Electrostimulation
Waveform Effects

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Topics

- A. Electrostimulation principles review.
- B. Monophasic vs. biphasic stimulation.
- C. Waveforms producing repetitive APs.
- D. Can waveform design reduce probability of pain & cardiac arrhythmias?
- E. Rating waveform electrostim. “strength.”
- F. Conditioning waveforms: CNS application.
A. Electrostimulation Principles
Modes of neural stimulation.

**Nerve end organs:**
Sensory receptors (illustrated), Nerve/muscle junctions.
(Responds to E-field @ terminus)

**Bends in neural trajectory,**
esp. sharp bends.
(Responds to E-field @ bend)

**Near electrode, or sharp conductive discontinuity.**
(Responds to spatial gradient of E-field)

Source: Reilly (1998)
Strength-duration curves (monophasic stimulus)

2-parameters:
• **Rheobase** ($I_o$)
• $\tau_e = Q_o/I_o$

Or......
• $I_o = I_t @ t_p >> t_e$
• $Q_o = I_o t_p @ t_p << t_e$

$$I = \frac{I_o}{1 - \exp\left(-\frac{t_p}{\tau_e}\right)}$$

After Fig. 4.2 of Reilly, 1998
Rheobase E-field gradient & S-D time constant vs. electrode radial distance

probe over interior node

monophasic pulse

$t_p = 2 \text{ ms}$

Fiber Diameter (d) vs scaling factor (k)

$\begin{align*}
1.00 & \quad 20 \mu m \\
0.50 & \quad 10 \mu m \\
0.25 & \quad 5 \mu m \\
\end{align*}$

etc.

Multiply $y/k$ scale by $k$
Divide deriv. scale by $k^2$
### Rheobase Excitation Threshold vs. Fiber Diameter: Uniform Field Stimulus

<table>
<thead>
<tr>
<th>Fiber Diameter (µm)</th>
<th>Rheobase Threshold (V/m)</th>
<th>*SENN model results</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.15</td>
<td>Monophasic square E-field stimulus, Constant E-field along fiber axon.</td>
</tr>
<tr>
<td>10</td>
<td>12.3</td>
<td>Fiber terminus oriented toward distant cathode,</td>
</tr>
<tr>
<td>5</td>
<td>24.6</td>
<td>*SD time constant ( \tau_e = 121 , \mu s ) (with perfectly constant E-field along fiber)</td>
</tr>
<tr>
<td>2.5</td>
<td>49.2</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>98.4</td>
<td></td>
</tr>
</tbody>
</table>

Results from SENN model, Reilly & Diamant 2011b
Fiber Diameter Distribution of PNS Myelinated Nerve

Example fiber function

C: delayed, dull, burning pain; post-ganglionic activity
A_δ: initial, sharp pain
A_β: mechano-reception
A_α: proprioception; Contract striated muscle
B. Monophasic vs. Biphasic Waveforms
The relevant ES waveform with EMF induction is $dB/dt$.

For magnetic induction, $dB/dt$ is necessarily biphasic and charge balanced.
Monophasic vs... Biphasic Waveform Stimulation

Strength-duration relationships for monophasic & biphasic squarewave excitation.

FD = 20 $\mu$m

Source: Reilly & Diamant (2011) Fig. 3.3
Monophasic vs. Biphasic Waveform Stimulation

SENN model results
Strength-duration relationships for monophasic & biphasic waveform excitation.

Source: Reilly (1998), Fig. 4.16
Sinusoidal Stimulation Response

Thresholds vs... frequency of sine wave stimulus.

Source: Reilly & Diamant (2011), Fig. 7.2
Variation of excitation threshold with number of sinusoidal cycles.

SENN Model results

20 µm fiber
Cathode 2 mm distant

Fig. 4.19 of Reilly, 1998
Perception Threshold vs. Number Cycles of Magnetic Stimulation

Human perception of Z-gradient sinusoidal field.

Source: Budinger et al., 1991  Fig. 9.19 of Reilly, 1998
Myelinated Nerve Model Response to Sinusoidal Stimulus

SENN model results

Titrated threshold waveforms with 1, 2, & 3 cycles at $f = 5\, \text{kHz}$

Fig. 4.18 of Reilly, 1998
C. Waveforms Producing Repetitive APs
Repetitive Response of Myelinated Neuron to Sinusoidal Stimulus

*SENN Model results

*f = 500 Hz

*Repetitive AP response enhances sensory magnitude & strength of motor response.

