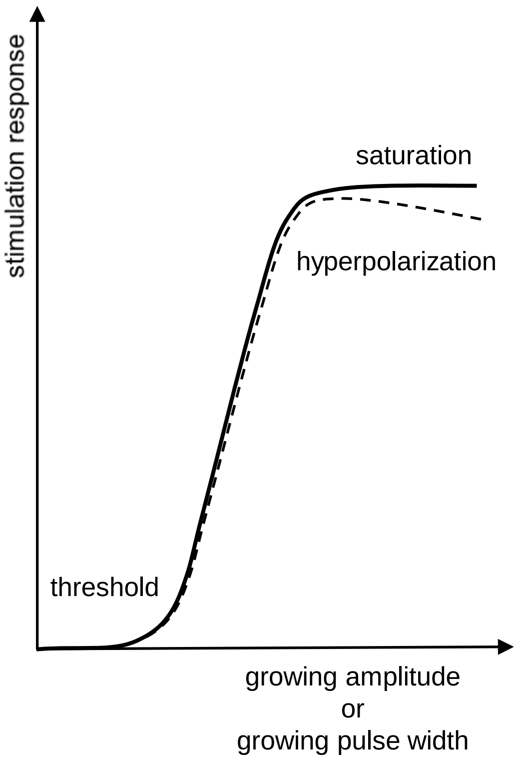
THRESHOLDS / Depolarisation / Hyperpolarisation:

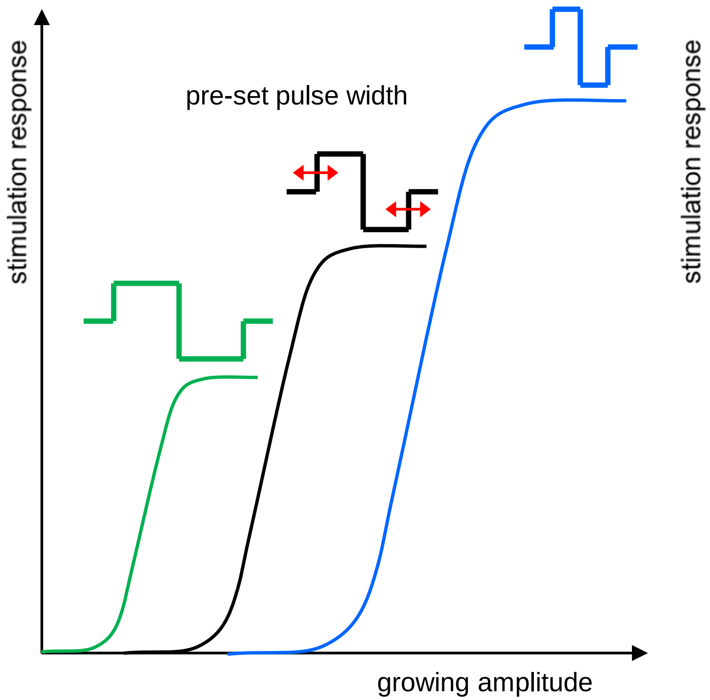
- Inverse proportional fiber size
- Prop. to square of distance



stimulation response

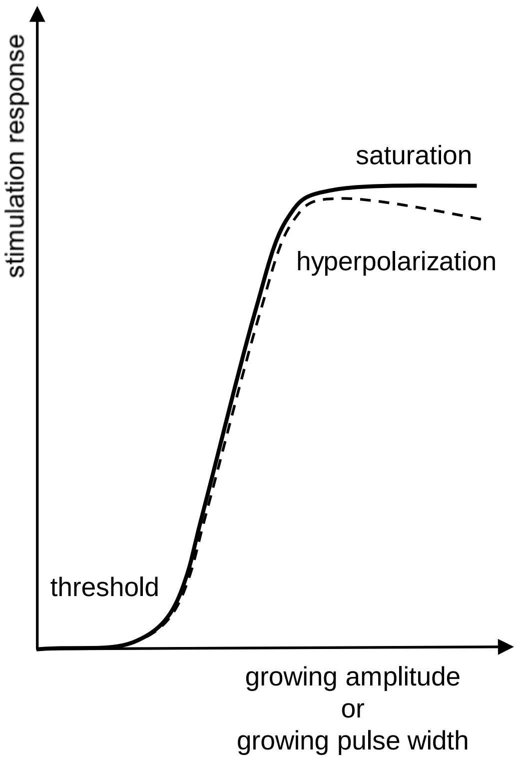
typical recruitment curve,
threshold to saturation



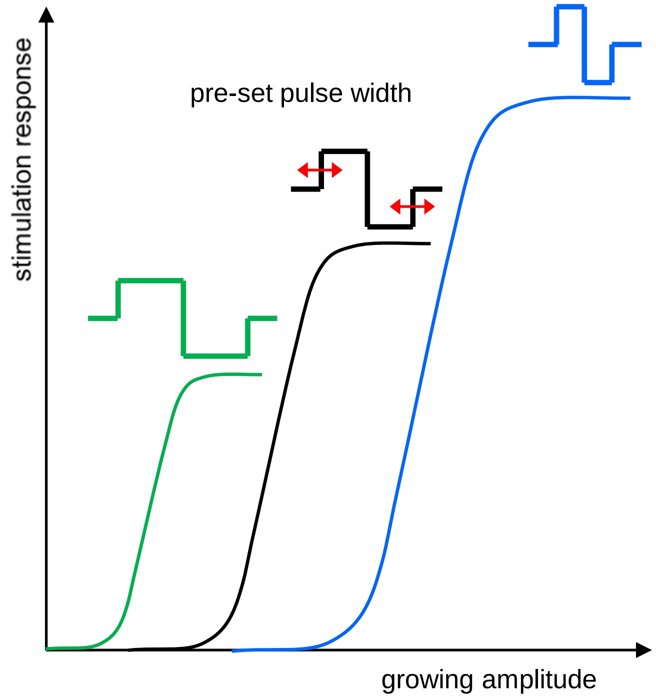


typical recruitment curve,
threshold to saturation

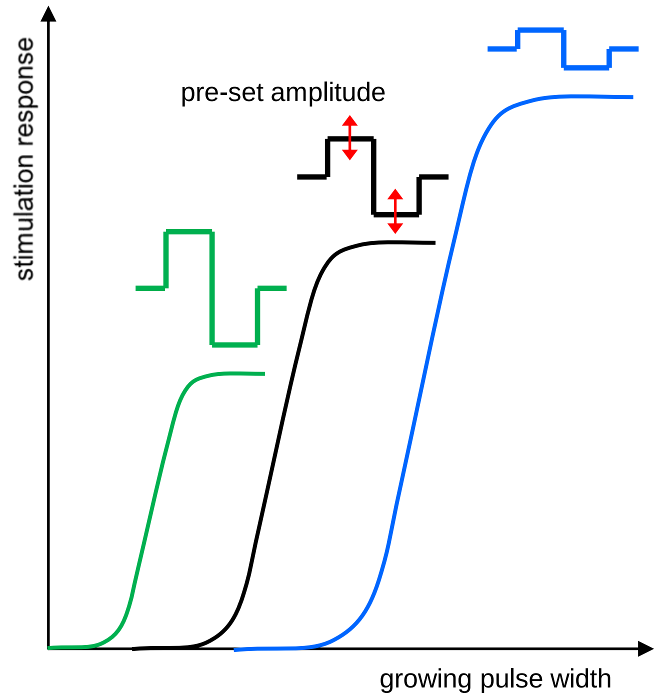
typical recruitment curve,
amplitude variation, constant pulse width



typical recruitment curve,
threshold to saturation



typical recruitment curve,
amplitude variation, constant pulse width

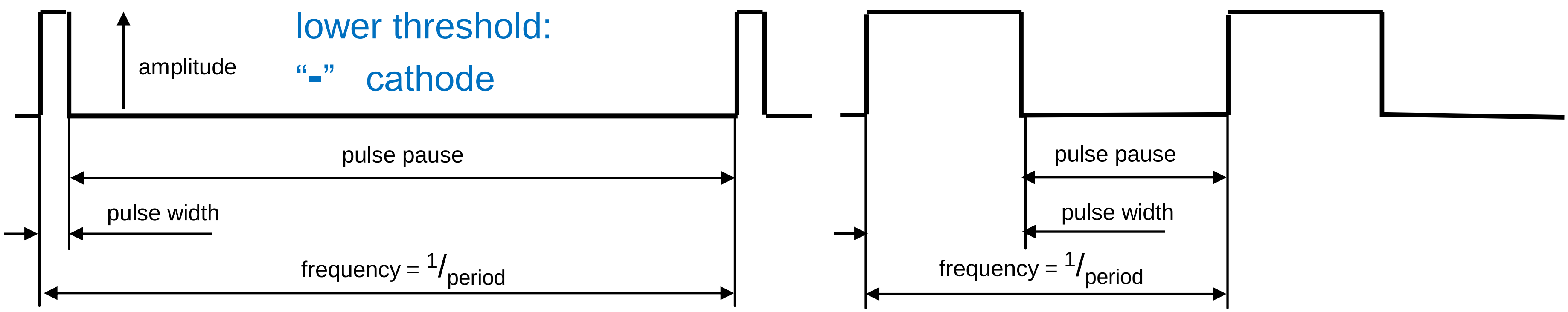


typical recruitment curve,
pulse width variation, constant amplitude

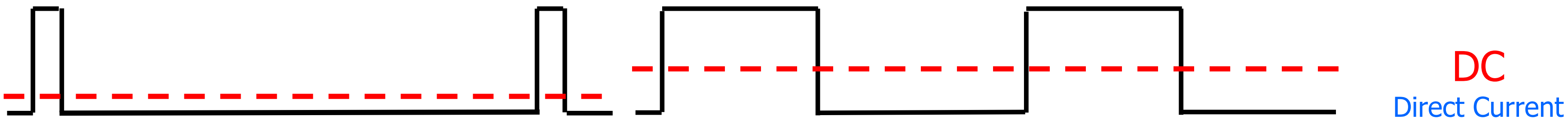
Nerve Stimulation

(Muscle Stimulation)

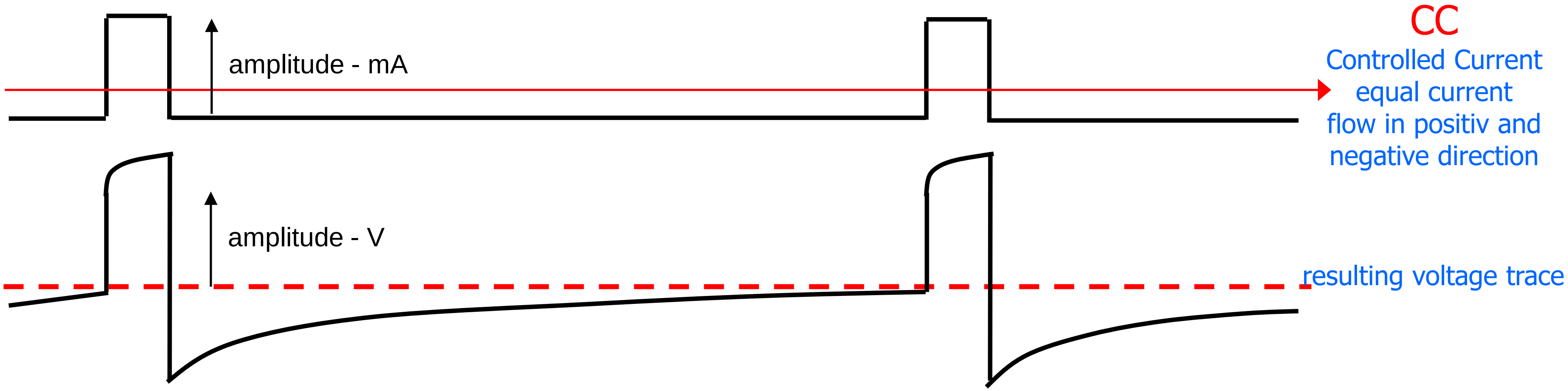
monophasic pulse shape

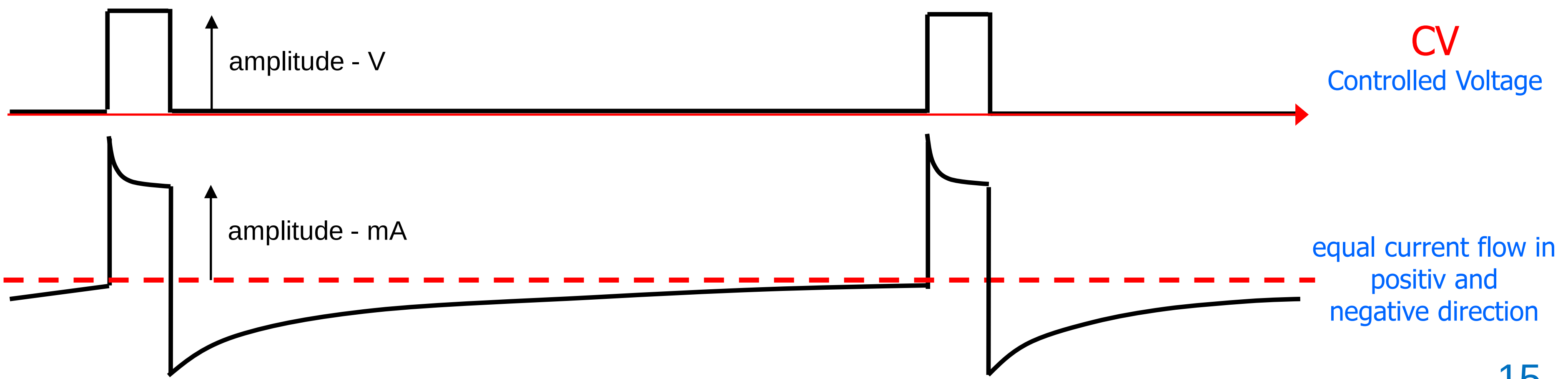


Cave: without DC-decoupling monophasic pulse trains have a DC-component !



DC-decoupling forces charge balance !

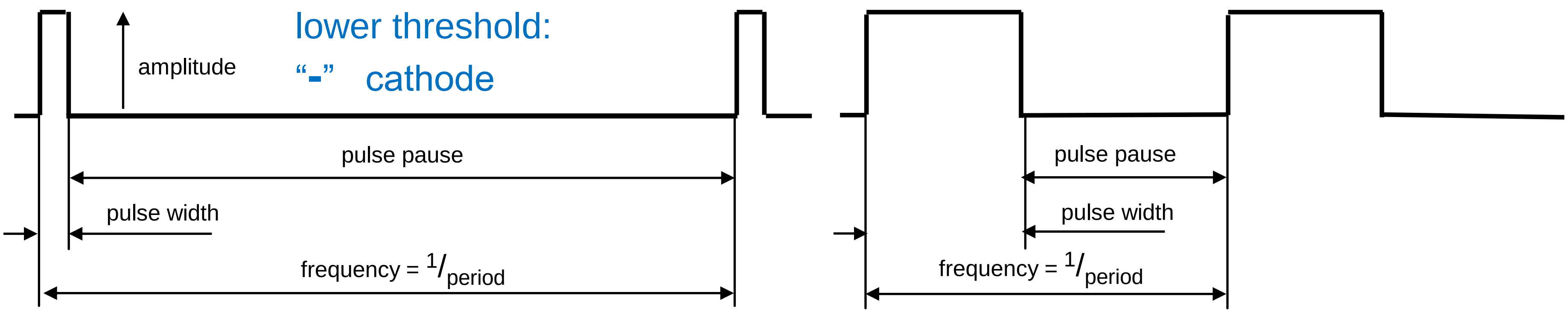




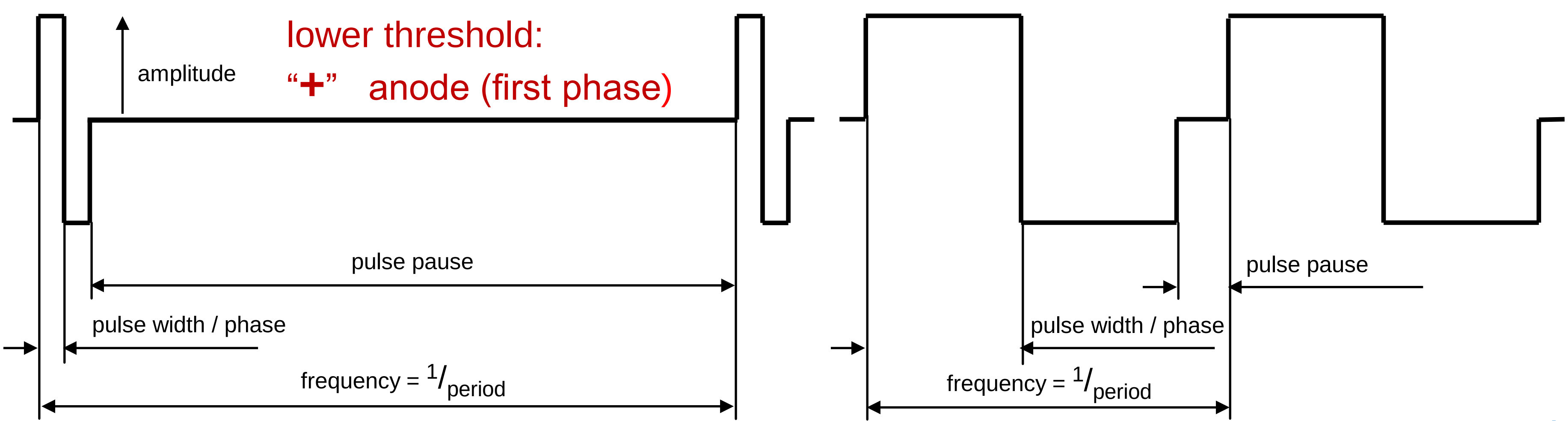
Nerve Stimulation

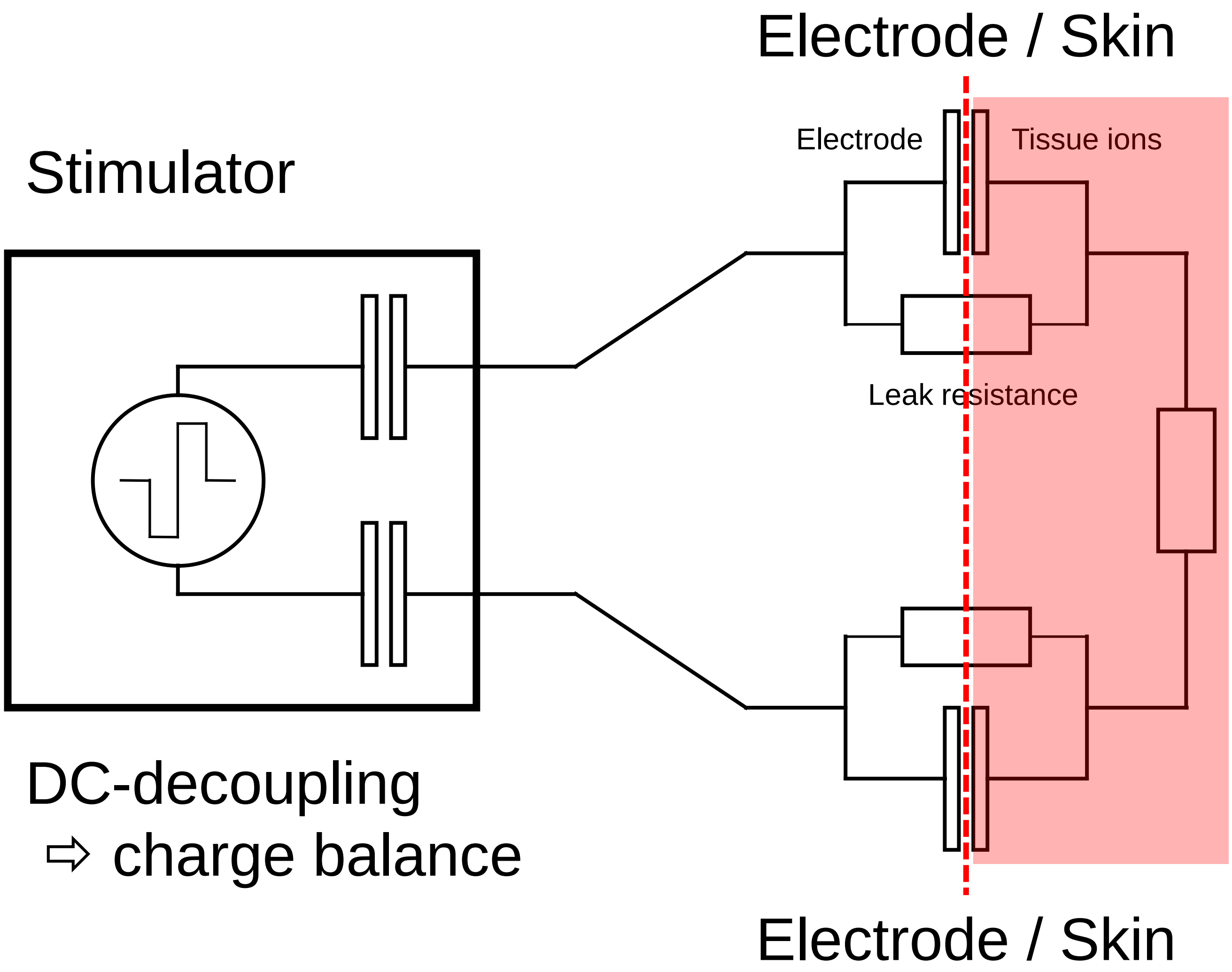
(Muscle Stimulation)

