Pediatric Diaphragm Pacing in the Acute Phase of Injury

Mary Jo Elmo CNP

Raymond P. Onders M.D.

Remen Chair of Surgical Innovation

University Hospitals Case Medical Center

Case Western Reserve University School of Medicine

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Respiratory Insufficiency
Challenges Health Systems Worldwide

- Leading cause of death in Spinal Cord Injury (SCI) is pneumonia
  (Source: National Spinal Cord Statistical Center, 2006)
- Most people with ALS (Lou Gehrig's Disease) die from respiratory failure, usually within 3 to 5 years from the onset of symptoms
  (Source: NINDS)
- Mechanical Ventilation is the 10th most frequent procedure in critical care (ICU) patients and highest aggregate "National Bill" in U.S.
  (source: HCUPnet / DHHS, 2005)
- Because of limited effectiveness of treatment…we need to find better treatments and devices for central sleep apnea
  (source: New England Journal of Medicine, 2005)

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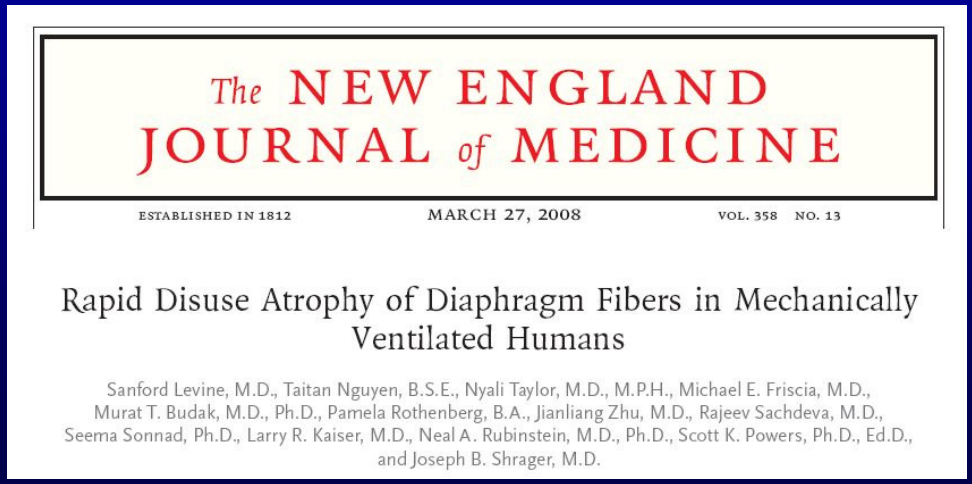
Mechanical Ventilators

- Difficulty with speech
- Decreases mobility
- Loud – draw unwanted attention
- Short battery span
- Increase anxiety
- Decreases Survival
  - Pneumonia is leading cause of death

- Damages Muscle
  - Diaphragm Muscles Rapidly atrophy and convert to less functional Fast twitch muscle fibers
  - Diaphragm Pacing maintains Strength
  - Converts and Maintains Type 1 fibers



The NEW ENGLAND JOURNAL of MEDICINE

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Rapid Disuse Atrophy of Diaphragm Fibers in Mechanically Ventilated Humans

Sanford Levine, M.D., Taitan Nguyen, B.S.E., Nyali Taylor, M.D., M.P.H., Michael E. Friscia, M.D., Murat T. Budak, M.D., Ph.D., Pamela Rothenberg, B.A., Jianliang Zhu, M.D., Rajeev Sachdeva, M.D., Seema Sonnad, Ph.D., Larry R. Kaiser, M.D., Neal A. Rubinstein, M.D., Ph.D., Scott K. Powers, Ph.D., Ed.D., and Joseph B. Shrager, M.D.

Ventilated Child

- Cervical SCI disproportionately high < 9 yo
- Caring for ventilator dependant child
  - Parental fatigue
  - Inadequate social support
  - Deficient sleep
  - Sense of hopelessness with home nursing shortages and/or competence of home care

•Hadley MN, Zabramski JM, Browner CM, et al: Pediatric spinal trauma. A review of 122 cases of spinal cord and vertebral column injuries. J Neurosurgery 1988;68:18-24.
•Elerkay M, Nicholas T, Adams M, et al: Pediatric cervical spine injuries: report of 12 cases and review of literature. J Neurosurg: Spine 2000;92: 12-17.
•Boroughs D, Dougherty J: Care of technology dependent children in the home. Home Health Care Nursing: 2009;27: 37-42.