*Response shown at multiples of threshold current x1.01, x1.2, x1.5

Source: Reilly, 1998, Fig. 4.20
Stimulated Multiple AP Rate

Myelinated Nerve Model

Unmyelinated Nerve Model

Source: Krauthamer & Crosheck, 2002
Figs. 3.9 & 3.10 of Reilly & Diamant, 2011
D. Can Waveform Design Reduce Pain & Cardiac Arrhythmias?
## Median Reaction Threshold Parameters

\[ f_e = \frac{1}{2\tau_e} \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( E_0 ) peak (V/m)</th>
<th>( \tau_e ) (ms)</th>
<th>( f_e ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synapse activity alteration, brain</td>
<td>0.075</td>
<td>25.0</td>
<td>20</td>
</tr>
<tr>
<td>10-( \mu )m nerve excitation, brain</td>
<td>12.30</td>
<td>0.149</td>
<td>3350</td>
</tr>
<tr>
<td>20-( \mu )m nerve excitation, body</td>
<td>6.15</td>
<td>0.149</td>
<td>3350</td>
</tr>
<tr>
<td>Cardiac excitation</td>
<td>12.0</td>
<td>3.0</td>
<td>167</td>
</tr>
</tbody>
</table>

Interpretation of Table as follows:
\( E_i = E_0 \) for \( t_p \geq \tau_e \);
\( E_i = E_0(\tau_e/t_p) \) for \( t_p \leq \tau_e \).

Also, \( E_i = E_0 \) for \( f < f_e \);
\( E_i = E_0(f/f_e) \) for \( f \geq f_e \).

Adapted from Reilly [1998] and IEEE (2002)
SENN Model Application to C-Fibers and the Heart

Parameters for obtaining A-fiber, C-fiber and heart excitation thresholds for end mode stimulation within a constant electric field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-fiber</th>
<th>C-fiber</th>
<th>Heart</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENN-equivalent fiber diameter (μm)*</td>
<td>20</td>
<td>1</td>
<td>10.3</td>
</tr>
<tr>
<td>Rheobase (V/m)</td>
<td>6.15</td>
<td>124</td>
<td>12.0</td>
</tr>
<tr>
<td>$\tau_e$ (μs), uniform field</td>
<td>120.7</td>
<td>1000</td>
<td>3000</td>
</tr>
<tr>
<td>SENN temporal scaling factor</td>
<td>1</td>
<td>8.29</td>
<td>24.9</td>
</tr>
</tbody>
</table>

The fiber diameter of a myelinated neuron having the same rheobase as the listed issue type.

Source: Table 6.1 of Reilly & Diamant, 2011
Threshold margins relative to 20 µm A-Fiber
Square-wave stimulus

Results from scaled SENN model
Normalized SENN Thresholds, Various stimulation geometry

Source: Sarolic et al., 2016
Normalized experimental SD data, Unmyelinated worm nerve

Source: Sarolic et al., 2016
Normalized experimental SF data, Unmyelinated worm nerve

Source: Sarolic et al., 2016
E. Rating Electrostimulation
Waveform Strength
Temporal Factors:

Taser® Exposure: A Timely example

Output Current Comparison "Shaped Charge" versus "Taser M26"

-10
-5
0
5
10
15
0.00E+00
1.00E-05
2.00E-05
3.00E-05
4.00E-05
5.00E-05
6.00E-05
7.00E-05
8.00E-05
9.00E-05
1.00E-04

Shaped Charge Current [A]
M26 Taser Current [A]

TASER M26 (red)
TASER X26 (black)

PRF = 19/s
Burst duration = 5 s
(Vertical Scale: 5 A/div., Horizontal Scale: 10 μs/div.)

Load = 400 Ω
Electrical dose can depend on load impedance

Taser M26, 100 Ω

Taser X26, 100 Ω

Taser M26, 1000 Ω

Taser X26, 1000 Ω
More Stun Weapon Waveforms

(T1000 Ω Load)

TaserTron Current Waveform, Thinned 9/13/06

StickyShocker Current Waveform, Thinned 9/13/06

TaserTron Stun Weapon

Sticky Shocking Stun Weapon
Threshold Factor ($F_T$)

$F_T = \text{Multiple above the excitation threshold for:}$

- $20 \, \mu m$ diameter myelinated fiber,
- Negative polarity of nearest electrode,
- $1 \, \text{cm}$ radial distance of electrode,
- Electrode over interior part of axon,
- Uniform conductivity volume,

\[
F_{T,s} \Rightarrow \text{electrode on surface semi-infinite volume,} \\
F_{T,i} \Rightarrow \text{electrode within infinite volume (} F_{T,s} = 2F_{T,i} \text{)}
\]

Additional relevant parameters in stimulation efficacy:

- Pulse repetition frequency
- Duration of pulse train
- Locations of electrodes

As published in Reilly et al., 2009
Procedure for determining $F_T$

(1) Use SENN model; set up reference stimulus scenario:
   * 20 $\mu$m diameter myelinated fiber,
   * Negative polarity of nearest electrode,
   * 1 cm radial distance of electrode to fiber,
   * Electrode over interior part of axon,
   * Uniform conductivity volume,
   * Chose either surface or *in-situ* electrode case.

(2) Input digital waveform (either laboratory recording of real waveform, or mathematically derived).