monophasic pulse shape



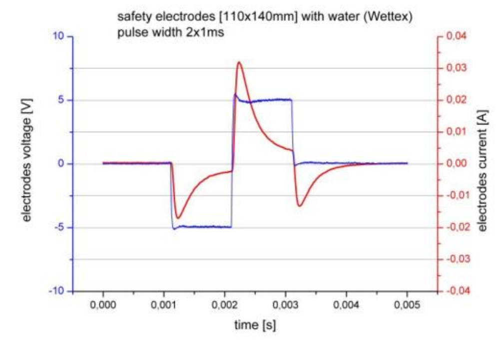
biphasic pulse shape



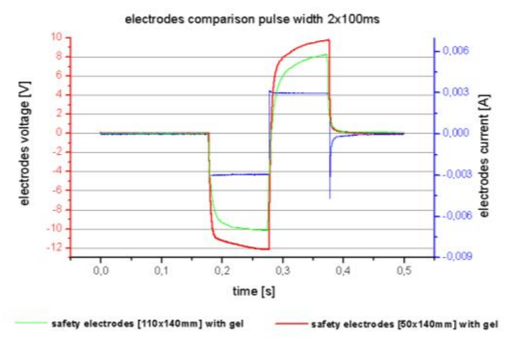


Electrode / Skin
Stimulator
Electrode
Tissue ions
Leak resistance
Subcutaneous tissue
DC-decoupling
⇨ charge balance
Electrode / Skin

CV



safety electrodes [110x140mm] with water (Wettex)
pulse width 2x1ms
electrodes voltage [V]
electrodes current [A]
time [s]



electrodes comparison pulse width 2x100ms
electrodes voltage [V]
electrodes current [A]
time [s]
safety electrodes [110x140mm] with gel
safety electrodes [50x140mm] with gel

CC

Juan Capistrano, CA, USA). The stimulation waveform was biphasic, rectangular, 1 ms pulses at a frequency of 30 Hz, filled with a carrier frequency of 10 kHz (Fig. 2) [17]. This permitted stimulation intensities of 80–120 milliamperes (mA) to be delivered to the skin over the cervical spinal cord without discomfort.

Inanici F, et al.
Transcutaneous Electrical Spinal Stimulation Promotes Long-Term Recovery of Upper Extremity Function in Chronic Tetraplegia.
IEEE Trans Neural Syst Rehabil Eng. 2018 Jun;;26(6):1272-1278

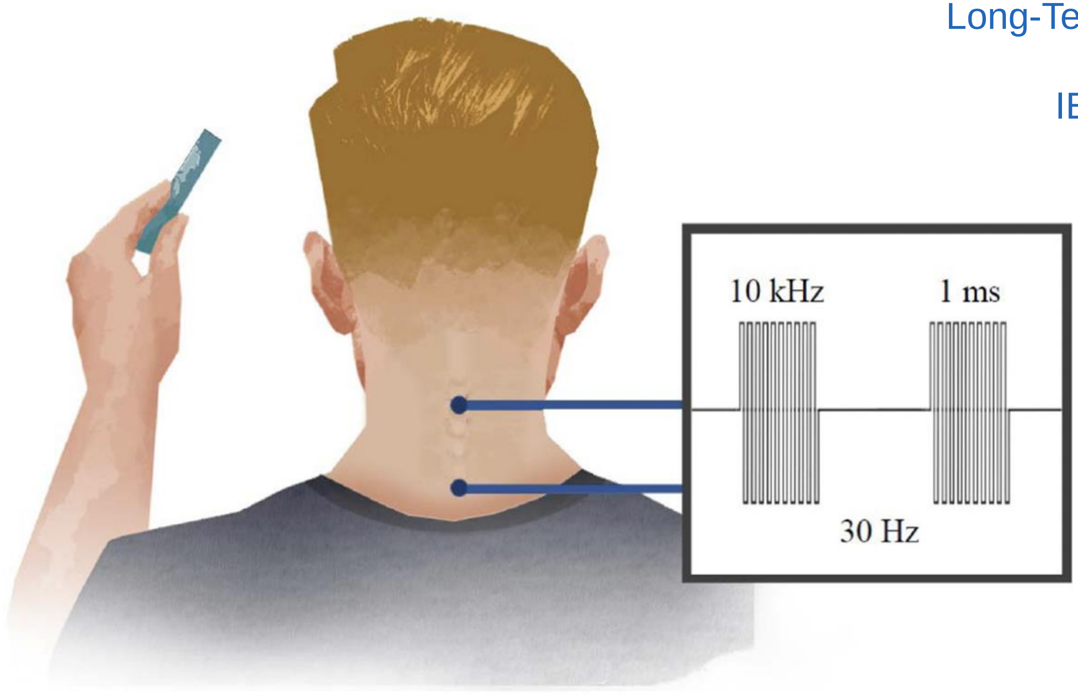
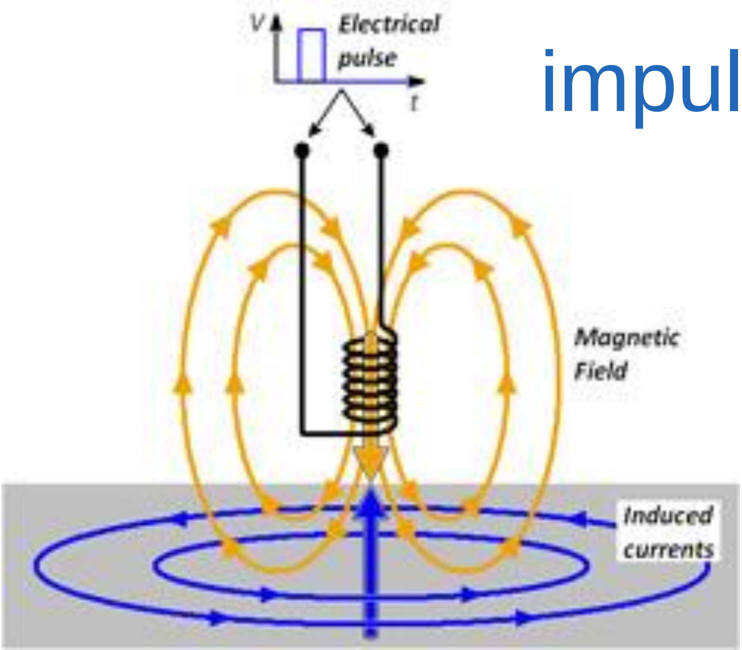
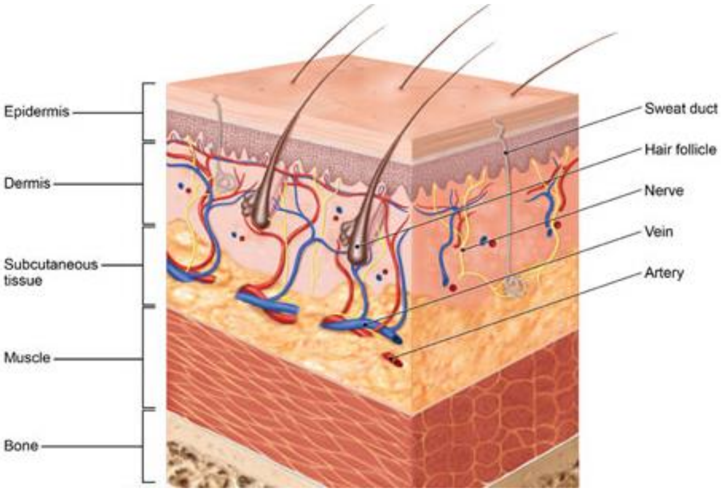


Fig. 2.
Schematic of the intervention showing electrical cervical spinal stimulation applied to the surface of the skin via electrodes placed midline at C3–4 and C6–7 bony landmarks. (Inset) Biphasic, rectangular, 1 ms pulses are delivered at a frequency of 30 Hz. Each pulse is filled with a carrier frequency of 10 kHz to permit stimulation intensities of 80–120mA to pass through the skin and reach the spinal cord without discomfort.

Stimulation was delivered via two 2.5 cm round electrodes placed midline at C3–4 and C6–7 spinous processes as cathodes and two 5 × 10 cm rectangular plates (Axelgaard Manufacturing Co., Ltd., USA) placed symmetrically over the iliac crests as anodes. A total of 1451 minutes of stimulation was applied over the five weeks (mean duration was 60 ± 20 minutes/session, range 25 – 120 minutes/session).

impulses - up to 2 Tesla

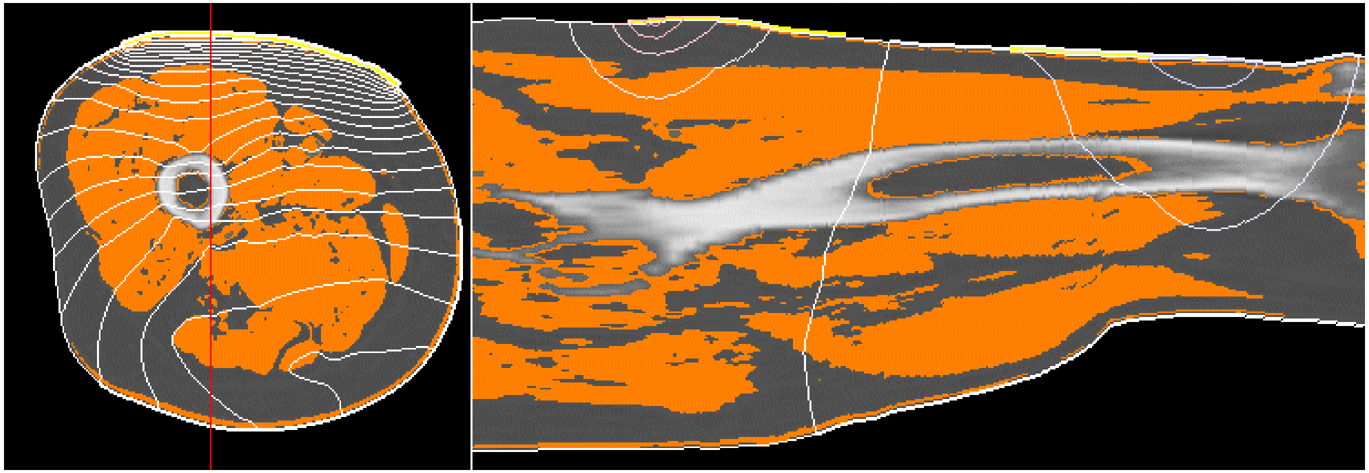




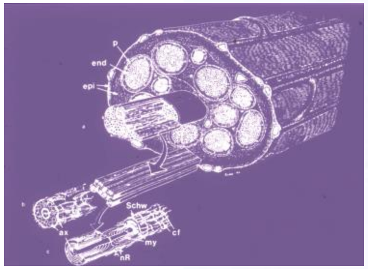
FMS

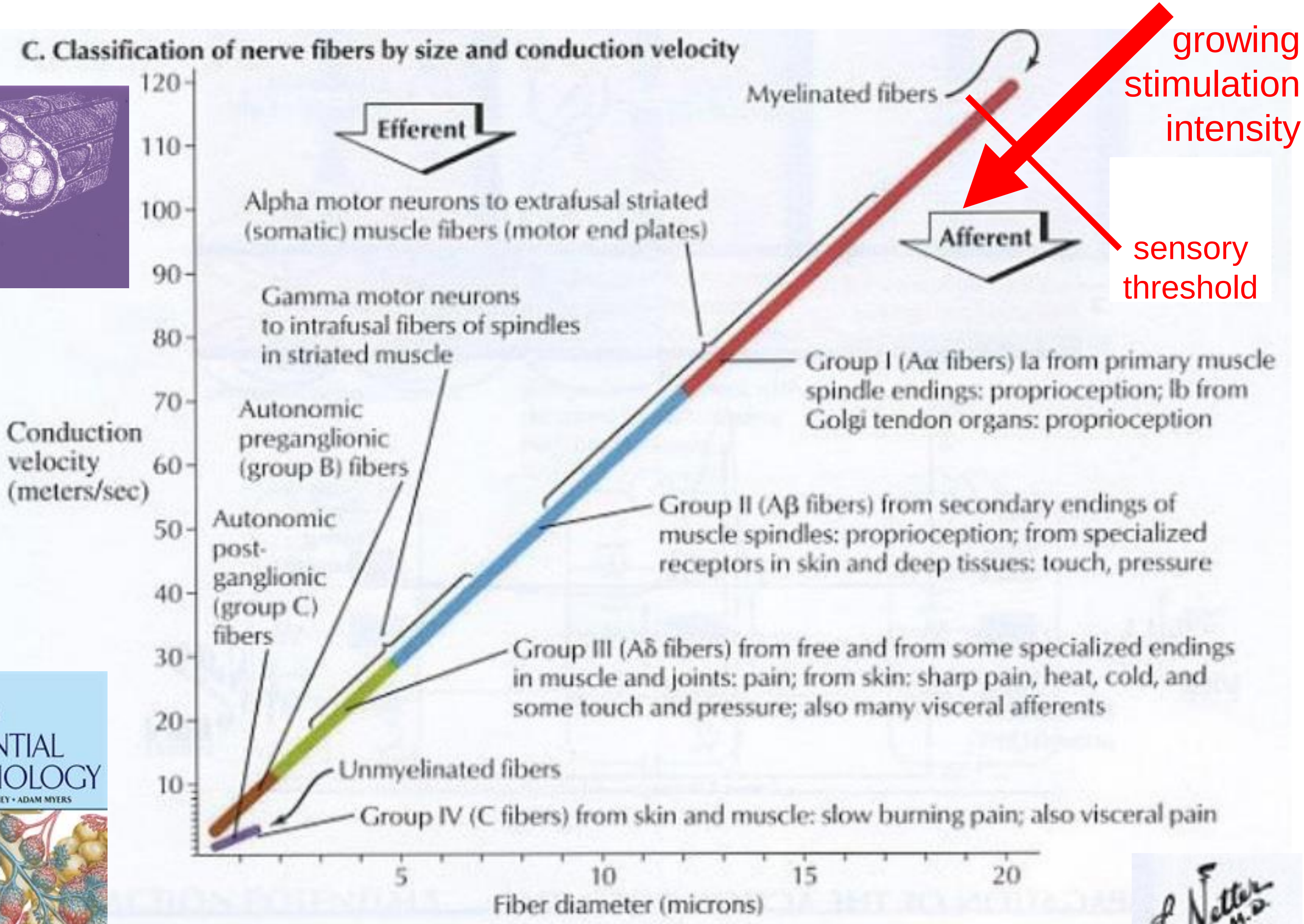
cave : “induction heating” !

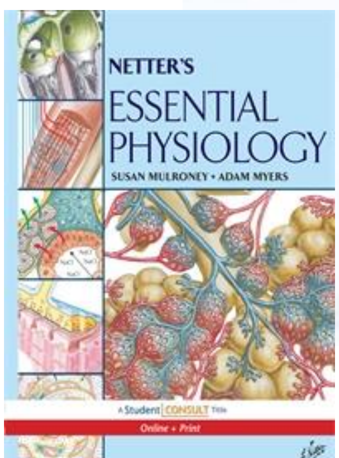
FES



Afferent Neurons




C. Classification of nerve fibers by size and conduction velocity
Conduction velocity (meters/sec)
120
110
100
90
80
70
60
50
40
30
20
10
Fiber diameter (microns)
5
10
15
20
Efferent
Afferent
Myelinated fibers
Unmyelinated fibers
Alpha motor neurons to extrafusal striated (somatic) muscle fibers (motor end plates)
Gamma motor neurons to intrafusal fibers of spindles in striated muscle
Autonomic preganglionic (group B) fibers
Autonomic post-ganglionic (group C) fibers
Group I (Aα fibers) Ia from primary muscle spindle endings: proprioception; Ib from Golgi tendon organs: proprioception
Group II (Aβ fibers) from secondary endings of muscle spindles: proprioception; from specialized receptors in skin and deep tissues: touch, pressure
Group III (Aδ fibers) from free and from some specialized endings in muscle and joints: pain; from skin: sharp pain, heat, cold, and some touch and pressure; also many visceral afferents
Group IV (C fibers) from skin and muscle: slow burning pain; also visceral pain
growing stimulation intensity
sensory threshold


NETTER'S
ESSENTIAL PHYSIOLOGY
SUSAN MULRONEY • ADAM MYERS

If we have an idea on fiber recruitment –

- what about neural processing / control of movement ?

