WHY WAVEFORMS LOOK THE WAY THEY DO: VOLUME CONDUCTIVITY THEORY AND PRACTICAL APPLICATION

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GOALS
- Explain Generation Of RMP
- Generate An Intracellular Action Potential
- Explain The Extracellular Wave Shape Of A Non-Propagating IAP
- Propagate An IAP
- Explain The Various Extracellular Wave Shapes Of Propagating IAPs Based On The IAP And Its Interactions With Tissue/Recording Electrode
GOALS

- Define/Explain The Six Fundamental Waveforms In Clinical Neurophysiology Upon Which All Other Waveforms Are Based
- Explain The Wave Shape Of All Observed Waveforms In EDM
- Detail Various Pitfalls
LET’S GET MORE EXPLICIT

Extracellular Waveform Configuration

- All of our EDM recordings are extracellular (surface/needle)
- To fully appreciate why extracellular waveforms appear as they do, we need to appreciate the RMP and its relationship to the IAP
- We begin with the IAP and work our way to the extracellular space
  - From inside to outside the cell
RESTING MEMBRANE POTENTIAL

- RMP Formation (-90 mV)
  - Semipermeable Membrane
  - Impermeable Intracellular Anions [−]
    - These Anions In Part Form The Basis Of The Negativity Of The RMP
  - Permeable Extracellular Anions (Cl−) And Cations (Na+, K+)
    - Support The RMP (K+ & Cl−)
    - Generates The IAP (Na+)
    - Repolarization (K+)}
ACTION POTENTIAL

- Action Potential Generation
  - Focal Depolarization: Reversal Of Trans-Membrane Potential (Neg/Pos) To (Pos/Neg)
  - Depolarization: Less Negative Intracellular/Extracellular Trans-Membrane Potential Secondary To An Input Of Energy:
    - Mechanical
    - Electrical
    - Chemical

- Energy Input: Elec, Mech, Chem
- Induces Na⁺ Entry
- If Enough Na⁺ Causes RMP (-90mV) To Reach -60 mV, Na Channels Undergo Voltage Induced Conformation Change And All Open To Cause Influx Of Na Ions To Try To Reach +30 mV (Sodium Equilibrium Potential)
- Sodium Inactivation Then Shuts Down Influx
ACTION POTENTIAL CONFIGURATION

- Intracellular IAP Configuration
  - Monophasic
  - Positive

CURRENT FLOW VOLTAGE DISTRIBUTION

- We Generated An IAP
- How Did That Occur?
  - Na+ Movement Extracellular To Intracellular
  - Positive Charge Movement Because Of A Voltage Difference Between Outside/Inside
  - Electrical vs Concentration Gradients
  - Charge Movement Means Current Flow
  - Voltage Associated With Current Flow Is Measured By Us As The Difference Between The Active And Reference Electrodes
ACTION POTENTIAL PROPAGATION

- Generate An IAP
- Propagate An IAP
- How Do We Propagate An IAP
**ACTION POTENTIAL PROPAGATION**

- **Excitable Tissue Resting State**
  - Net Negative Intracellular Charge (-90mV)
  - Transmembrane Electrostatic Attraction For Positive Ions Causes Clustering Of Positive Ions Along The Exterior Of The Cell

- **Excitable Tissue: Energy Input To Open Sodium Channels**
ACTION POTENTIAL PROPAGATION

- Excitable Tissue: Energy Input to Open Sodium Channels
  - Electrical; Chemical; Physical

ACTION POTENTIAL PROPAGATION

- Excitable Tissue: Extracellular Na⁺ Enter Cell “Down” Electrical & Concentration Gradients
ACTION POTENTIAL PROPAGATION

- Excitable Tissue: Extracellular Na⁺ Enter Cell “Down” Electrical & Concentration Gradients
  - Na⁺ Spreads Longitudinally: Reduce RMP

ACTION POTENTIAL PROPAGATION

- Excitable Tissue: Extracellular Na⁺ Enter Cell “Down” Electrical & Concentration Gradients
  - Neutralizes Transmembrane Attraction Na⁺
ACTION POTENTIAL PROPAGATION

- Excitable Tissue: Extracellular Na⁺ Enter Cell “Down” Electrical & Concentration Gradients
  - Adjacent Opening Of Na⁺ Channels

LOCAL CIRCUIT VOLTAGES

- IAP ➔ Extracellular Voltage: + - - +/-+/-
LET’S GET SPECIFIC: WHAT WE SEE DEPENDS ON