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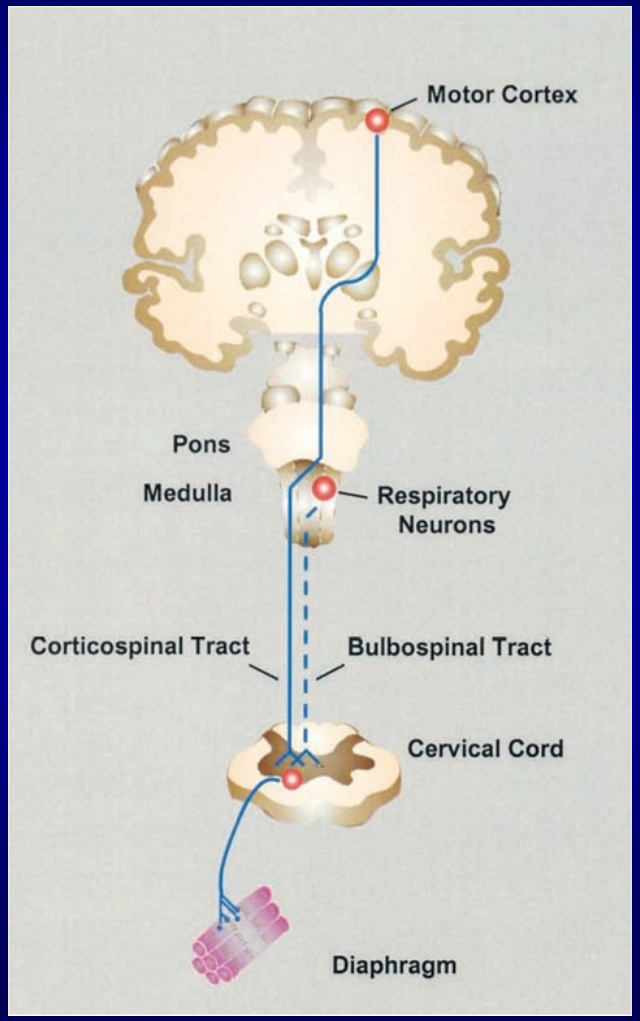
How Do We Breathe?
Consists of UMN & LMN Components



- UMN
  - Cerebral Cortex- volitional
  - Carotid Body
    - O2 saturation
  - Brainstem- Special somatic nuclei
    - CO2 levels
- LMN
  - C3-5
  - Small, medium and large neurons with different resistance levels
- Diaphragm Motor Units
  - Slow twitch Type I
  - Fast Twitch Type IIb

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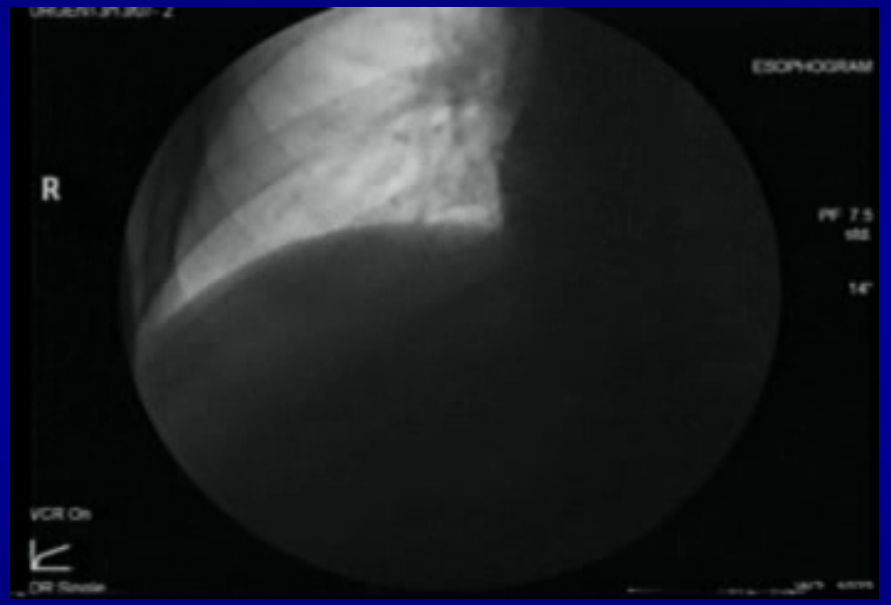
The Diaphragm is the Key for Breathing

- 24 hour use (24/7/365)
- Different day/night control
- Night REM - diaphragm
- Atrophy occurs faster than extremity muscles from disuse
- Disuse causes change of slow twitch oxidative (Type I) to fast twitch glycolytic (Type IIb)



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Objectives of the DP Program