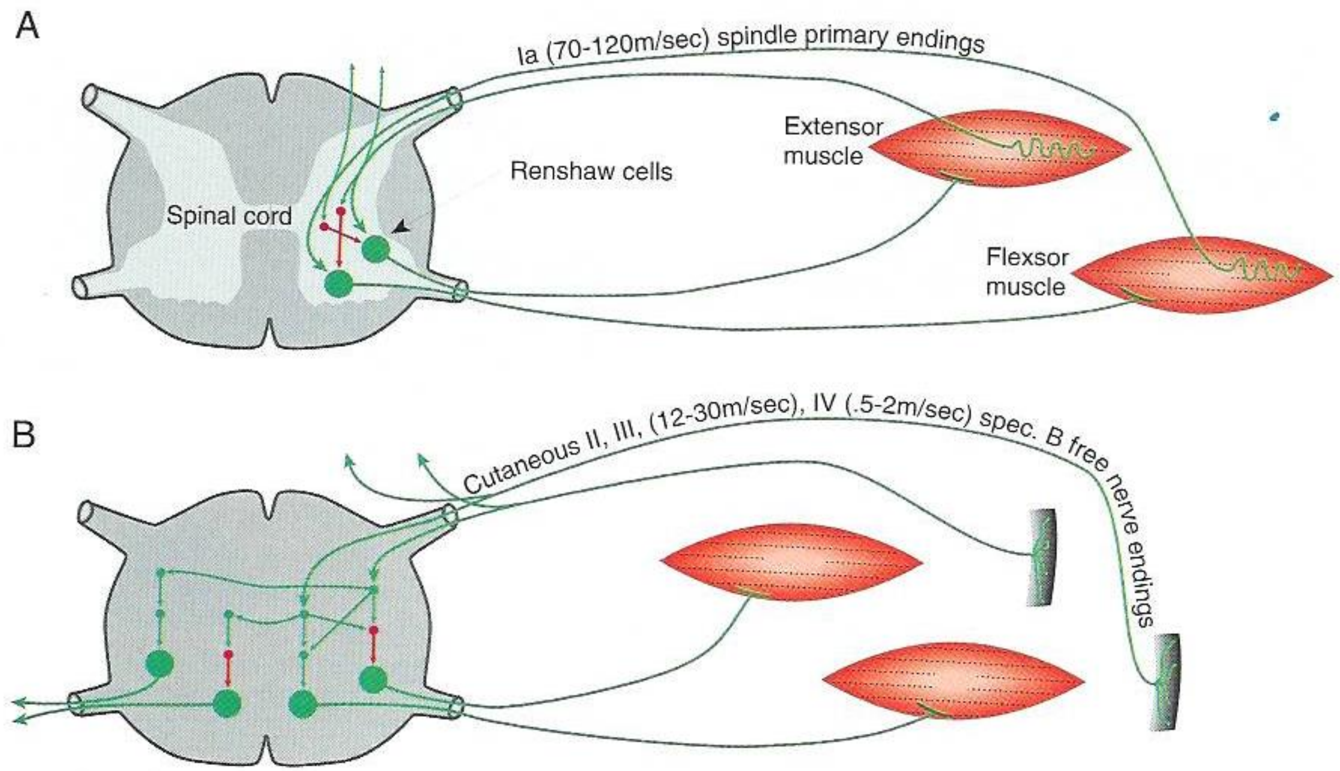
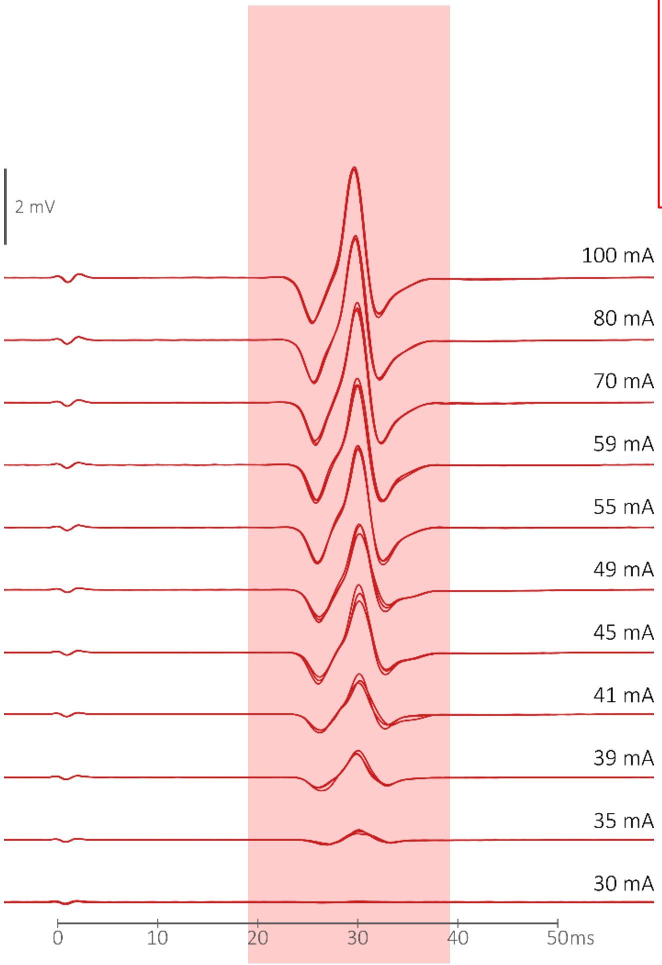


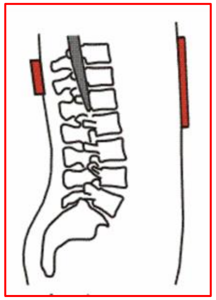
FIGURE 29.3 Circuitry for segmental spinal reflexes. Ia spindle reflexes are activated by stretch of the muscle and cause excitation of that muscle and its synergists and reciprocal inhibition of its antagonists. Skin reflexes (activated by a noxious stimulus) may cause withdrawal of the limb away from the stimulus with a supporting reaction in the opposite limb. Adapted from Thach and Montgomery, *Neurobiology of Disease*, Oxford University Press, New York, 1990.

Electrical stimulation of peripheral nerves or posterior roots can activate monosynaptic and polysynaptic reflex arcs

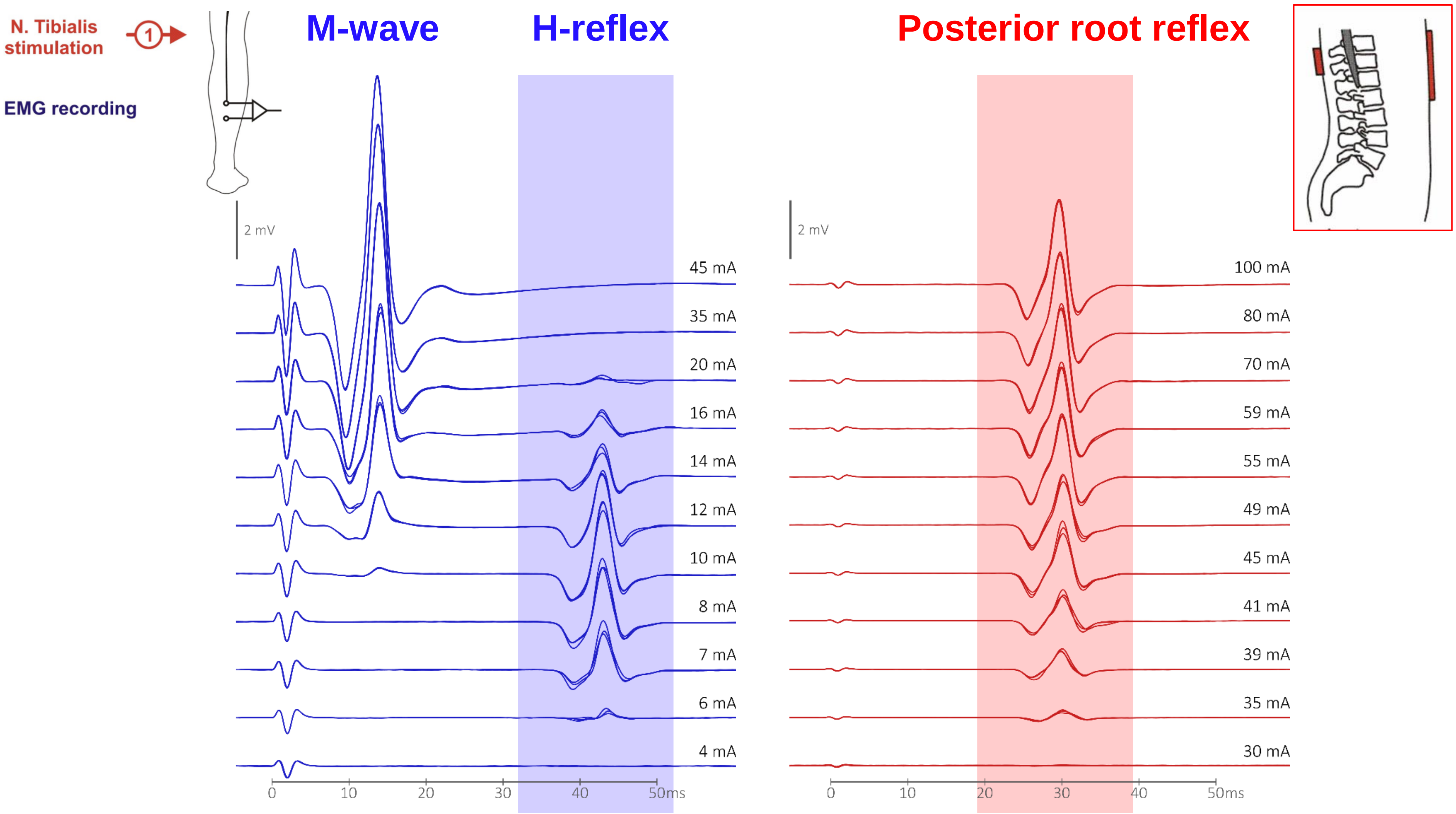
H-reflex and posterior root reflex in the soleus muscle

Posterior root reflex

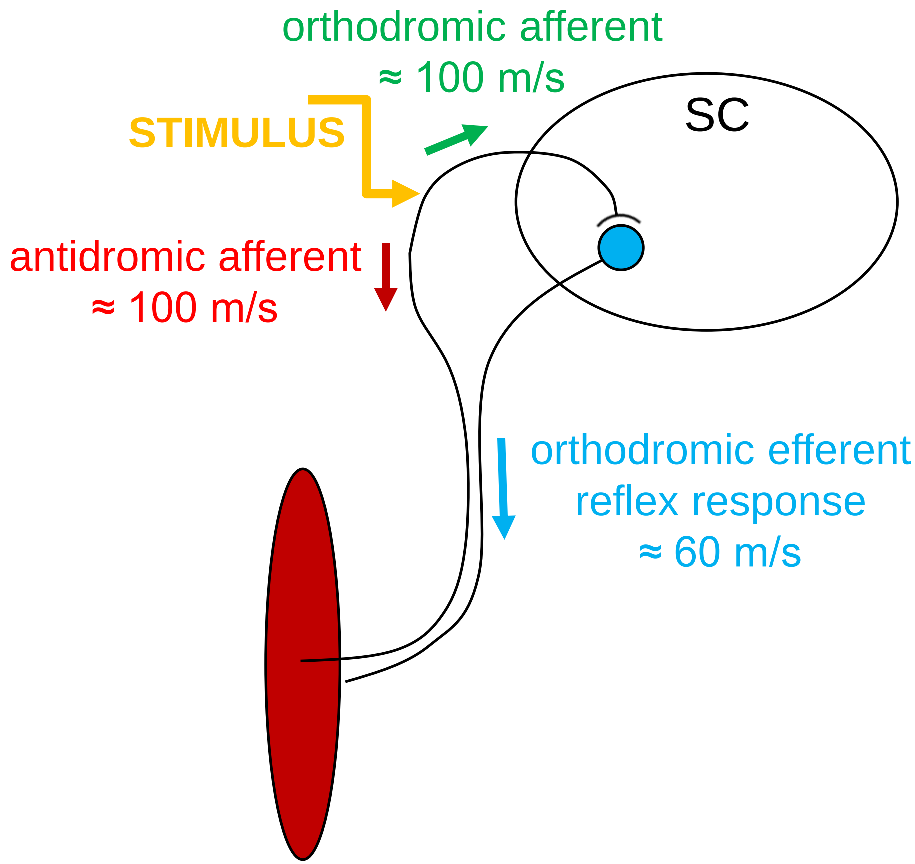




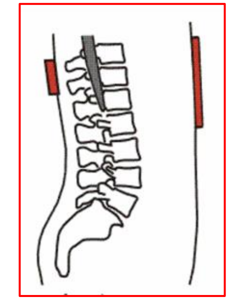
H-reflex and posterior root reflex in the soleus muscle

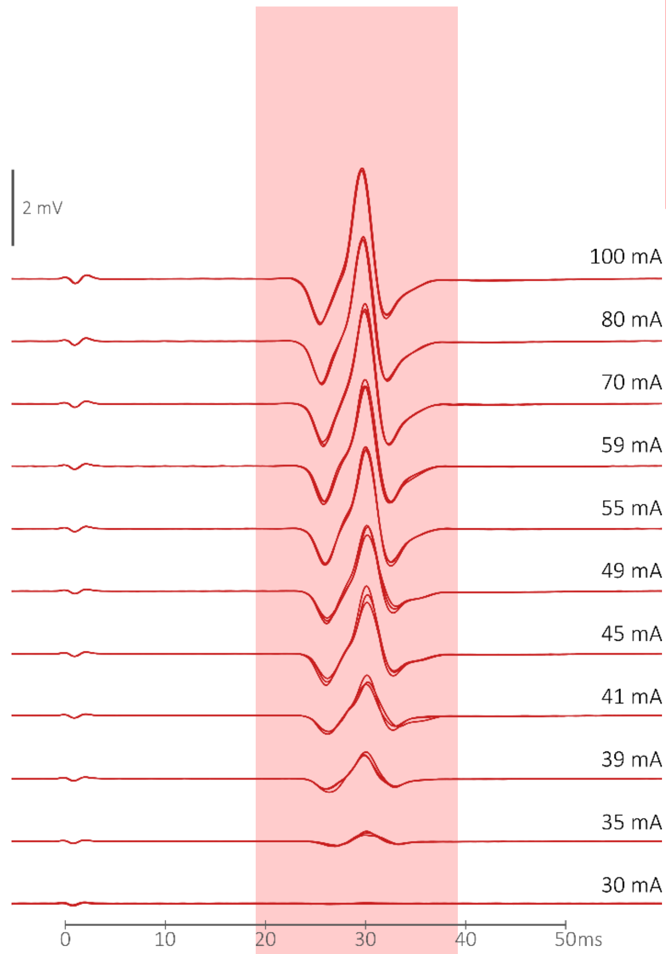


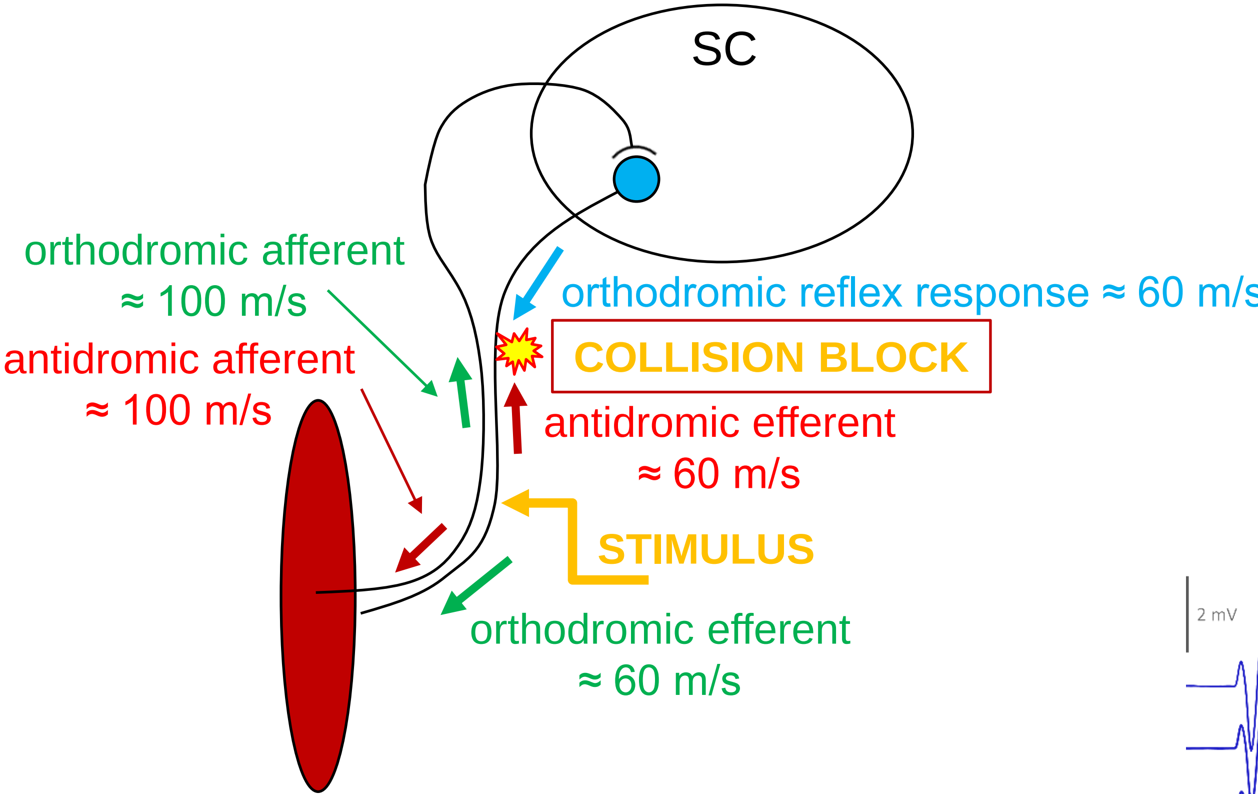
by Matthias Krenn

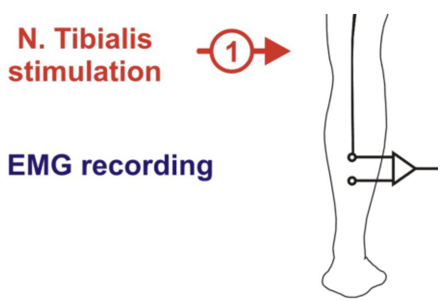


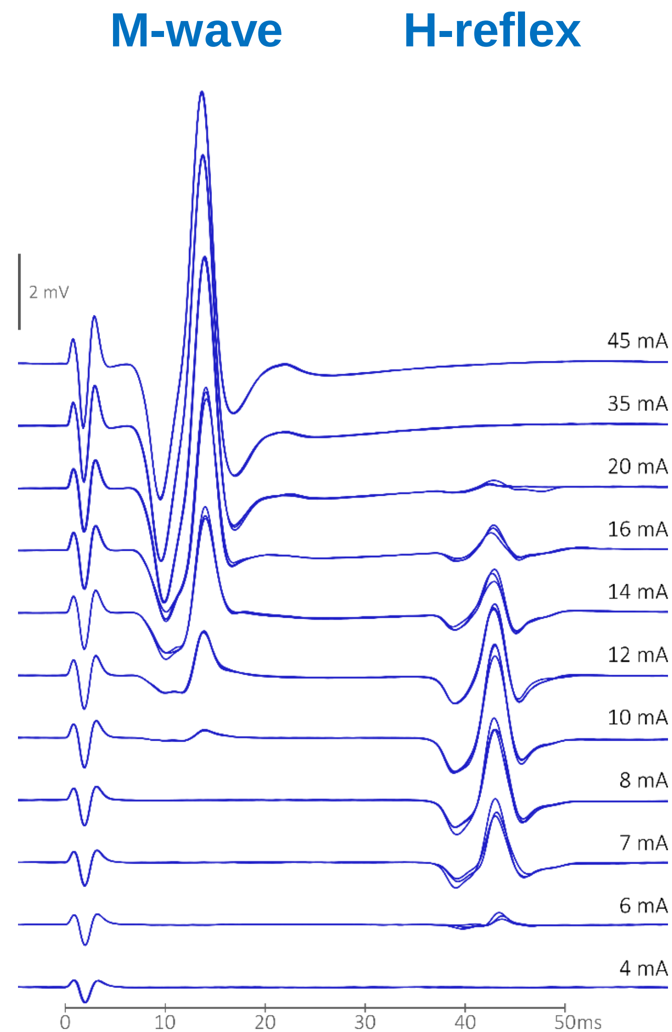
Posterior root reflex






SC
orthodromic afferent
≈ 100 m/s
antidromic afferent
≈ 100 m/s
orthodromic reflex response ≈ 60 m/s
COLLISION BLOCK
antidromic efferent
≈ 60 m/s
STIMULUS
orthodromic efferent
≈ 60 m/s