+ - - +

1) Propagate: Yes Or No
2) Where Record From Along The Tissue
3) Does It Interact With The Electrode
   1) No
   2) Yes: Sealed End
   3) Yes: Crushed End

NEEDLE EMG RECORDINGS END-PLATE REGION

- Potentials Recorded With The Needle EMG Electrode
- EMG Electrode Positioned So As To Be Coincident With The Site Of AP Initiation, i.e. End-Plate
- Assume Single Muscle Fiber
- Principle Applies To Nerve As Well From A Volume Conduction Standpoint
INTRA/EXTRACELLULAR IAP CONFIGURATION: NONPROPAGATING

- Extracellular Configuration: Monophasic (-)

MINIATURE END-PLATE POTENTIALS

- Spontaneous, Subthreshold, Non-Propagating, Monophasic Negative
  - + - - +
INTRA/EXTRA-CELLULAR AP WAVEFORM CONFIGURATION PROPAGATING AP

- Assumptions:
  - IAP Generated At End-Plate (Single MF)
  - Suprathreshold: Propagates Away From EP
  - Record From: (Relocate Our Electrode)
    - 1) End-Plate, 2) ½ Between EP & MTJ, 3) At MTJ

END-PLATE RECORDING
WAVEFORMS RECORDED FROM THE END-PLATE

- Miniature End-Plate Potentials
  - Monophasic Negative
  - Irregular Discharge Rate
  - So Called “Sea Shell Murmur”

- End-Plate Spikes
  - Prototypically Biphasic Initially Negative: - +
  - Atypical: Pitfall: Confuse with Fibs/PSWs
    - Triphasic, Biphasic Initially Positive, Monophasic Positive, Complex

PROTOTYPICAL BIPHASIC INITIALLY NEGATIVE EPS
PROTOTYPICAL BIPHASIC INITIALLY NEGATIVE EPS

NEEDLE EMG RECORDING END-PLATE: MUAP

- Biphasic Initially Negative
- Rather Regular/Under Voluntary Control
NEEDLE EMG RECORDING
END-PLATE: FIB

- Spontaneous: Not Under Voluntary Control
- Rate/Rhythm: Slow/Very Regular
END-PLATE RECORDING
SURFACE ELECTRODE

- Active Electrode Over Motor Point
- Reference Electrode Off Muscle/Nearby

END-PLATE RECORDING
SURFACE ELECTRODE

- Active Electrode Over Motor Point
- Reference Electrode Off Muscle/Nearby

A

B

CMAP
GENERAL PRINCIPLE

- Any Recording Electrode (Surface/Needle) Coincident With The Site Of Action Potential Initiation Will Describe A Biphasic Initially Negative Waveform (- +)
- CMAP, MUAP, Myotonic Discharge, Fibrillation Potential, Fasciculation, etc.
- Corollary: Any Waveform With An Initial Negative Deflection Originates At The Site Of The Recording Electrode

PROPAGATING IAP RECORDING BETWEEN END-PLATE AND MTJ
PROPAGATING IAP RECORDING BETWEEN END-PLATE AND MTJ

- EPS
- Fibs
- MUAPs
- CMAPs

Fibs: Triphasic + - +
IAP: Approaches (+)/Reaches (-)/Passes (+)
PROPAGATING IAP RECORDING BETWEEN END-PLATE AND MTJ

- EPS: Note Configuration/Rate/Rhythm
PROPAGATING IAP RECORDING BETWEEN END-PLATE AND MTJ

- CMAP: Off Motor Point

PROPAGATING IAP RECORDING AT MTJ

- Site Of Action Potential Extinction
PROPAGATING IAP RECORDING AT MTJ

- IAP Propagates Up To The MTJ & Stops
- EPS, MUAPs, Fibrillation Potentials

INTERIM SUMMARY

- IAP: Monophasic Positive (+)
- Extracellular: Negative Sink Surrounded By Positive Source Currents/Voltage
  - + - - +
- Extracellular Wave Shapes/Conditions
INTERIM SUMMARY

 Extracelluar Wave Shapes/Conditions
  - Non-Propagated: Monophasic Negative: -
  - Propagated: Initiation, Middle, Termination

 Electrode Coincident With Initiation Site
  - Biphasic Initially Negative: - +

 Electrode Between Initiation & Termination
  - Triphasic Initially Positive: + - +