(3) Decrease or increase amplitude of entire waveform to determine threshold within 1%

(4) $F_T = $ Decrement (or increment) factor.
<table>
<thead>
<tr>
<th>Load (Ω)</th>
<th>Threshold Factor, $F_{T,s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M26</td>
</tr>
<tr>
<td>100</td>
<td>105</td>
</tr>
<tr>
<td>200</td>
<td>97.5</td>
</tr>
<tr>
<td>400</td>
<td>84.5</td>
</tr>
<tr>
<td>600</td>
<td>75.2</td>
</tr>
<tr>
<td>800</td>
<td>70.0</td>
</tr>
<tr>
<td>1000</td>
<td>64.0</td>
</tr>
<tr>
<td>Pig lose posture?</td>
<td>yes</td>
</tr>
</tbody>
</table>

Small surface electrode

Porcine tests from Sherry et al. (2003). Interdart impedance not reported.
### TASER Waveform Properties, Resistive Loads
(Unmodified Waveforms)

<table>
<thead>
<tr>
<th>Load $R_L$ (Ω) =&gt;</th>
<th>Taser M26</th>
<th>Taser X26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>F&lt;sub&gt;T,s&lt;/sub&gt;</td>
</tr>
<tr>
<td>I(pk+)</td>
<td>A</td>
<td>19.6</td>
</tr>
<tr>
<td>I(pk-)</td>
<td>A</td>
<td>-13.8</td>
</tr>
<tr>
<td>Q(max+)</td>
<td>µC</td>
<td>111</td>
</tr>
<tr>
<td>Q(max-)</td>
<td>µC</td>
<td>-84.3</td>
</tr>
<tr>
<td>Q(net)</td>
<td>µC</td>
<td>42.2</td>
</tr>
<tr>
<td>tp(+)</td>
<td>µs</td>
<td>8.92</td>
</tr>
<tr>
<td>tp(-)</td>
<td>µs</td>
<td>9.72</td>
</tr>
<tr>
<td>J(net)</td>
<td>mJ</td>
<td>317</td>
</tr>
</tbody>
</table>
## TASER Waveform Properties Resistive Loads
(Amplitude Reduced to $F_T = 1$)

<table>
<thead>
<tr>
<th>Load $R_L$ (Ω) =&gt;</th>
<th>Taser M26</th>
<th>Taser X26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>1</td>
</tr>
<tr>
<td>$F_{Ts}$</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>$I(pk+)$</td>
<td>mA</td>
<td>186</td>
</tr>
<tr>
<td>$I(pk-)$</td>
<td>mA</td>
<td>-131</td>
</tr>
<tr>
<td>$Q(max+)$</td>
<td>µC</td>
<td>1.06</td>
</tr>
<tr>
<td>$Q(max-)$</td>
<td>µC</td>
<td>-0.803</td>
</tr>
<tr>
<td>$Q(net)$</td>
<td>µC</td>
<td>0.402</td>
</tr>
<tr>
<td>$t_p(+) $</td>
<td>µs</td>
<td>8.92</td>
</tr>
<tr>
<td>$t_p(-) $</td>
<td>µs</td>
<td>9.72</td>
</tr>
<tr>
<td>$J(net)$</td>
<td>µJ</td>
<td>28.8</td>
</tr>
</tbody>
</table>
Recommended Use of $F_T$

- $F_T$ for a particular waveform is defined in terms of a “Reference Case” neuron.
- For specific cases, choose the Reference Neuron to be compatible with the particular neuron/electrode configuration of interest.
F. Conditioning Pulses: CNS Application
Multiple Waveform Conditioning

Sequential CP

Concurrent CP

SENN model excitation thresholds with two-function stimulus waveforms.

Fig. 4.24 of Reilly, 1998
Improved CNS Stimulation Focality with Dual Coil System

Stimulation coil current
Coil 1: 0.2 ms ramp
Coil 2: 80 kHz sinewave

SENN model is available free of cost or copyright restrictions

J. Patrick Reilly & A.M. Diamant

Electrostimulation
Theory, Applications, and Computational Model (2011)
www.artechhouse.com

SENN Model (Source code & executables for PC or Mac) can be obtained from:
http://www.artechhouse.com/static/reslib/reilly/reilly.html
Reference Source

J. Patrick Reilly

*Applied Bioelectricity*
*From Electrostimulation to Electropathology*
Springer, 1998
Notice

The foregoing information has been derived from experiments and computational models attributable to various sources bearing on principles of biological reaction to electrical forces. Sources of information may be incomplete, and in some cases inconsistent. Experimental data used here may not be comprehensive or fully expository of disagreement among various researchers. Numerical models have not in all cases been adequately validated.

Where safe and/or efficacious exposure of humans or animals to electrical forces is important, the information presented here should only serve as a guide to a more focused study by the user.
Citations


Reilly, JP. Survey of electrostimulation models with application to human reactions to exposure by electromagnetic fields and contact current. (Submitted August, 2015).


http://www.artechhouse.com/static/reslib/reilly/reilly.html

Citations Continued