- Provide Natural Negative Pressure Ventilation with the patient's own diaphragm
- Provide it with limited trauma or risk
- Inexpensive
- Outpatient management
- Removable

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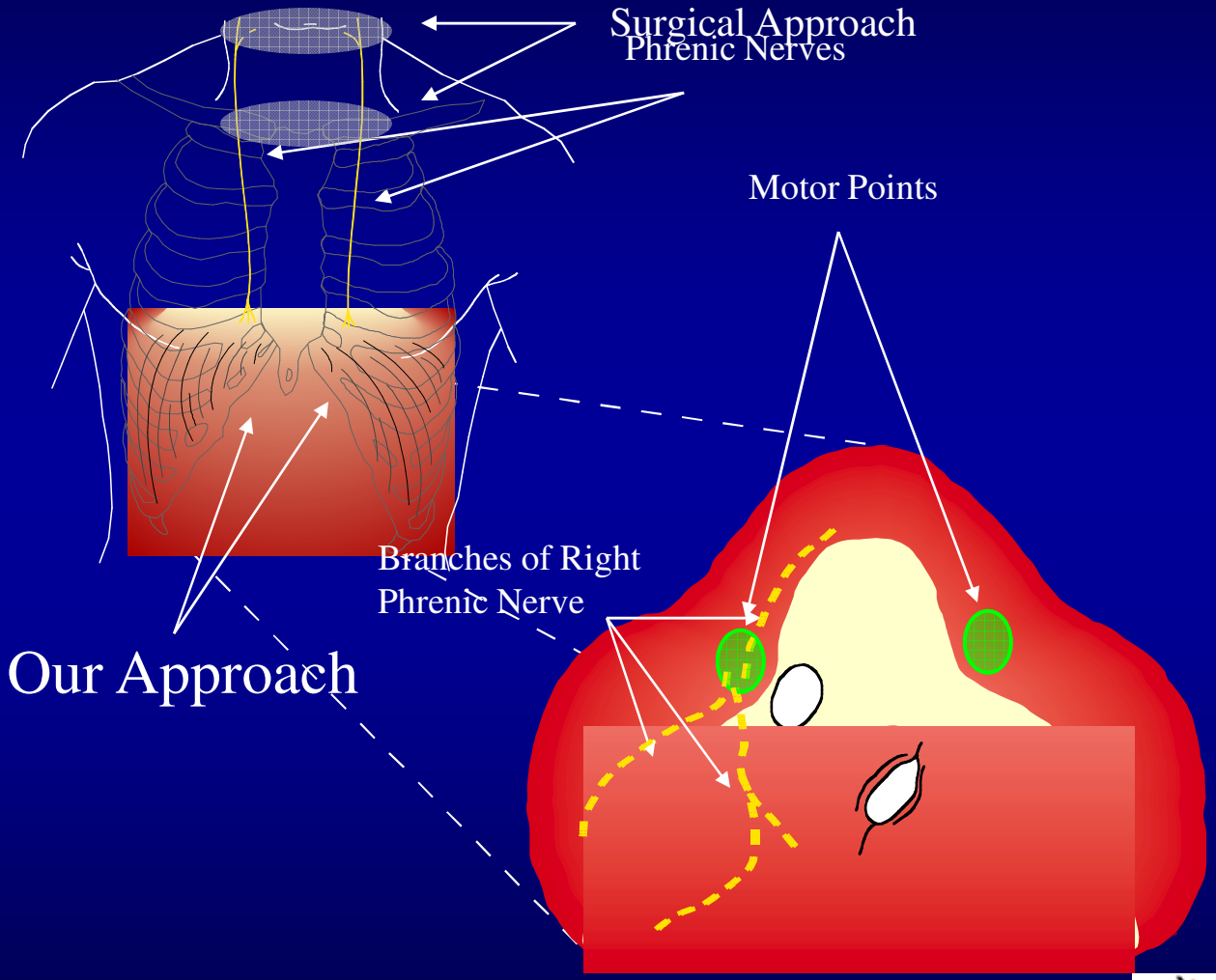
Options for Stimulating Diaphragm Muscle



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Background

Over 20 years of work
(ten years of engineering before first patient)

- Animal Models
  - Canine, swine, and rats
- Human - over 350 patients worldwide
  - 25 normal
  - >100 SCI patients
  - >120 ALS patients
  - Multiple various other patients including acute

Summarizing multiple IDE trials and over ten IRB protocols at UHCMC

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Phrenic Nerves Need to be Intact