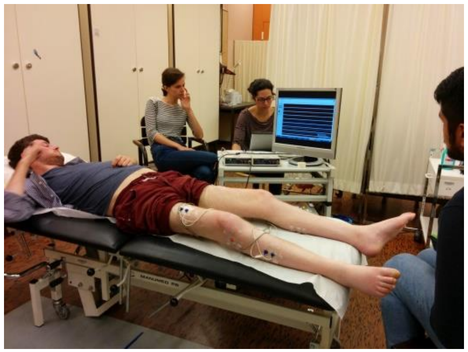

N. Tibialis
stimulation
1
EMG recording

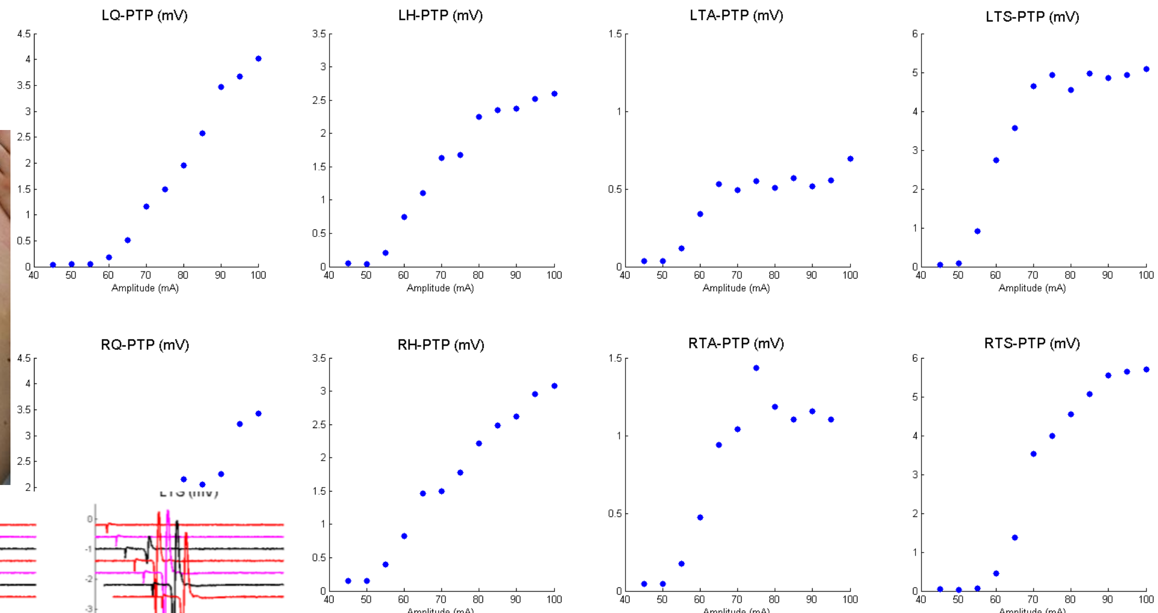

M-wave
H-reflex
2 mV
45 mA
35 mA
20 mA
16 mA
14 mA
12 mA
10 mA
8 mA
7 mA
6 mA
4 mA
0
10
20
30
40
50ms

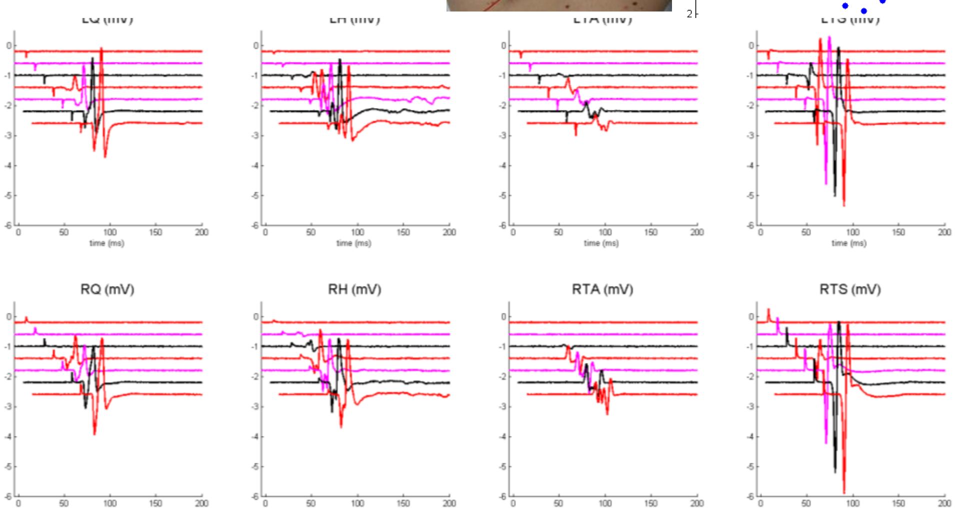
WWTF

LS11-057

Augmentation of residual neural control by non-invasive spinal cord stimulation to modify spasticity in spinal cord injured people







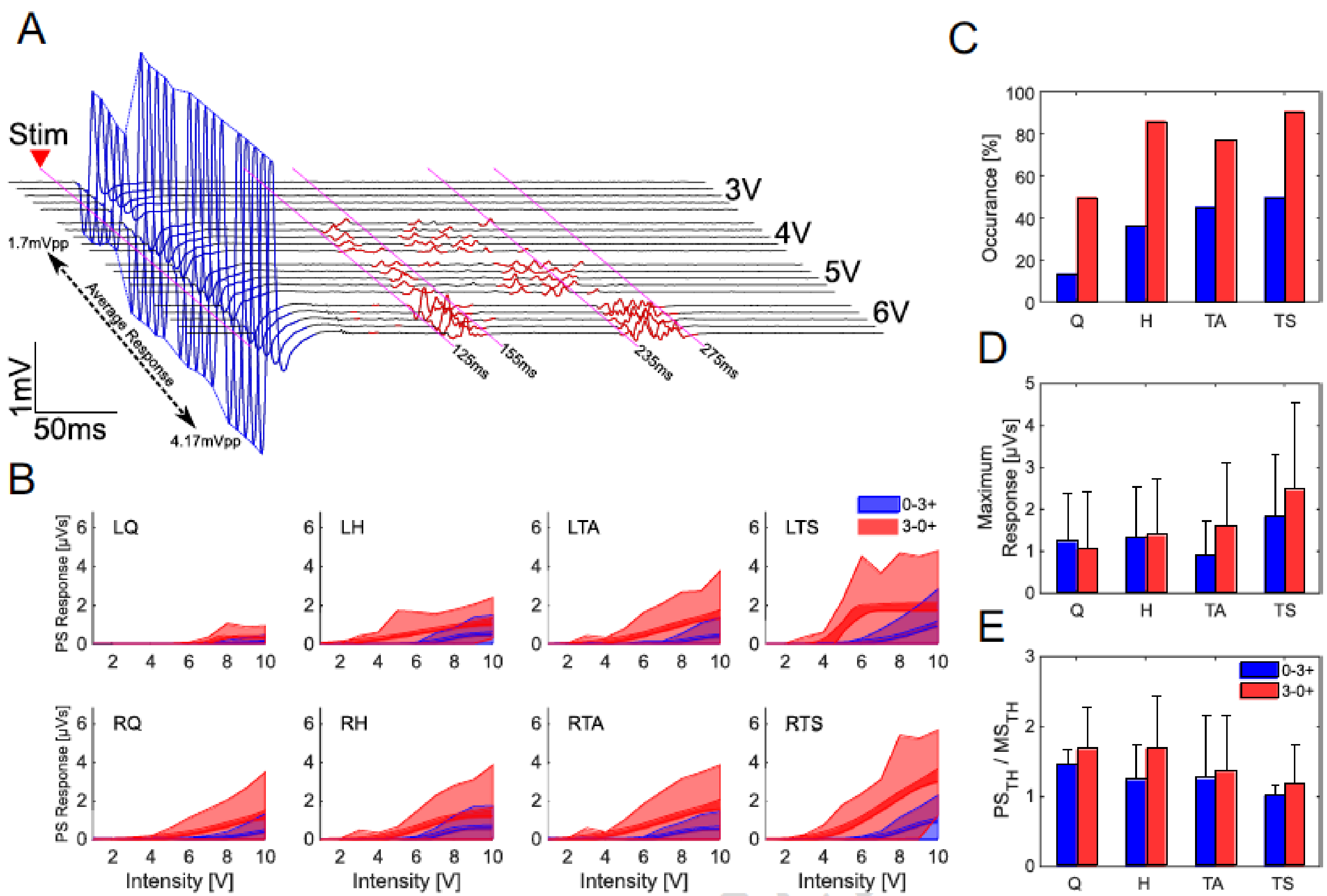
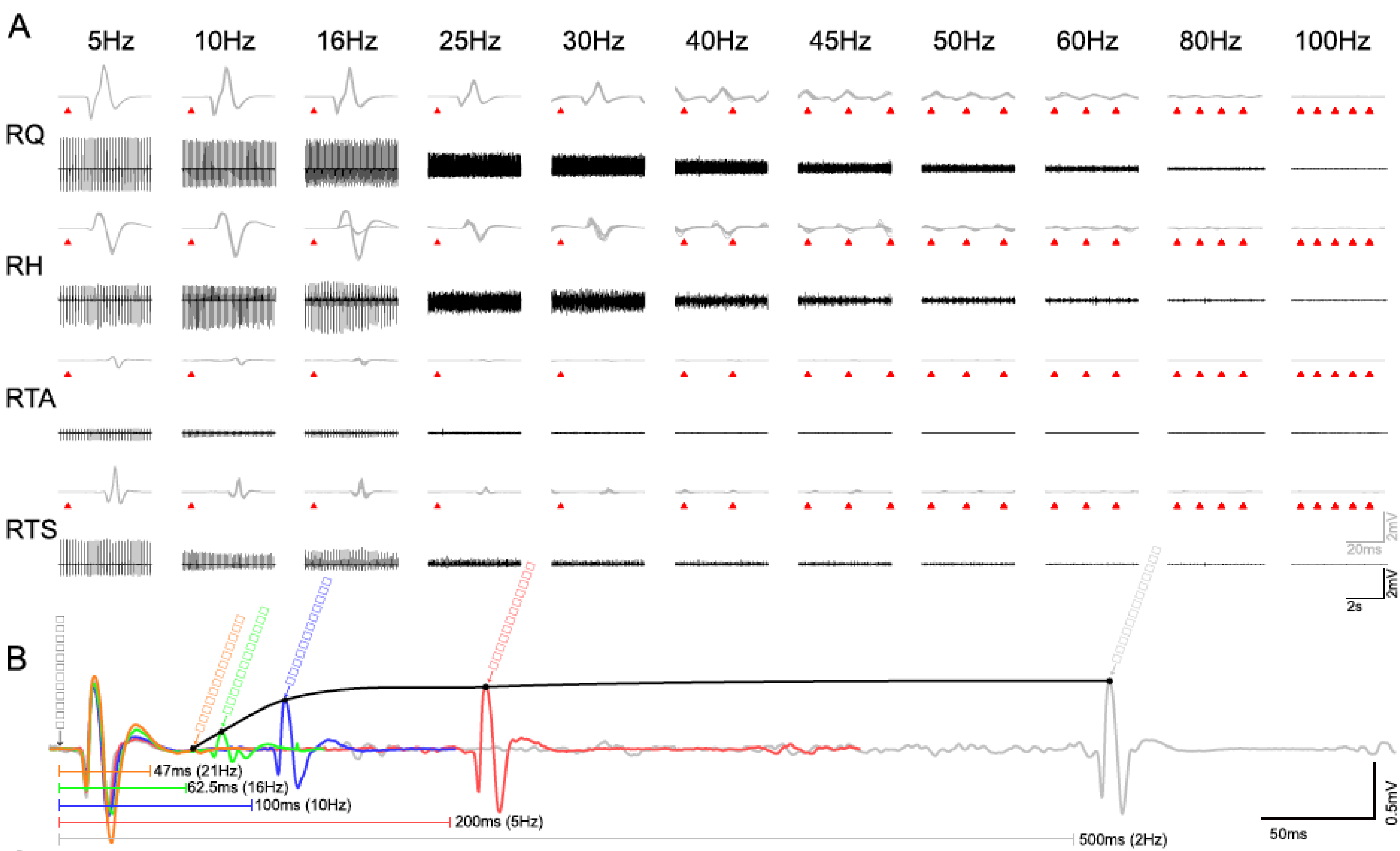
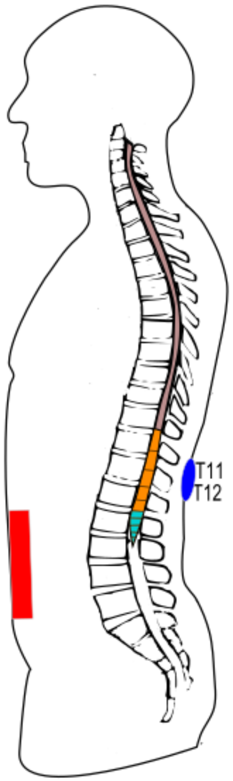
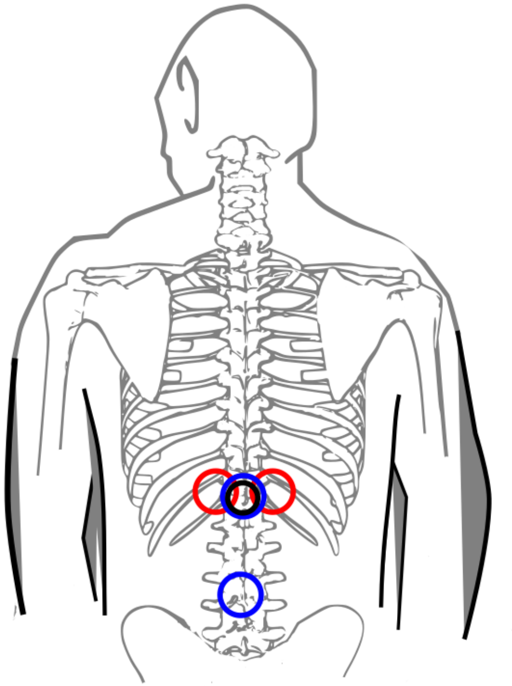


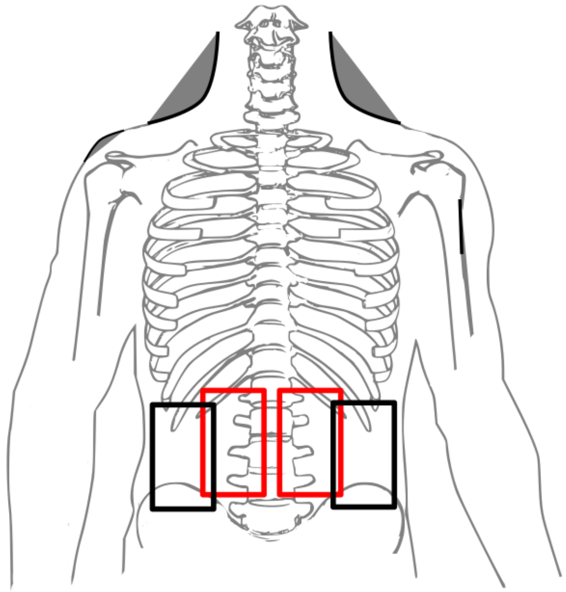
Fig. 2 Characteristics of the Polysynaptic responses. **A** Exemplary responses from RH on SID 10 with 3–0 + electrode configuration. The sEMG show in blue the short-latency (monosynaptic) responses, appearing after ~7 ms, and, in red, the long-latency (polysynaptic) responses, which appear in two groups with latencies of around 130 ms and 260 ms. Both types of responses evolve when the stimulus intensity is increased. **B** Estimated recruitment curve for eight subjects (SID2 and SID8 excluded), showing the 95% confidence interval for the mean amplitude (narrowband) and standard deviation of the samples at each intensity (shadowed area) for the lower limbs with both electrode configurations. **C** Shows the percentage of polysynaptic activity occurrence on each muscle group (both sides grouped together). **D** shows the mean maximum response for each muscle and electrode configuration (SID8 excluded due to continuous activity not associated with the stimulation). Finally, **E** Shows the relative threshold of the polysynaptic activity compared to the monosynaptic activity


A
5Hz
10Hz
16Hz
25Hz
30Hz
40Hz
45Hz
50Hz
60Hz
80Hz
100Hz
RQ
RH
RTA
RTS
20ms
2mV
2s
2mV
B
47ms (21Hz)
62.5ms (16Hz)
100ms (10Hz)
200ms (5Hz)
500ms (2Hz)
50ms
0.5mV