 Electrode Coincident With Termination
  - Biphasic Initially Positive: + -

INTERIM SUMMARY

 A Single Monophasic Positive IAP Generates The Following Extracellular Waveforms Depending Upon If IAP Is Sub/Supratheshold; Electrode Location With Respect To AP Initiation/Propagation:
  - Monophasic Negative (-): Nonpropagating
  - Biphasic Initially Negative (-+): End-Plate
  - Triphasic Initially Positive (+-+): Middle
  - Biphasic Initially Positive (+-): Termination
CONCEPTS

- Just Reviewed Electrical Concept
- Let’s Consider The Needle Electrode Concept And Its Relationship To Tissue

NEEDLE ELECTRODE/TISSUE INTERACTION

- Presently Many EMGrs Erroneously Assume The Needle Electrode Is Simply A Passive Bystander Solely Recording Electrical Activity As A Point Recording
- The Needle EMG Electrode Is Neither A Point Recording Nor A Passive Bystander
- It Is A Comparatively Large Unyielding Cylinder Of Stainless Steel That Can Dramatically Deform Muscle Tissue With Significant Waveform Configuration Consequences
NEEDLE ELECTRODE TISSUE INTERACTION

- Needle Electrode Is Metal
- Muscle Tissue Is Malleable/Compliant
- Needle Electrode Plows/Cuts Through Muscle Tissue And Deforms The Single Muscle Fibers
- This Tissue Deformation Has Profound Consequences And Implications Regarding The Waveforms’ Recorded Configurations
NEEDLE/TISSUE INTERACTION SCENARIOS

- No Interaction: Permits AP To Approach, Reach, And Travel Away From The Electrode
- Produce Sealed End Effect: Similar To MTJ
  - AP Approaches, Reaches, But Does Not Propagate Past Electrode
- Produce Crushed End Effect
  - AP Approaches, Reaches, But Does Not Propagate Past Electrode
- Sealed End Vs Crushed End
  - Produces Different Effects With Different Ensuing Waveforms Recorded

SEALED END EFFECT (MTJ)
SEALED END EFFECT (MTJ)

Recording Electrode

Single Muscle Fiber

- + - +

Functional Sodium Channels
Dysfunctional Sodium Channels
CRUSHED END EFFECT

Recording Electrode

Crush Zone

Functional Sodium Channels
Dysfunctional Sodium Channels

CRUSHED END EFFECT
CRUSHED END EFFECT

- No Adverse Interaction
  - Coincident With AP Initiation
    - Monophasic – (subthreshold; MEPP)
    - Biphasic Initially – (- +): EPS
  - Between Initiation/Termination: Triphasic: +--
  - Coincident With Termination: Biphasic: + -

- Sealed End (Similar To MTJ): Biphasic: +-
- Crush End: Monophasic +
  - (-) (-+) (+-) (+-) (+)

ELECTRODE/TISSUE INTERACTION

- No Adverse Interaction
  - Coincident With AP Initiation
    - Monophasic – (subthreshold; MEPP)
    - Biphasic Initially – (- +): EPS
  - Between Initiation/Termination: Triphasic: +--
  - Coincident With Termination: Biphasic: + -

- Sealed End (Similar To MTJ): Biphasic: +-
- Crush End: Monophasic +
  - (-) (-+) (+-) (+-) (+)
POTENTIAL PITFALLS

- Failing To Account For Tissue Needle Interactions Can Lead To A Number Of Erroneous Conclusions

ATYPICAL TRIPHASIC EPS
ATYPICAL BIPHASIC INITIALLY POSITIVE EPS
ATYPICAL MONOPHASIC POSITIVE EPS

L/T Dipole Model
- LD Approached The Crushed End Region
- When LD Reaches Crushed End It Stops But Continues To Be “Fed” By The Passive Source Current From The Crushed Region
- The Entire AP (L/T Dipole) Dissipates With Repolarization
- The End Result Is A Monophasic Positive Waveform

CRUSHED END
FUNDAMENTAL WAVEFORMS IN CLINICAL NEUROPYSIOLOGY

There Are Six Fundamental Waveforms

1) Monophasic Negative: MEPP, 
2) Monophasic Positive: EPS, Insertional Activity 
3) Biphasic Initially Negative: EPS, CMAP, MUAP 
4) Biphasic Initially Positive: EPS, Fibs, MUAP 
5) Triphasic Initially Positive: Fibs, MUAP, CMAP 
6) Biphasic Initially Positive: Long Duration: PSW

