Clinical Advances in Diaphragm Pacing: How, Why and When

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Objectives

- Review the anatomy of the diaphragm and the physiology of breathing
- Define the diagnostic evaluation of phrenic nerve dysfunction and instances where diaphragm pacing may apply
- Discuss device types and implantation schemes

Nothing to disclose
Respiratory Physiology
respiratory centers

- Upper motor neurons in pons and medulla
- **Medullary**: reticular formation, rhythmic inspiration and expiration
- **Apneustic**: lower pons, prolongs inspiration
- **Pneumotaxic**: upper pons, inhibits inspiration for fine tuning
Diaphragm Anatomy

phrenic nerve

- C3-C5 nerve roots: anterior scalene, IVC/pericardium
- Accessory nerves
- Motor point
- 70% slow twitch m fibers, resist fatigue
Diaphragm Pacing
early

- Cavallo (1777): CPR
- Hufeland (1783): asphyxia
- Ure (1818): feasibility in freshly hung criminal
- Duchenne (1849): cholera epidemic
- Israel (1927): apneic newborns
- Sarnoff (1950): polio victims
Diaphragm Pacing
contemporary

- Glenn (1966): human with chronic ventilatory insufficiency
- Glenn (1972): complete ventilator support in quadriplegic patient
- Mortimer (1983): motor point stimulation
- Mortimer (2002): pacing in tetraplegic pt
- Estimated that over 2500 devices implanted worldwide
Diaphragm Pacing

• **Indications**
  – Congenital central hypoventilation syndrome (CCHS)
  – High quadriplegia (above C-3)
  – {Intractable hiccups}
  – {End-stage COPD}

• **Contraindications**
  – Phrenic nerve injury or paralysis
  – Spinal cord injury (SCI) to C3-5 region
  – {Primary neuromuscular disorder}
  – Restrictive lung disease
Central Hypoventilation Syndrome
Ondine’s curse

- Failure of respiratory drive itself exists, unlike sleep apnea- no anatomic obstruction
- Stems from malfunction of the respiratory control center in the medulla
- Infection, stroke, trauma, idiopathic-dysfunction in medullary chemoreceptors that detect hypoxia and hypercarbia
Tetraplegia

- More patients are surviving the accident
- Over 250,000 SCI pts in US, most often from motor vehicle crash
- Cervical spine most common site of SCI w/ 12,000 new injuries/yr- half result in tetraplegia
- Site of injury determines phrenic function- above, at or below C3-5
- Leading causes of death are pneumonia, PE, sepsis
Amyotrophic Lateral Sclerosis
Lou Gehrig’s Disease

- Rapidly progressive, incurable and fatal neuromuscular disease
- Attacks nerve cells controlling voluntary muscles
- Progressive weakness resulting in paralysis with avg time from sx to death of 3 yrs
- Approx 30,000 pts living with it, with 5,600 dx each year
Preoperative Evaluation

- **Chest radiograph** - elevated hemidiaphragm, inspiratory/expiratory films
- **CT scan** - neck and chest
- **Fluoroscopy** - average excursion 3-5 cm, ranging 2-10 cm; sensitive when supine
- **Sniff test** - paralysis from weakness
- **Phrenic stimulation** - cervical thimble electrode with EMG
Diaphragmatic Paralysis

May occur following:
cardiac surgery, direct invasion by tumor,
aneurysm, traction, electrocautery, infx,
trauma, TB therapy, neuromuscular disorders
Pacing Devices

- **Avery Biomedical Devices** (Commack, NY)
  - Mark IV Breathing Pacemaker System
  - Direct implantation on phrenic

- **Synapse Biomedical, Inc** (Oberlin, OH)
  - NeuRx Diaphragm Pacing System
  - Implants into motor point on diaphragm
Phrenic Nerve Pacemaker
external transmitter

- Transmits RF energy to the implanted receiver transcutaneously via antenna
- Two independent channels, standard 9-volt batteries
- Lightweight and small for portability
Phrenic Nerve Pacemaker antenna

- Delivers RF energy from transmitter to implanted receiver transcutaneously
- Affixes directly over the implanted receiver by tape or strap
Phrenic Nerve Pacemaker implanted receiver

- Placed in subcutaneous pocket
- Simple design, easy to locate and cover with antenna
- Adaptable version available for connection to other implants
Phrenic Nerve Pacemaker
phrenic nerve electrode

- Surgically placed around phrenic nerve
- Cervical or thoracic implantation
- Reliable unipolar design for long-term function
Phrenic Nerve Pacemaker
transtelephonic monitor

Useful in tracking patients
and verifying function
Phrenic Nerve Pacemaker
transtelephonic monitor

TEST DATA ANALYSIS

<table>
<thead>
<tr>
<th>STIMULUS-RESPONSE RELATION</th>
<th>50 mm/sec</th>
<th>○ BASELINE</th>
<th>☐ FOLLOW-UP</th>
<th>○ LEFT</th>
<th>○ RIGHT</th>
</tr>
</thead>
</table>