Surface electrode configuration







Stimulation electrode

- Dimension: 2 x 5 cm

Reference electrode

- Dimension: 8 x 13 cm

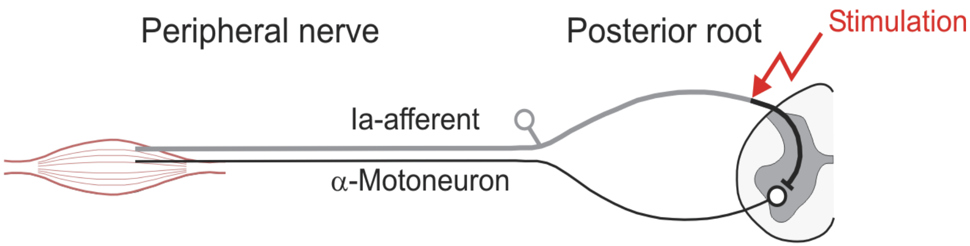
Transversal setup

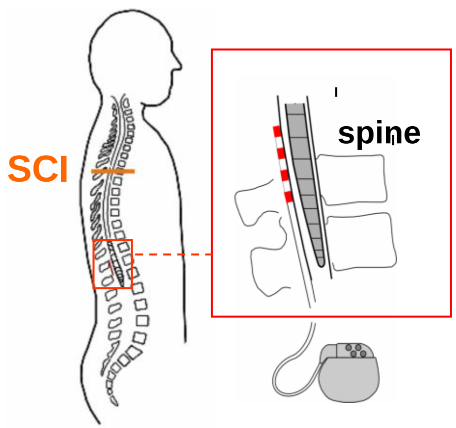
- Lower thresholds
- Flexibility on reference electrode position
- necessary option for adipose persons

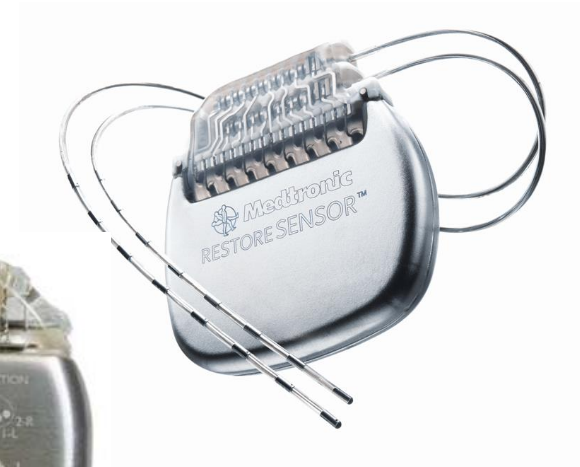
Bipolar setup

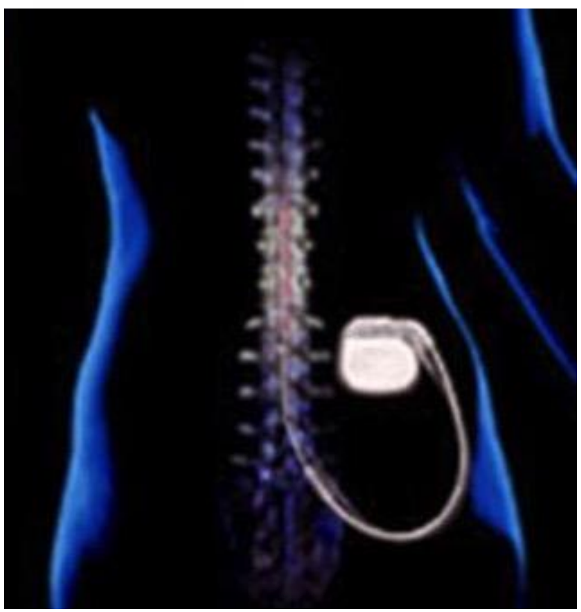
- Avoids abdominal muscle contractions
- Avoids issues with percutaneous catheters
- Minimize breathing problems

Examples for available sytems





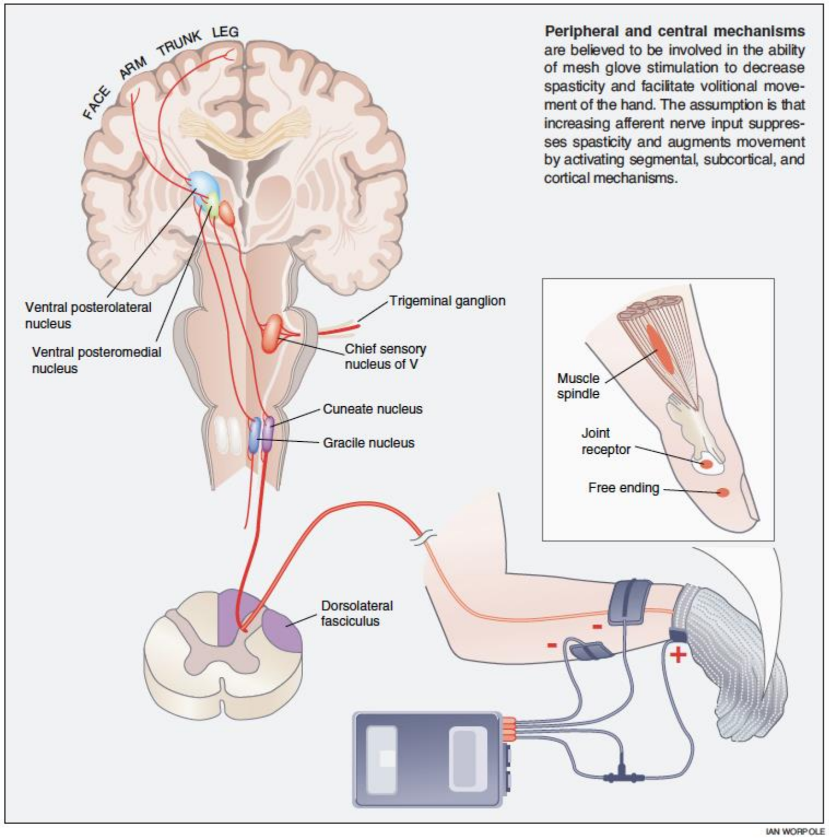




4-pole electrode
Pisces-Quad
3487A Medtronic
(T11/L1)

3625 Test
Stimulator or

implanted Itrel3
7425, Medtronic
2,1 – 120 Hz
0 – 12 V



EXOPULSE Mollii Suit
Stockholm, Sweden

EXOPULSE

ottobock.

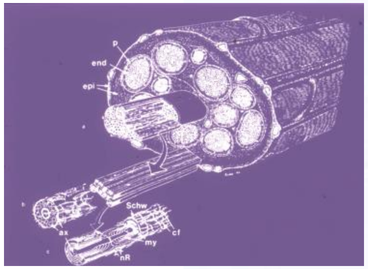
Mesh Glove Electrical Stimulation

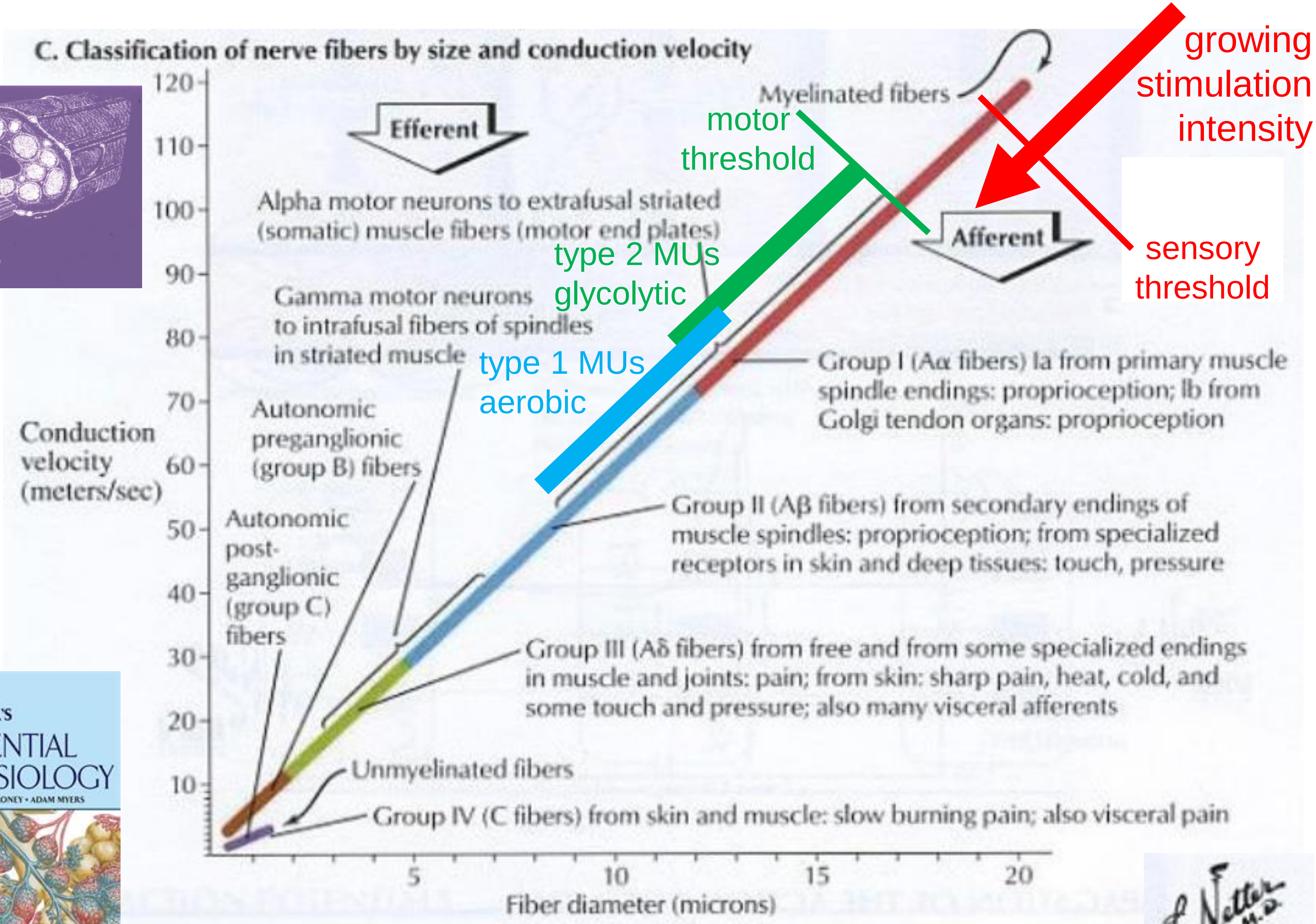
by M. Meta Dimitrijević, Nachum Soroker, and Fabian E. Pollo

SCIENCE & MEDICINE

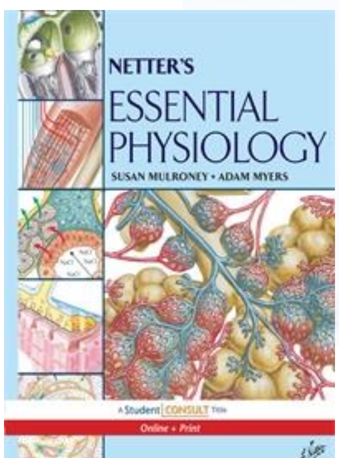
May/June 1996

Efferent Neurons





C. Classification of nerve fibers by size and conduction velocity
Conduction velocity (meters/sec)
120
110
100
90
80
70
60
50
40
30
20
10
5
10
15
20
Fiber diameter (microns)
Efferent
Afferent
Myelinated fibers
Unmyelinated fibers
Alpha motor neurons to extrafusal striated (somatic) muscle fibers (motor end plates)
Gamma motor neurons to intrafusal fibers of spindles in striated muscle
Autonomic preganglionic (group B) fibers
Autonomic post-ganglionic (group C) fibers
Group I (Aα fibers) Ia from primary muscle spindle endings: proprioception; Ib from Golgi tendon organs: proprioception
Group II (Aβ fibers) from secondary endings of muscle spindles: proprioception; from specialized receptors in skin and deep tissues: touch, pressure
Group III (Aδ fibers) from free and from some specialized endings in muscle and joints: pain; from skin: sharp pain, heat, cold, and some touch and pressure; also many visceral afferents
Group IV (C fibers) from skin and muscle: slow burning pain; also visceral pain
motor threshold
type 2 MUs glycolytic
type 1 MUs aerobic
growing stimulation intensity
sensory threshold



NETTER'S
ESSENTIAL PHYSIOLOGY
SUSAN MULRONEY • ADAM MYERS

SELECTIVITY

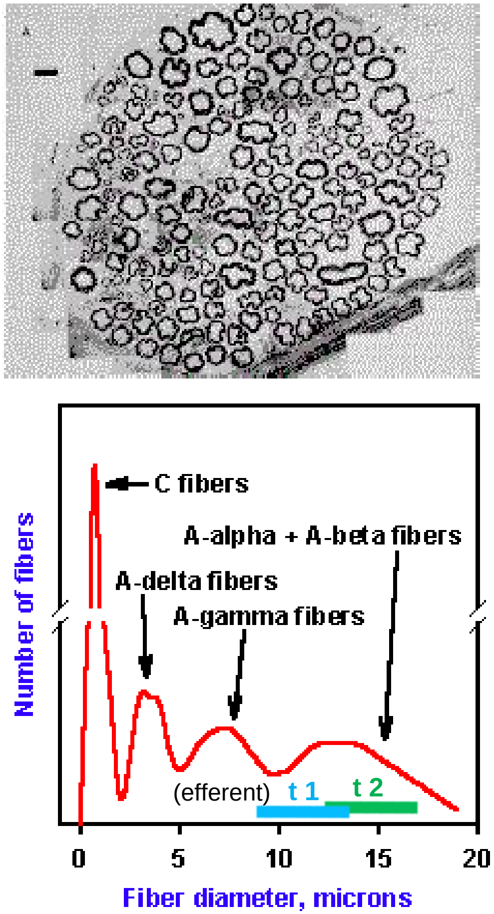
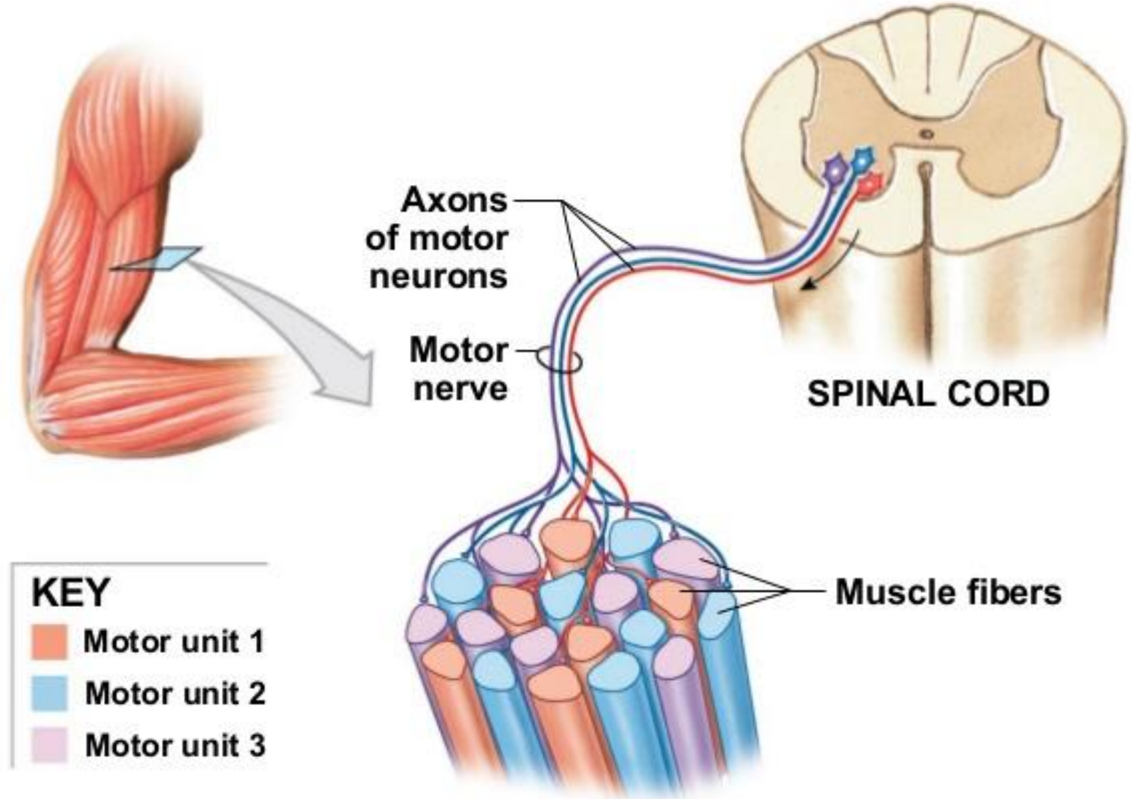


Fig. 5-13. Distribution of fibers within a peripheral nerve. Upper: A cross section of the posterior articular nerve of the cat showing fibers of different diameters. Calibration: 10 microns (Courtesy of F.J. Clark). Lower: A plot of the number of fibers of different diameters in a peripheral nerve. Note the predominance of fibers less than 2 microns in diameter.