FUNDAMENTAL WAVEFORMS

- Monophasic Negative (MEEP: not shown): (-)
- Monophasic Positive: (- +); EPS; IA; MUAPs; Myotonia
- Biphasic Initially Negative: (- +); EPS; IA; MUAPs; Fibs; Myotonia
- Biphasic Initially Positive: (+ -); Fibs; MUAPs; Myotonia
- Triphasic Initially Positive: (+ - +); EPS; Fibs; MUAPs; Myotonia
- Biphasic Initially Positive: (+ ----); (PSW)

Distinguishing Characteristics

- Configuration (waveshape); Firing Rate; Discharge Rhythm
PROTOTYPICAL EPS

EPS NONPROTOTYPICAL
TRIPHASIC EPS

POSITIVE EPS
RAPID FIRING EPS

TRANSITIONAL EPS
DENERVATED MUSCLE TISSUE

- Biphasic IAP With Long Duration
- Spontaneous Repetitive AP Generation
- Leading/Trailing IAP Is An Octapole
  - Backt-To-Back Quadrupoles Of Opposite Polarity
  - Depolarization/Repolarization/Hyperpolarization/Depolarization Back To RMP
DENERVATED MUSCLE TISSUE

- IAP is Biphasic Initially Positive (+ -)
- Single Muscle Fiber Discharges
  - Fibs
  - PSWs
- Denervated Muscle SMF Configuration
  - Biphasic Initially Negative (- +)
  - Triphasic Initially Positive (+ - +)
  - Biphasic Initially Positive (+ -)
  - Complex: Fused PSWs/Fibs
PSW: CRUSH END EFFECT

Recording Electrode

Crush Zone

Functional Potassium Channels
Dysfunctional Potassium Channels
PSW: CRUSH END EFFECT

Recording Electrode

Crush Zone

Functional Potassium Channels
Dysfunctional Potassium Channels
PSW: CRUSH END EFFECT

- Recording Electrode
- Crush Zone
- Functional Potassium Channels
- Dysfunctional Potassium Channels

Graph showing electrical activity with 100 µV scale and 20 ms time scale.
RECONCILIATION

- Need To Consider One’s Clinical Practice And What Is Reported In The Literature
- In My Clinical Practice I Do Not Observe 42% Of SYMPTOMATIC Patients With Back Pain To Have PSW/Fibs In PS Or FI Musculature
- About 20% Of Patients With Radiculopathies Have PS Abnormalities Only

RECONCILIATION

- Needle Electrode Is Not A Passive Bystander
- Needle Electrode And Muscle Fiber Form A Dynamic Pair Interaction
- Needle Electrode Can Deform A Muscle Fiber And Affect The Recorded Waveform’s Configuration
NORMAL/ABNORMAL SMF DISCHARGES

<table>
<thead>
<tr>
<th>Shape</th>
<th>Fibs/Psws</th>
<th>EPS</th>
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<tbody>
<tr>
<td>Biphasic -</td>
<td>Biph - +</td>
<td>Biph - +</td>
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<tr>
<td>Triphasic +</td>
<td>Triph + -</td>
<td>Triph + -</td>
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<td>Biphasic +</td>
<td>Biph + -</td>
<td>Biph + -</td>
</tr>
<tr>
<td>Complex</td>
<td>Complex</td>
<td>Monophasic +</td>
</tr>
</tbody>
</table>

Firing Rate | Regular | Irregular |
Discharge    | 7.4 Hz (15Hz) | 19Hz (20-50Hz) |

EPS VS FIBS/PSWs

- Firing Rate
- Discharge Rhythm
- Waveform Configuration Is A Necessary But Not Sufficient Condition
TRANSITIONAL WAVEFORMS

- We Frequently Observe One Waveform Transitioning Into Another
  - Fibs To PSW
  - Myotonia
  - MUAPs
- Explained By Needle Tissue Interaction
  - No Interaction To A Cut End Effect
  - No Interaction To A Crush End Effect
TRANSITIONAL WAVEFORMS

CONCLUSION

- Need To Distinguish Between “Normal” And “Asymptomatic”
- Consider Configuration Overlap Between Innervated And Denervated Single Muscle Fiber Discharges
- Waveform Configuration Is A Necessary But Not Sufficient Condition For Calling PSWs And Fibrillation Potentials