**Left Side**
- GAIN: 2.8
- FILTERS: 2.0 Hz, 60 Hz

**Right Side**
- GAIN: 2.9
- FILTERS: 2.0 Hz, 60 Hz

**TEST DATA ANALYSIS**

<table>
<thead>
<tr>
<th>LEFT SIDE</th>
<th>PULS WIDTH</th>
<th>PULS INTERVAL</th>
<th>INSPIRATION TIME</th>
<th>LATENCY</th>
<th>HEART RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 µs</td>
<td>50 ms</td>
<td>1.3 s</td>
<td>20 ms</td>
<td>75 b.p.m</td>
<td></td>
</tr>
<tr>
<td>RIGHT SIDE</td>
<td>160 µs</td>
<td>50 ms</td>
<td>1.3 s</td>
<td>20 ms</td>
<td>75 b.p.m</td>
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</tbody>
</table>

**STIMULUS COUNT**
- TOTAL #29
- SUPRA THRESHOLD: Yes
- O N D: Yes

**PATIENT DATA**

<table>
<thead>
<tr>
<th>AMPLITUDE</th>
<th>TOTAL VOLUME</th>
<th>PACING SCHEDULE</th>
<th>LIP/FINGERNAIL COLOR</th>
<th>BLOOD PRESSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>200 cc/h</td>
<td>No</td>
<td>Normal</td>
<td>120 / 60</td>
</tr>
<tr>
<td>2.9</td>
<td>200 cc/h</td>
<td>No</td>
<td>Normal</td>
<td>120 / 60</td>
</tr>
</tbody>
</table>

**BILATERAL VELOCITY**
- 520 cc/h
- 24 hours
- No

**SYMPTOMS**
- No
- O N D

**PACIENT COMMENTS**

This is the place for other comments from the patient or caregiver.

**ANALYSIS**

Equipment is operating properly.
Biphasic muscle potentials show adequate spindle fiber recruitment.
As reported by patient, breathing is adequate while pacing.
No changes recommended at this time.

Date / Time of Analysis: 11/04 08:00
Auton: FAX
Analyst: INITIALS
Surgical Implantation

cervical

- Phrenic is isolated over scalene muscle, potentially done using local anesthesia

thoracoscopic

- Phrenic is isolated alongside pericardium, using double-lung ventilation
Surgical Implantation
thoracoscopic approach

Courtesy Avery Biomedical Devices
Diaphragm Pacing System
device system
Surgical Implantation
laparoscopic approach
Diaphragm Pacing System mapping
Diaphragm Pacing System mapping

Courtesy Raymond Onders, MD
Diaphragm Pacing System
electrode insertion
Diaphragm Pacing System

electrode insertion
Diaphragm Pacing System
diaphragm stimulation

Courtesy Raymond Onders, MD
Surgical Implantation
postoperative management

- Device settings
- Conduct of pacing
- Tracheostomy
- Complications
Postoperative Management

device settings

- Rate: 12-16 bpm
- Pulse intensity: threshold of excitability
  - Amplitude: 10-25 mA
  - Pulse width: 100-200 µs
- Pulse frequency: 5-20 Hz
- Inspiratory time: 1.1-1.3 s
Postoperative Management

conduct of pacing

- Timing: 7 days to 7 months
- Tidal volume: compromise with ventilator
- Muscle conditioning: recruit slow-twitch fibers, resist fatigue
- Downsize tracheostomy, switch to button
Postoperative Management complications

- Nerve injury
- Muscle injury
  - Capnothorax
- Infection
- Device failure
Postoperative Results

general

- Decreased risk of tracheal complications
- More natural phonation, speech, taste
- Reduced health care costs: $13,000/mo
- Increased freedom: battery, attendants
- Better quality of life
Postoperative Results
phrenic nerve pacemaker

- Glenn (1988)- 165/477 pts with detailed follow up
  - Pacing completely- 47%
  - Partial pacing- 35%
  - Unsuccessful- 17%
- Elefteriades (2002)- 6/12 quads pace full time out 10 years
  - Thresholds did not increase
  - No pt lost ability to pace the nerve
  - Path specimens show no evidence of nerve injury
Postoperative Results

Diaphragm pacing system

• Onders (2005): 50 SCI patients w/ avg f/u of 2 years
  – Longest pt pacing 8 yrs
  – One pt weaned after 28 yrs on vent
  – Those implanted over 6 mos
    • 50% off mech vent
    • 66% pacing over 12 hrs/day w/o attendant
    • None back on vent full time
Diaphragm Pacing System
ALS patients

- Oonders (2008): First 16 pts- 50 yrs, 13 male
- 23 mos post Dx, FVC > 50% (59%)
- Five 30-min sessions/day
- Diaphragm thickened on u/s, improved excursion on fluoro
- FVC declined 0.9%/mo vs 2.4%/mo
- Delay need for mechanical ventilation for up to 2 yrs
Diaphragm Pacing summary

- Need thorough assessment: phrenic, diaphragm, lungs; cognitive ability, social environment, financial situation
- Proven benefits: SCI, CCHS
- Emerging technology: ALS… marginal lung function patients for resection, lung transplants, acute lung injury
"It feels like I'm breathing on my own... just like I used to"