Figure 9.12 The Arrangement of Motor Units in a Skeletal Muscle



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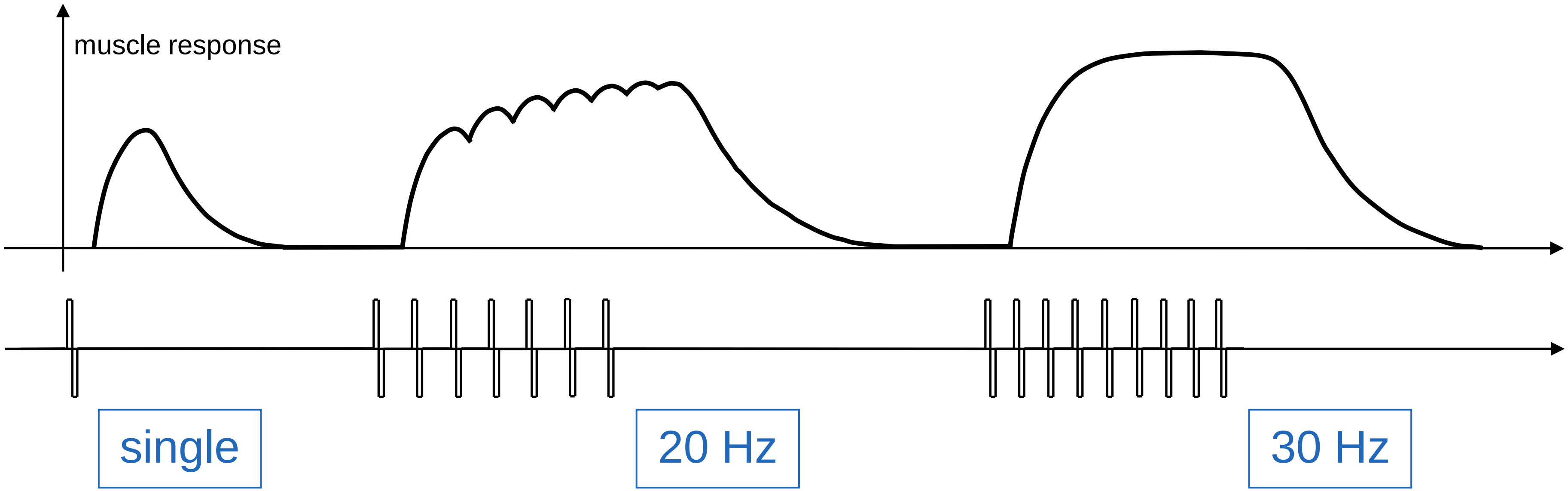
Michael D. Mann:
The Nervous System in Action
http://michaeldmann.net

MIXED NERVE, predominantly afferent

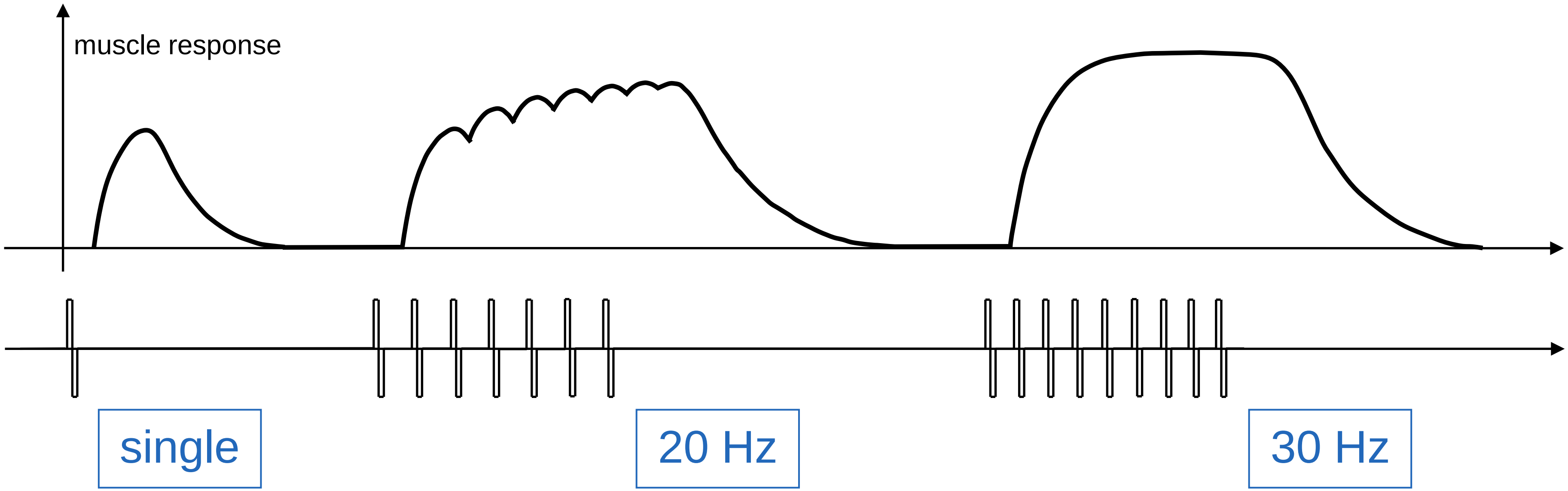
Glycolytic & aerobic motor units –
- mixed morphology in nerve and muscle

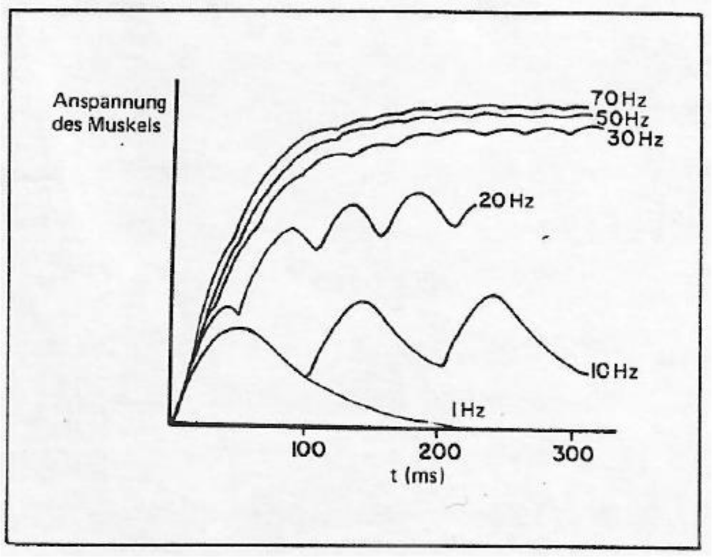
Control-, metabolic and biomechanical issues

Frequency dependence of neuromuscular stimulation: contraction force development versus muscle fatigue

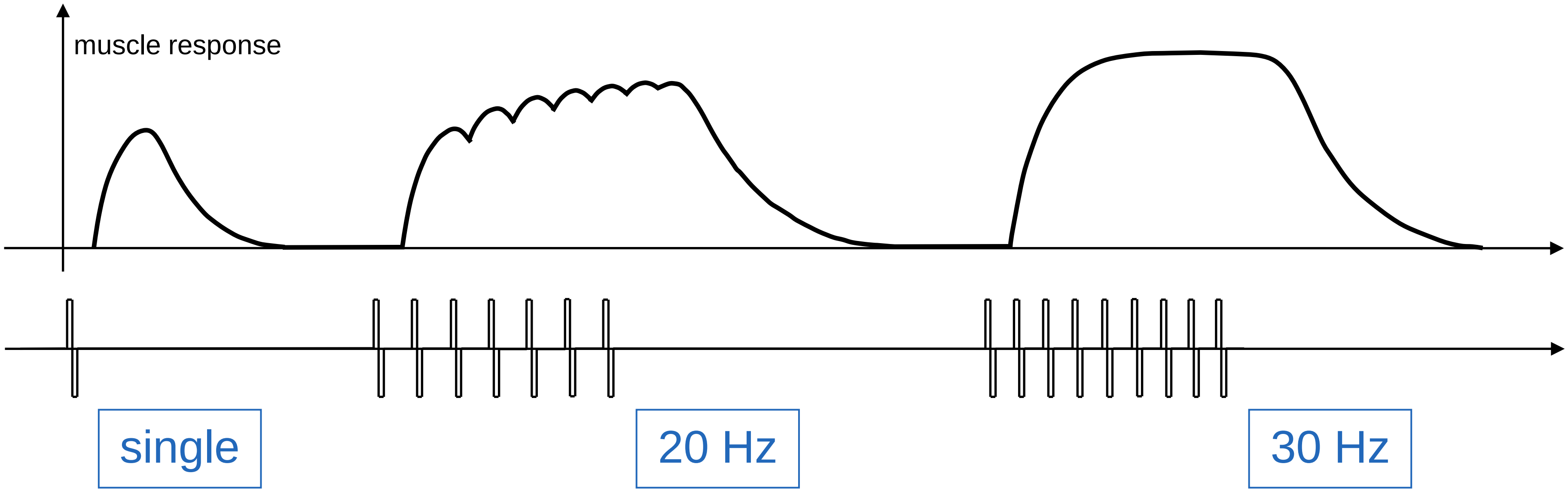


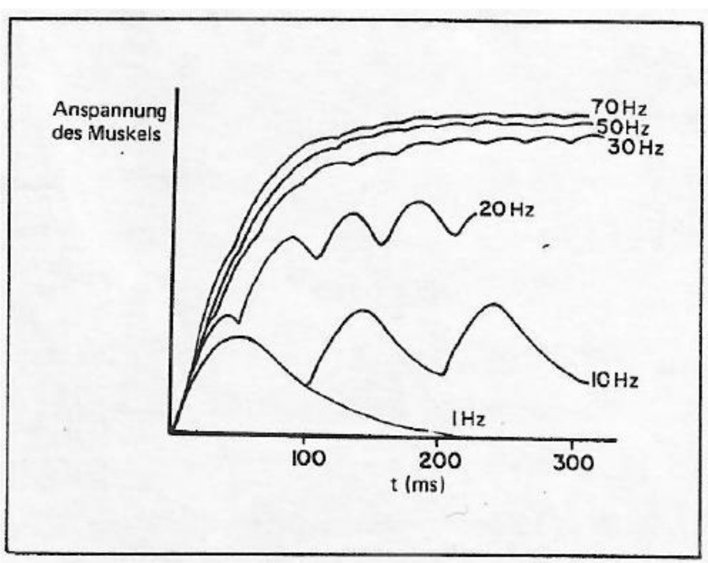
Frequency dependence of neuromuscular stimulation: contraction force development versus muscle fatigue

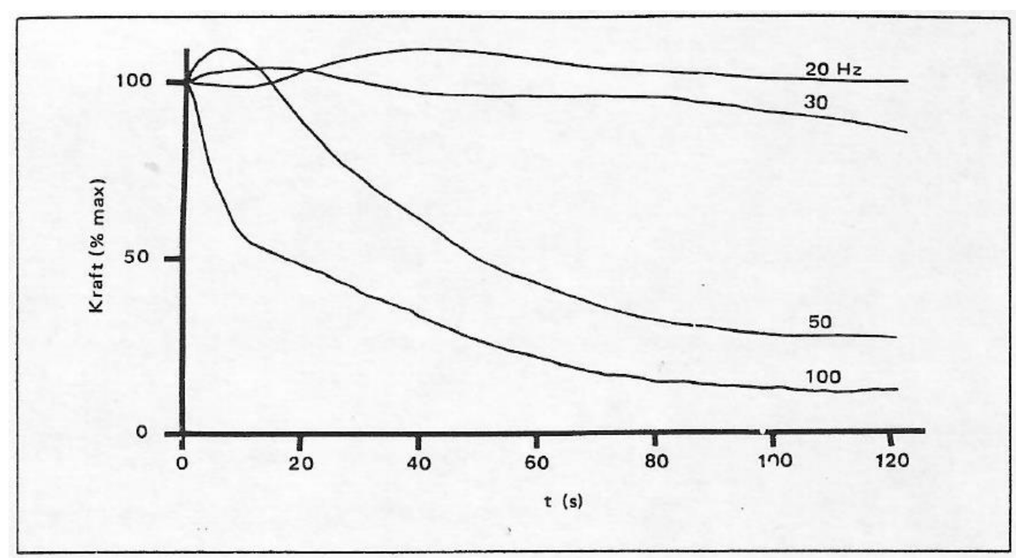




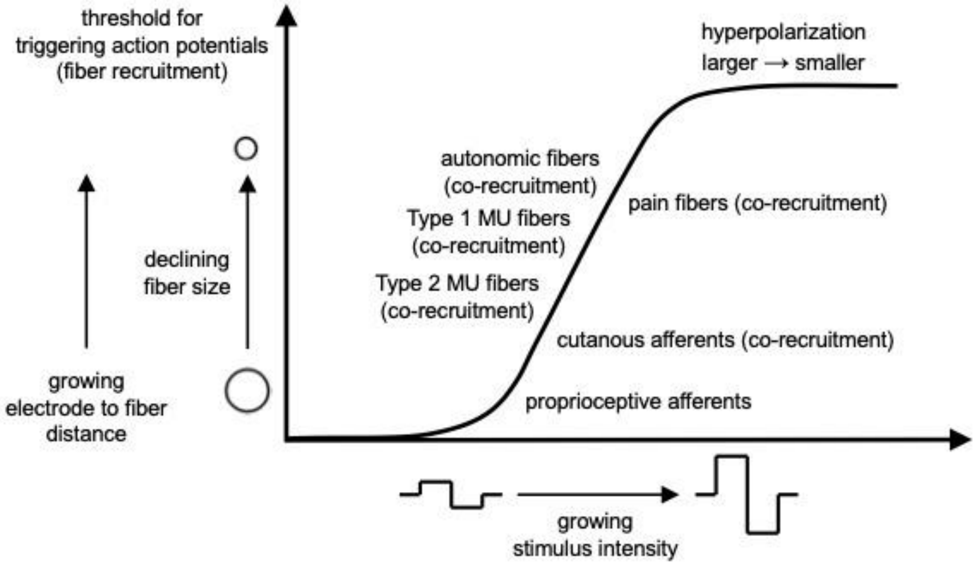
Frequency dependence of neuromuscular stimulation: contraction force development versus muscle fatigue







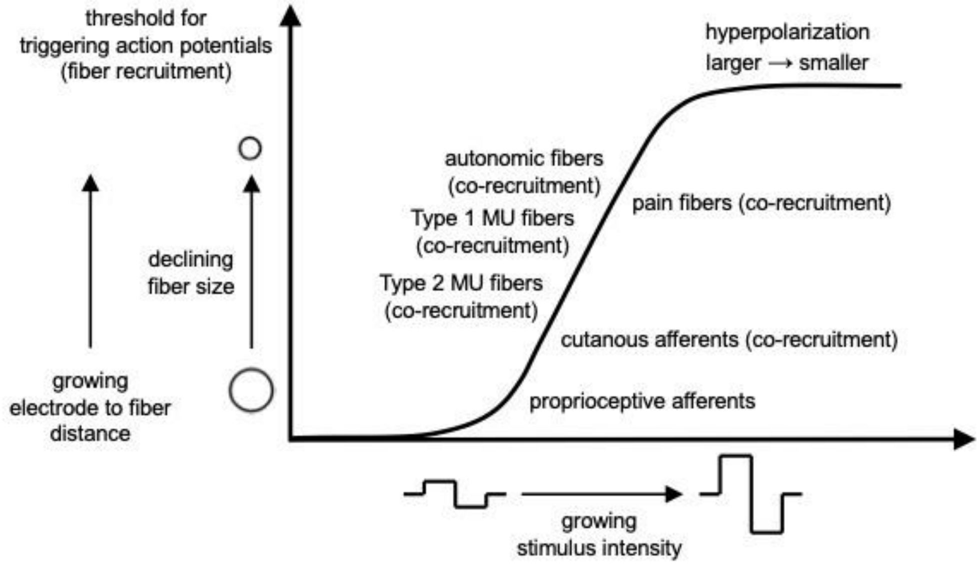
Summary
on interaction of stimuli with neuron pools

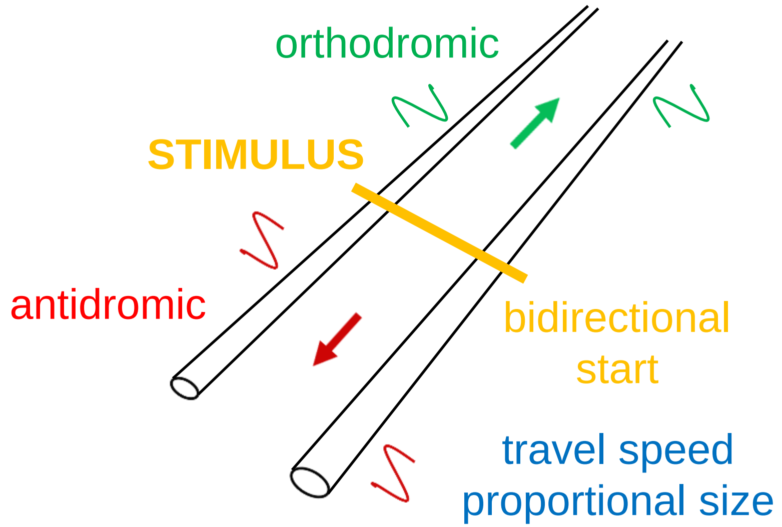


Stimulation interface – neuron activation

Size and distance dependent recruitment of fibers (in groups)

- Lowest threshold – large afferents
- Growing intensity co-recruits smaller fibers gradually

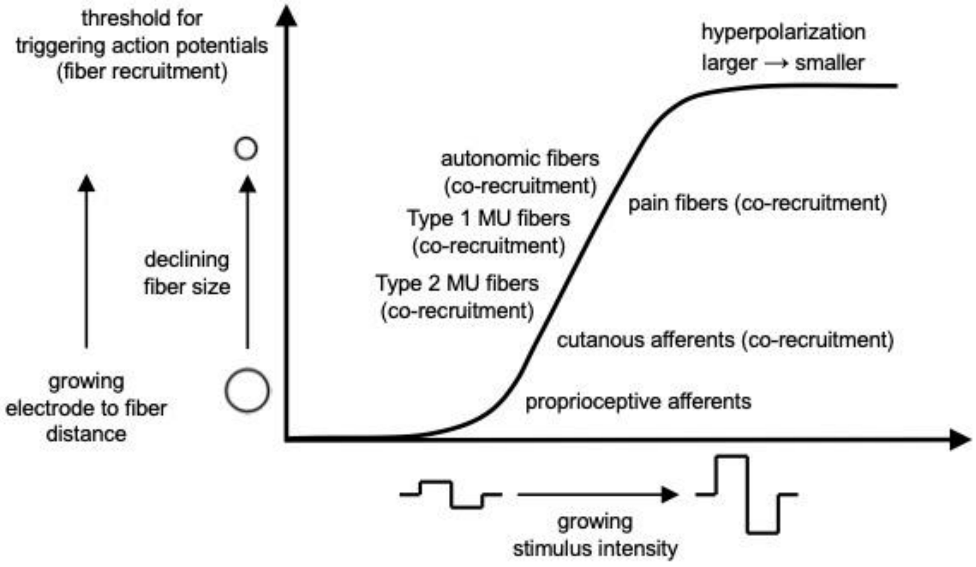


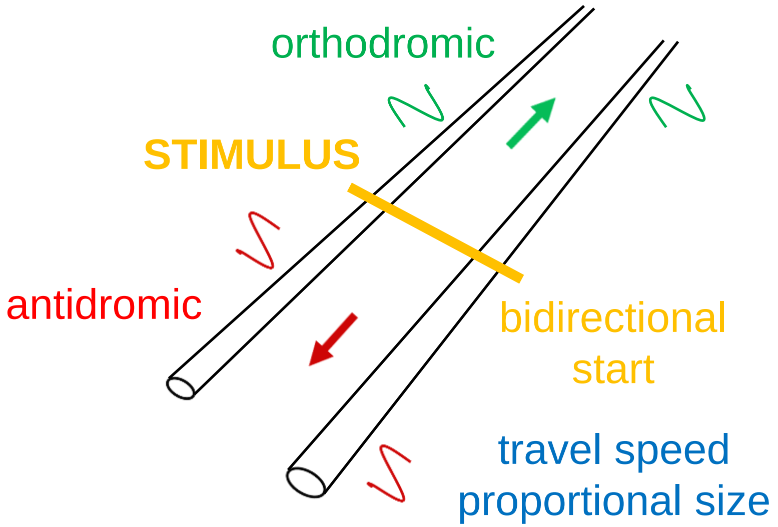


Stimulation interface – neuron activation

Size and distance dependent recruitment of fibers (in groups)
- Lowest threshold – large afferents
- Growing intensity co-recruits smaller fibers gradually

• Synchronous start – dispersion by distance and conduction velocity
– bidirectional





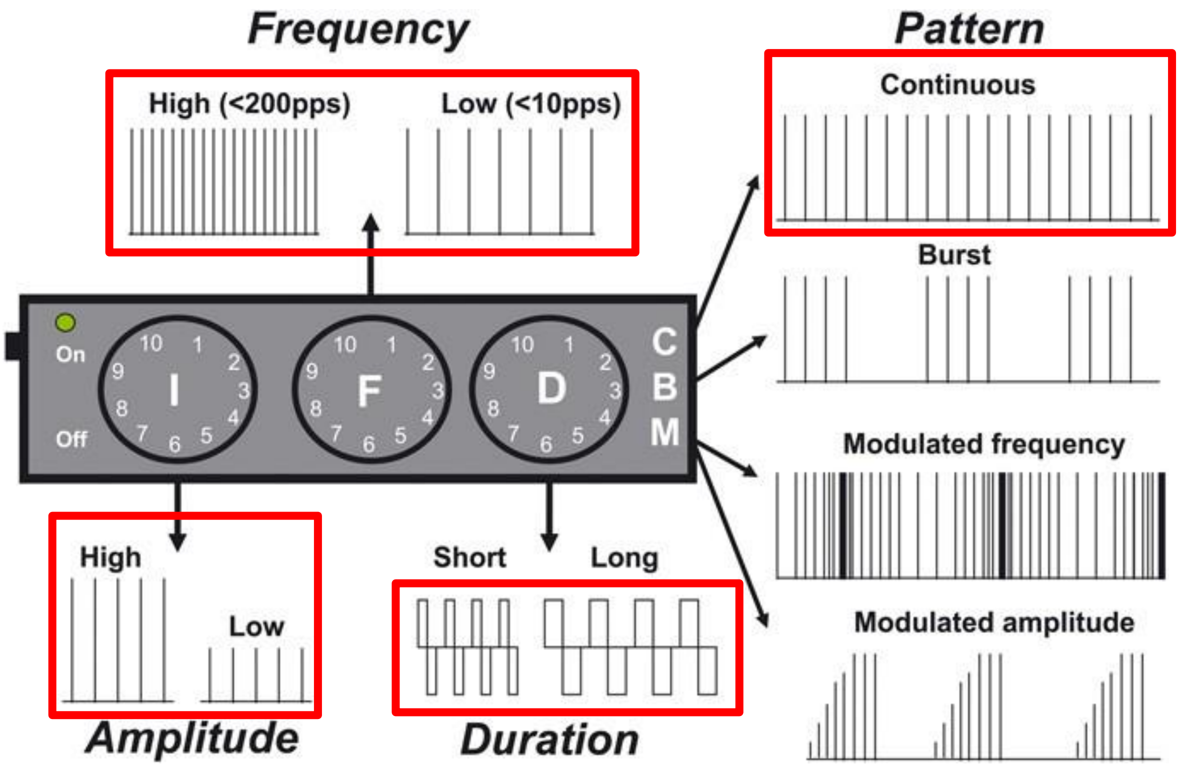
Stimulation interface – neuron activation

Size and distance dependent recruitment of fibers (in groups)
- Lowest threshold – large afferents
- Growing intensity co-recruits smaller fibers gradually

• Synchronous start – dispersion by distance and conduction velocity
– bidirectional

• Beyond recruitment with intensity - frequency influences
- central interneuron processing as afferent input
- contraction properties in efferent neuromuscular activation

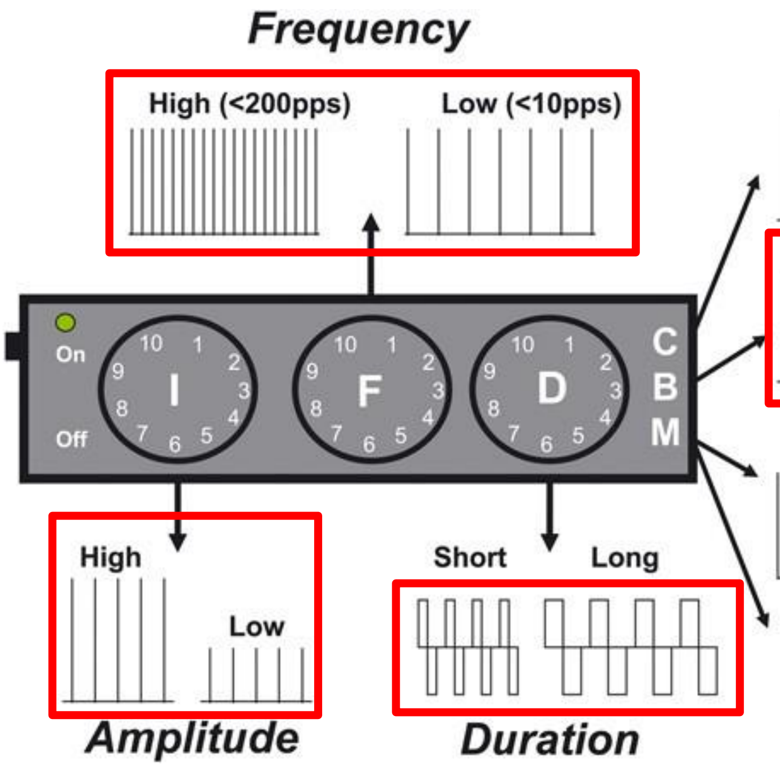
Examples for available sytems



AFFERENT NERVE STIMULATION:
- Continuous biphasic pulses
- 1 – 120 Hz,
- 0,1-1ms per phase (100-1000µs)
- Posterior roots: up to 120mA
- Peripheral nerves: < 50 mA

NEUROMUSCULAR STIMULATION:
- Phasic pattern, var. on-/off-time
- 10 – 50 Hz,
- 0,1-1ms per phase (100-1000µs)

Essential device feature: resolution of amplitude adjustment finer then 0,5 mA !!!



AFFERENT NERVE STIMULATION:
- Continuous biphasic pulses
- 1 – 120 Hz,
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- Posterior roots: up to 120mA
- Peripheral nerves: < 50 mA

NEUROMUSCULAR STIMULATION:
- Phasic pattern, var. on-/off-time
- 10 – 50 Hz,
- 0,1-1ms per phase (100-1000µs)

Examples for available sytems

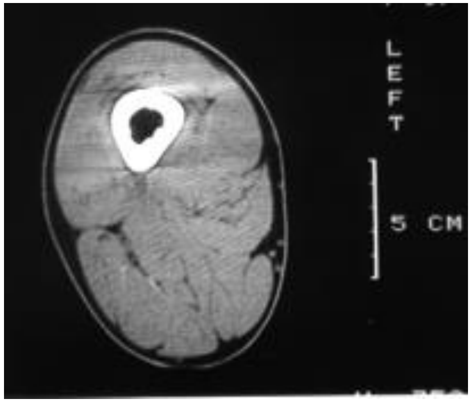
Muscle Stimulation

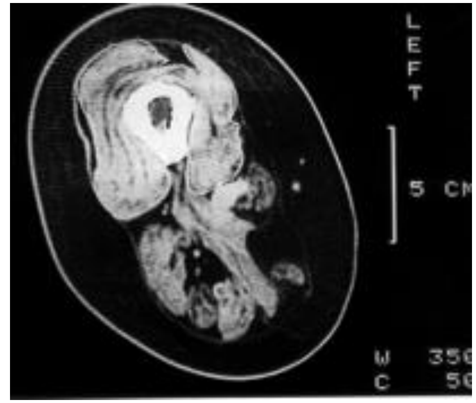
Consequences of muscle denervation

Healthy thigh

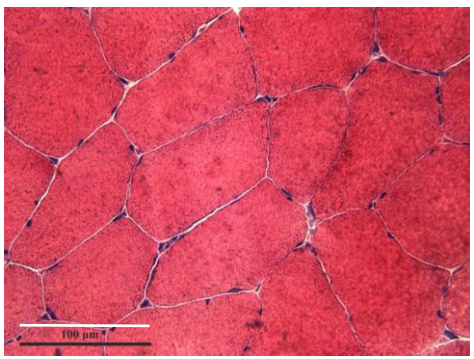
4 years denervated

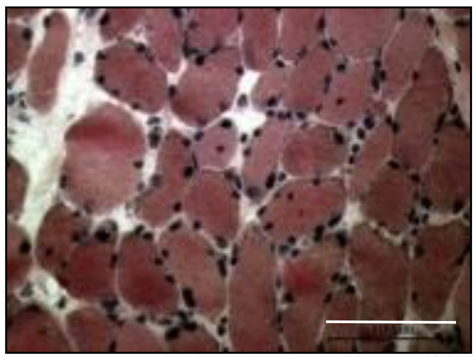
8,7 years denerv.

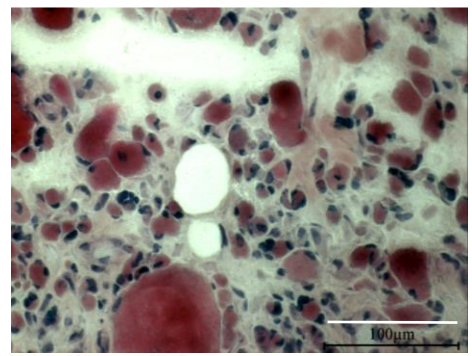


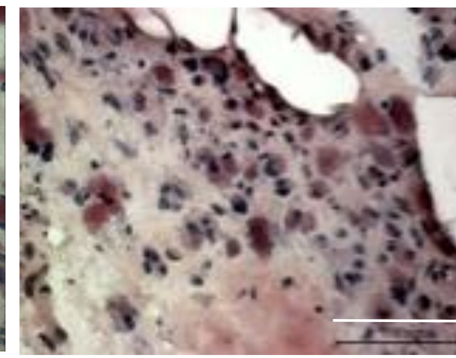


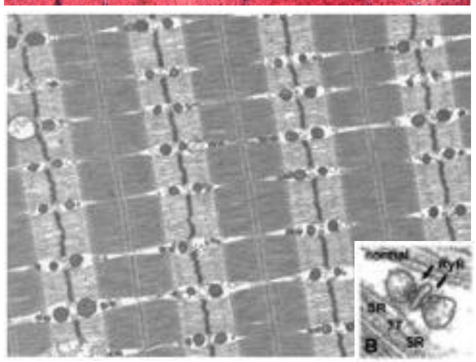
0,9y den



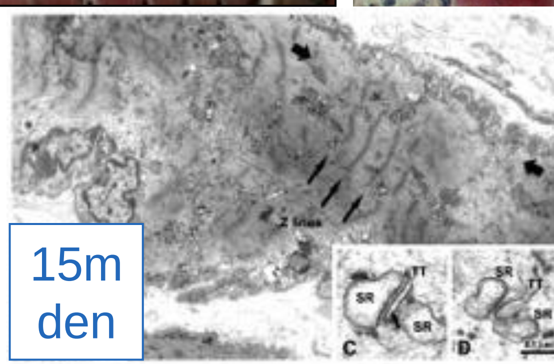








15m den



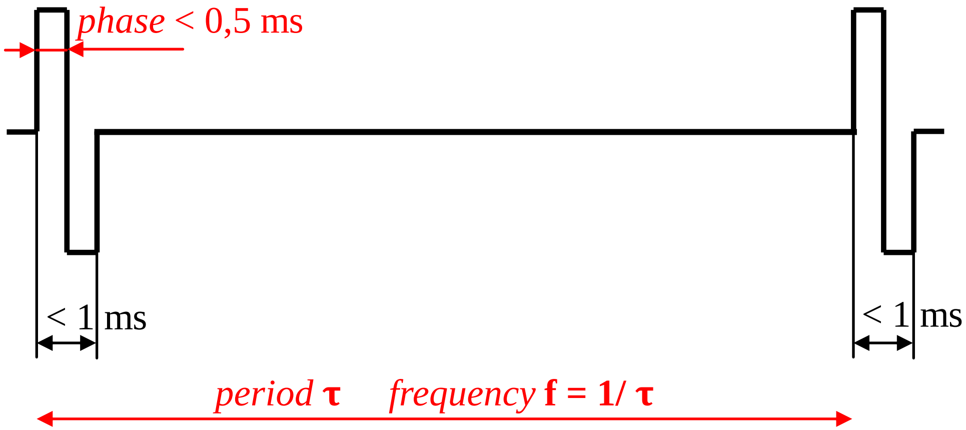
MFCV$_{max}$ vastus lat:

healthy	4,48 m/s
10mo den	2,40 m/s
30mo den	1,20 m/s

Stimulation parameter ranges

Nerve stimulation:

- Pulse width (biphasic)
  typ. < 0.5ms per phase
- Frequency (fused contr.)
  25 Hz
- Amplitude range (Surface)
  ⇨ ±100V / ⇨ ±300mA
- Amplitude range (Implant)
  ⇨ ±10V / ⇨ ±30mA



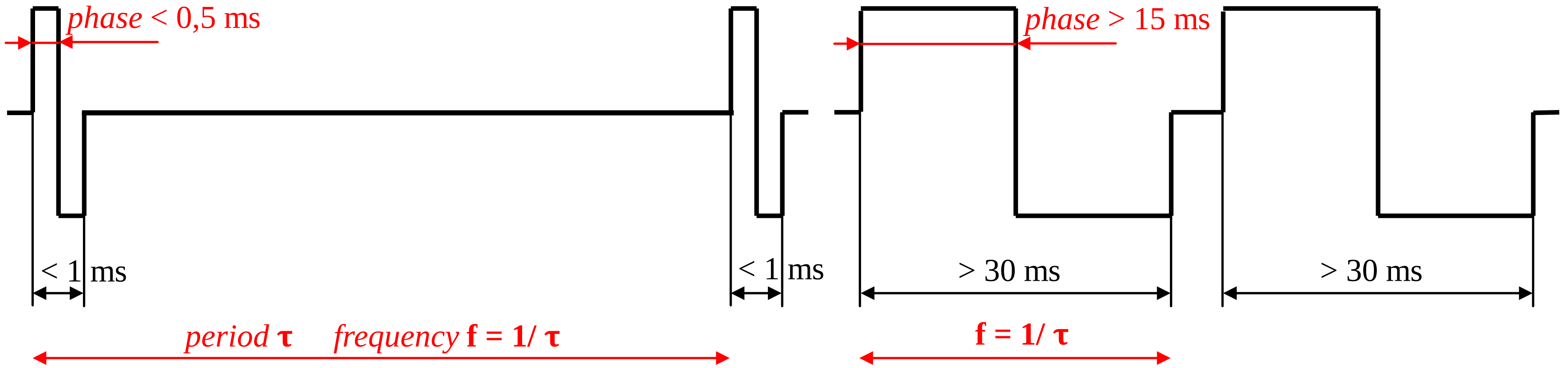
Stimulation parameter ranges

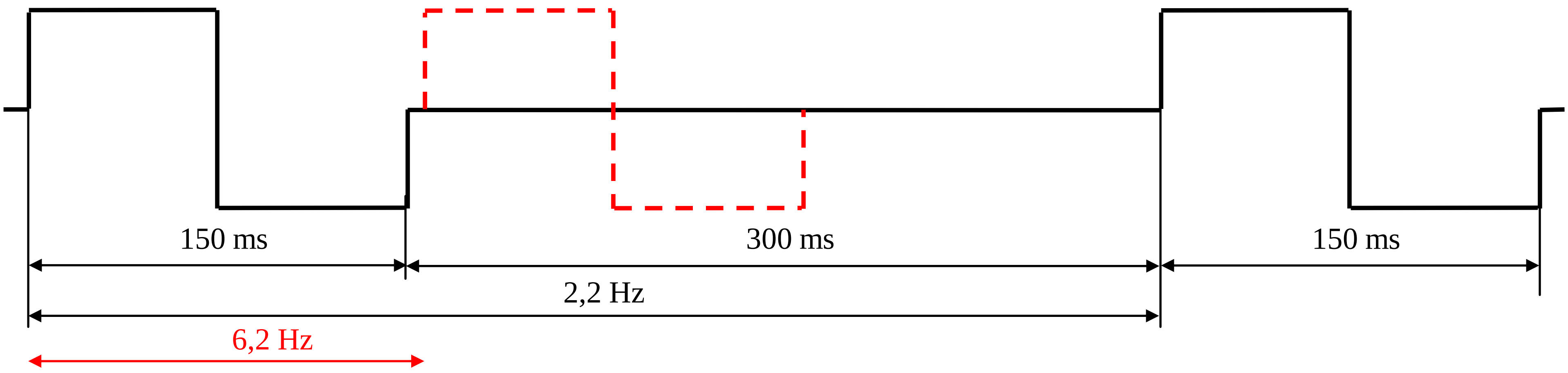
Nerve stimulation:

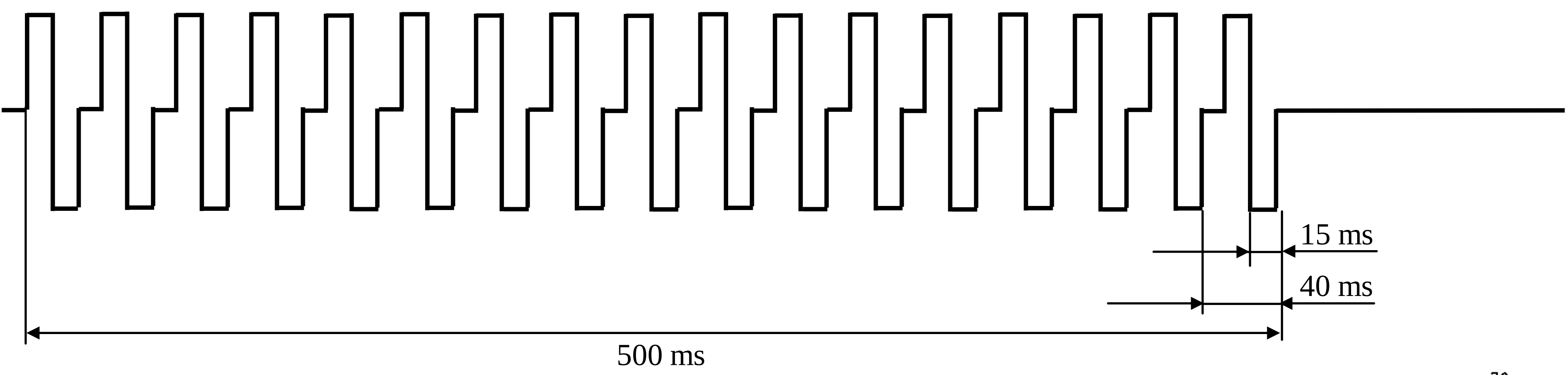
- Pulse width (biphasic)
  typ. < 0.5ms per phase
- Frequency (fused contr.)
  25 Hz
- Amplitude range (Surface)
  ⇨ ±100V / ⇨ ±300mA
- Amplitude range (Implant)
  ⇨ ±10V / ⇨ ±30mA

Muscle stimulation:

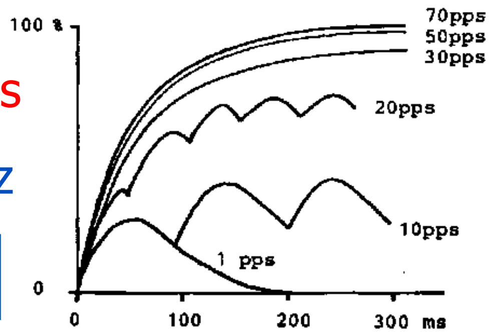
- Pulse width (biphasic)
  typ. >15ms (⇨250ms) per phase
- Frequency (fused contr.)
  25 Hz
- Amplitude range (Surface)
  ⇨ ±100V / ⇨ ±300mA
- Amplitude range (Implant)
  ⇨ ±10V / ⇨ ±30mA



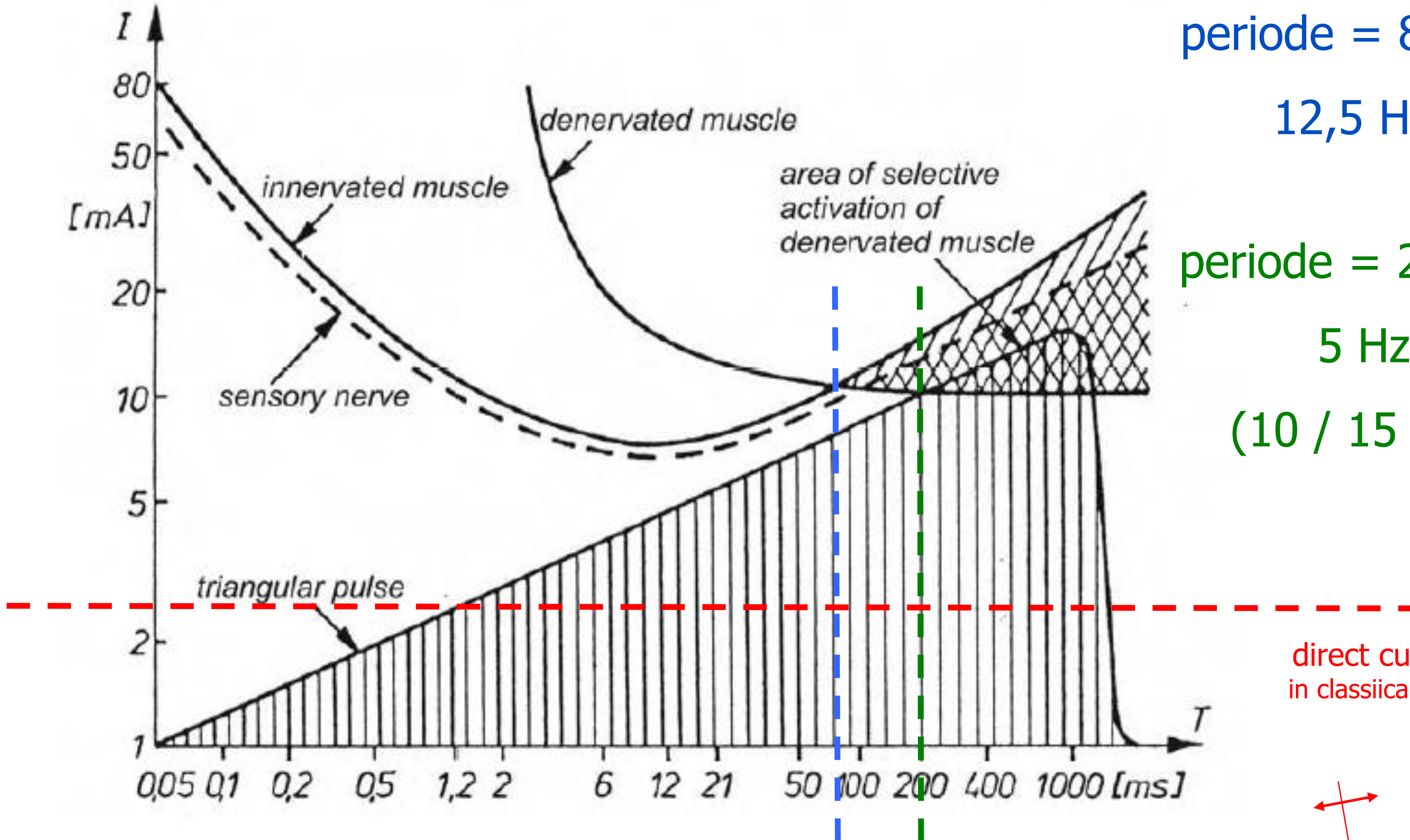




Excitability	Period < 50 ms	Pulse phase > 15 ms
conditioning	> 20 Hz	Period 40ms / 25 Hz



Single twitch ⇨ unfused tetanus ⇨ fused tetanus



periode = 80 ms

12,5 Hz

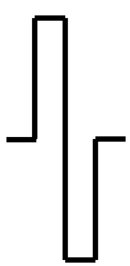
periode = 200 ms

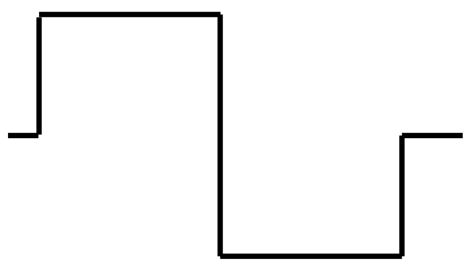
5 Hz

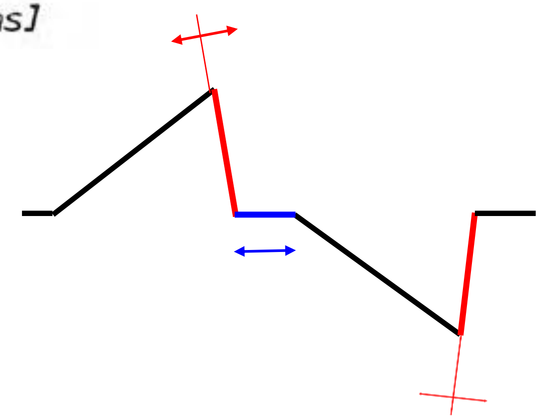
(10 / 15 mA)

DC

direct current component
in classiical exponential current





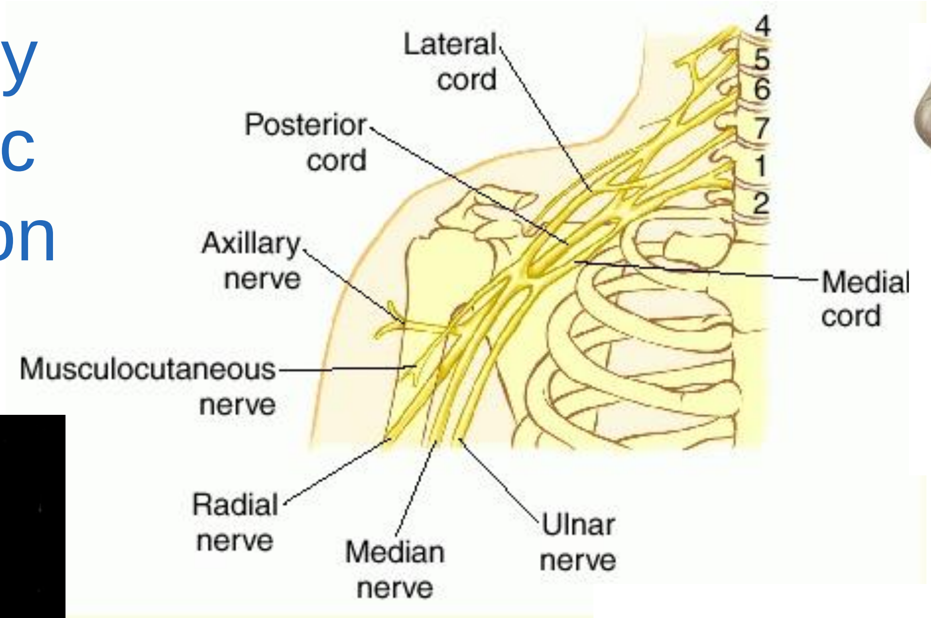


nerve stimulation

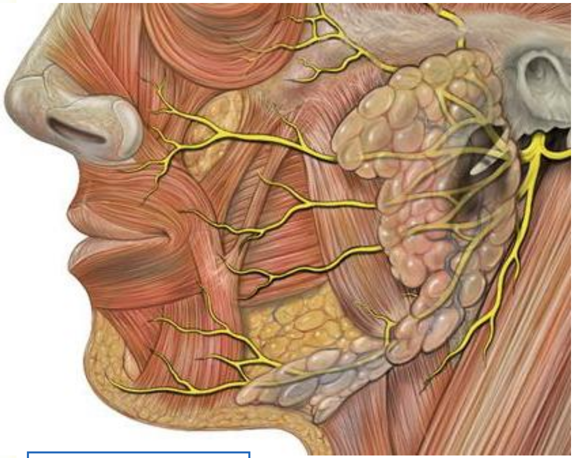
muscle stimulation

muscle stimulation,
reduced nerve stimulation

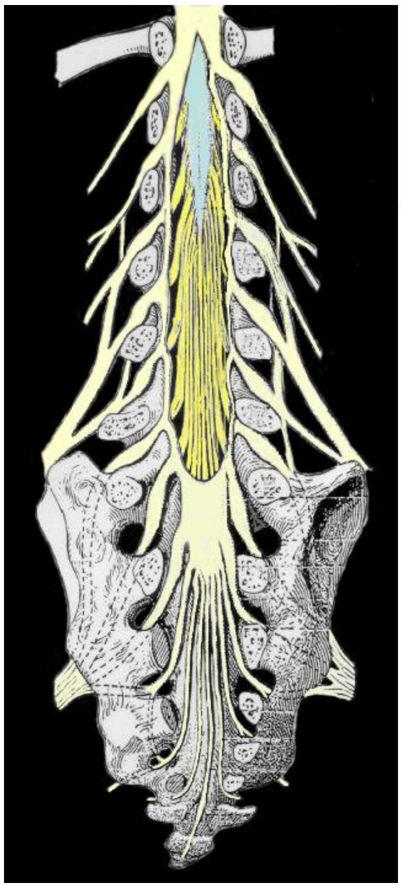
Temporary or chronic denervation



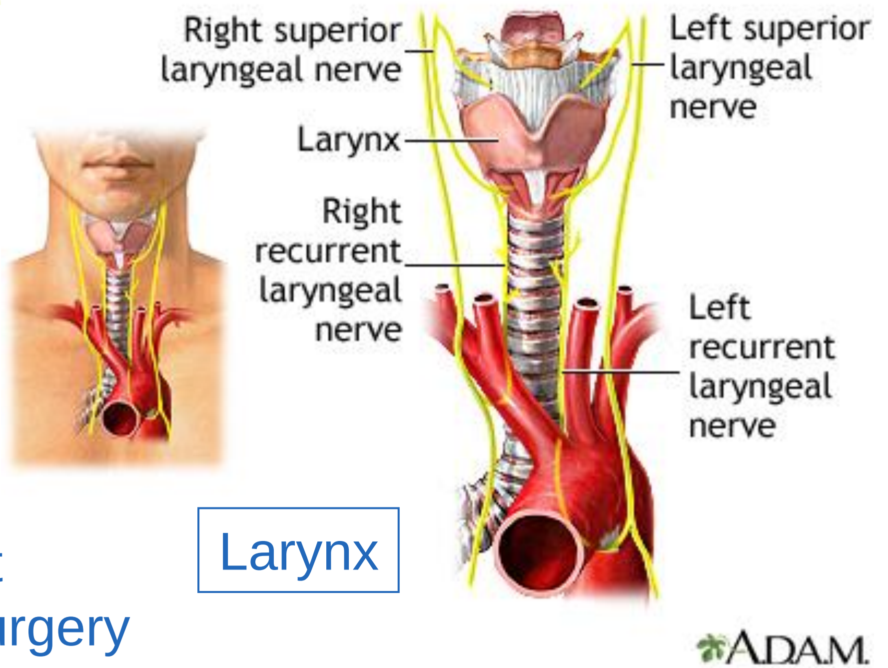
Plexus



Facialis



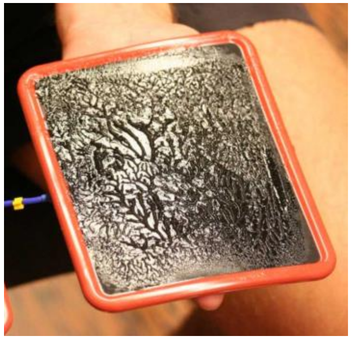
Cauda

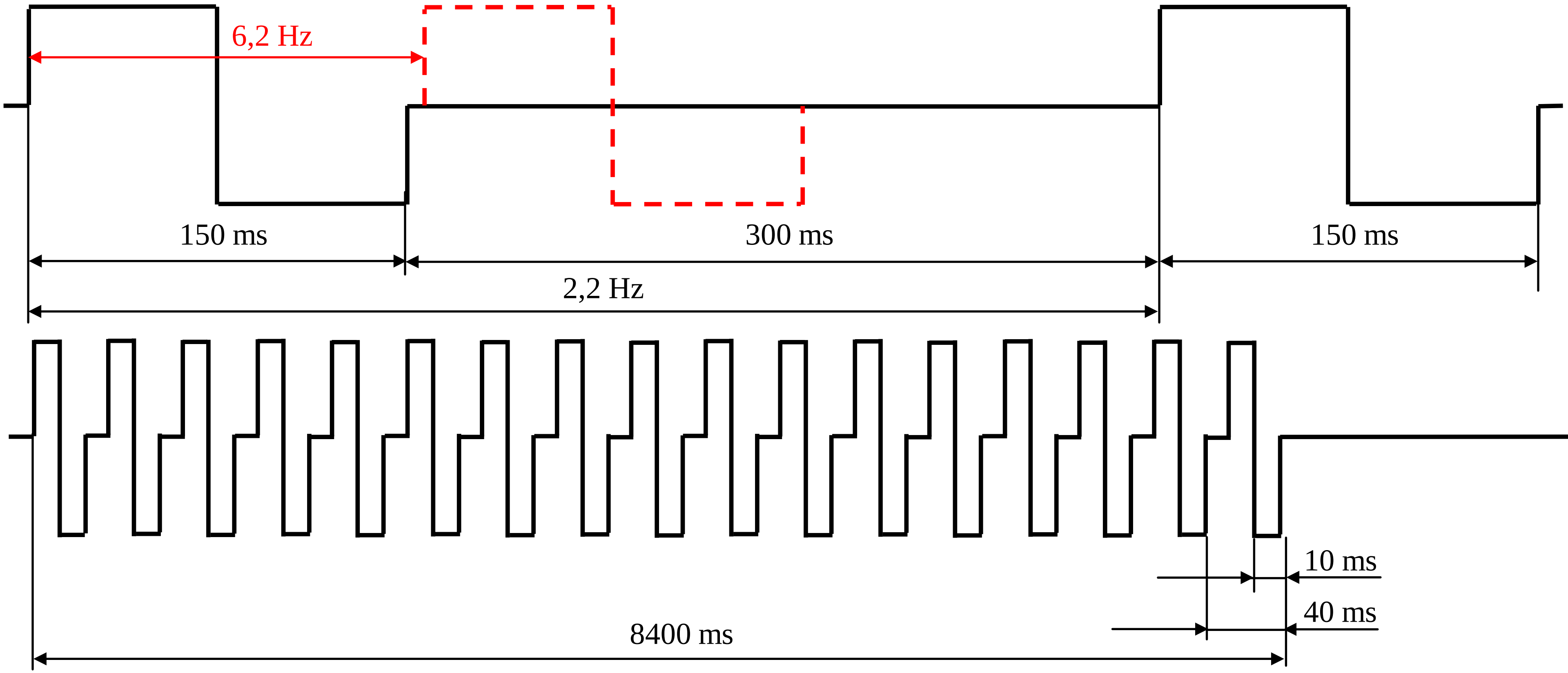


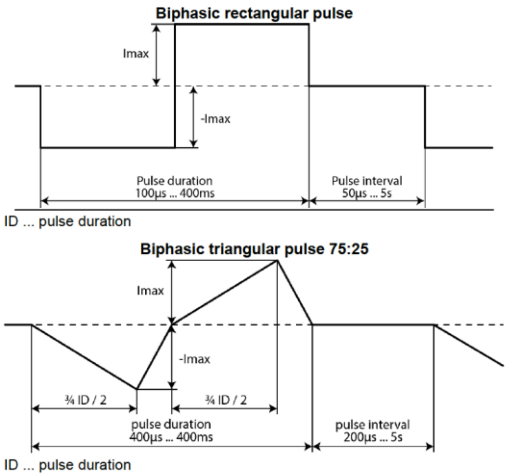
Larynx

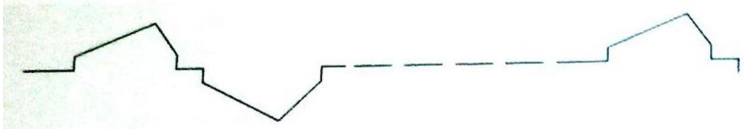
Recovery support
Reconstructive surgery

Electrodes









Examples for available sytems

implant

ASIA IMPAIRMENT SCALE

A – Complete: No motor or sensory function preserved in the sacral segments S4-S5.

B – Incomplete: Sensory but not motor function preserved below neurological level and includes the sacral segments S4-S5.

C – Incomplete: Motor function preserved below neurological level, and more than half of key muscles below the neurological level have muscle grade below 3.

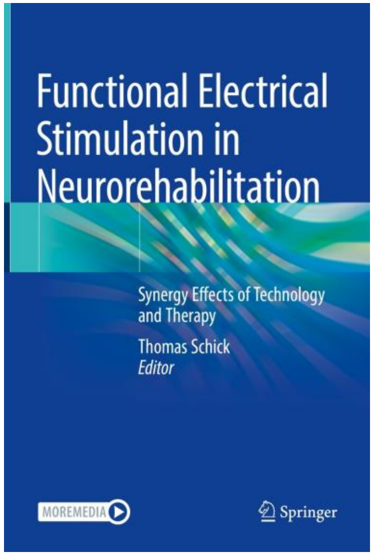
D – Incomplete: Motor function preserved below neurological level, and more than half of key muscles below the neurological level have muscle grade of 3 or more.

E – Normal: Motor and sensory function normal

surface

Paraplegia

Role of Technical Tools and Electrical Parameters in Functional Electrical Stimulation



https://link.springer.com/book/10.1007/978-3-030-90123-3

Chapters:

- *Role of Electrical Parameters in Functional Electrical Stimulation*
- *Absolute and Relative Contraindications*

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