- Phrenic nerve studies
  - High false positive and false negative test
- Surgical evaluation is the final test
- Diagnostic Laparoscopy is accepted by patients
  - "I need to know if I can get of the ventilator"

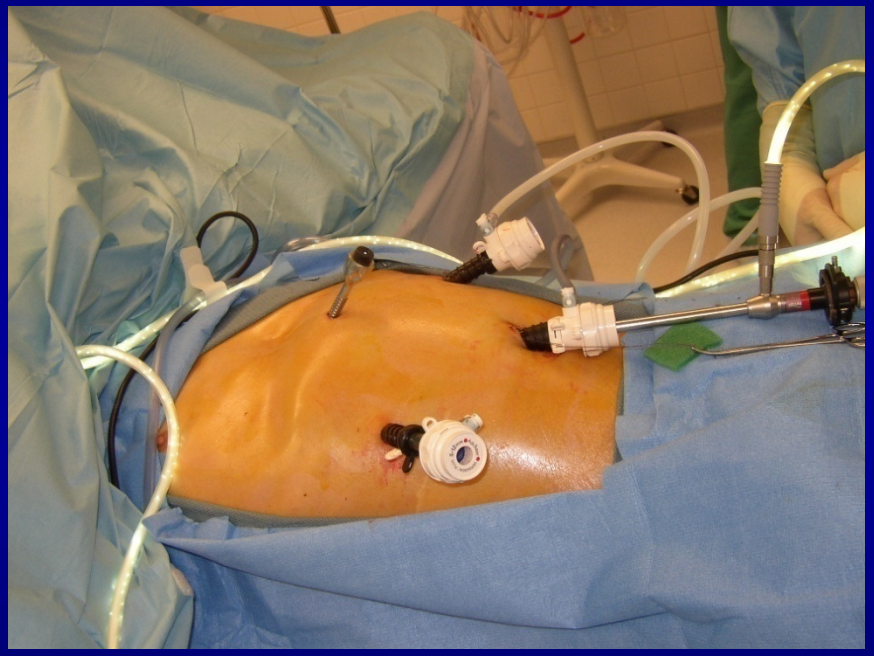
Muscle Nerve **38:** 1546–1552, 2008

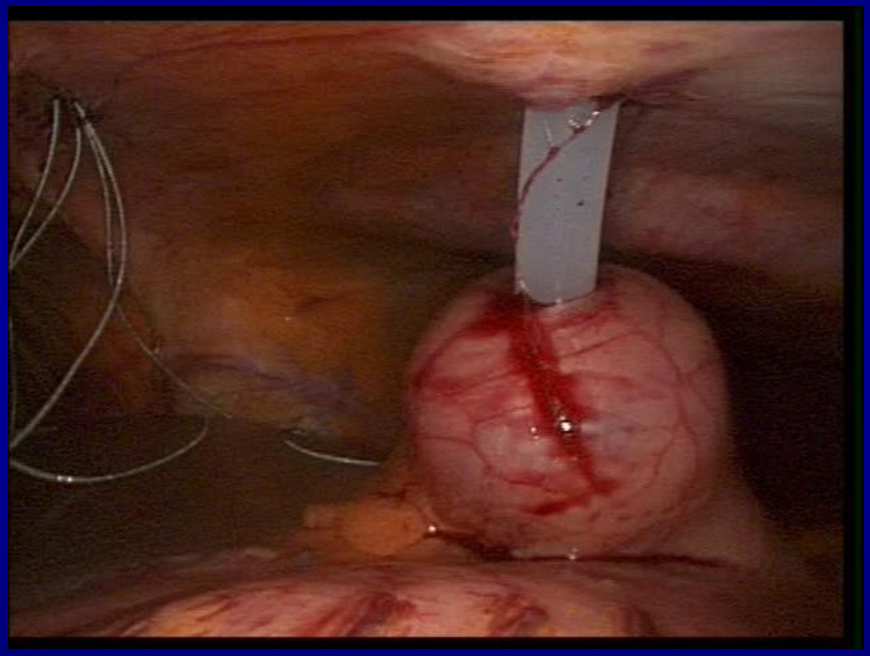
PHRENIC NERVE CONDUCTION STUDIES IN SPINAL CORD INJURY: APPLICATIONS FOR DIAPHRAGMATIC PACING

AMER ALSHEKHLEE, MD, MSc,[1] RAYMOND P. ONDERS, MD,[2] TANVIR U. SYED, MD, MPH,[1] MARYJO ELMO, ACNP,[2] and BASHAR KATIRJI, MD[1]

Methods: Outpatient Laparoscopic Procedure

Simultaneous Gastrostomy Tubes





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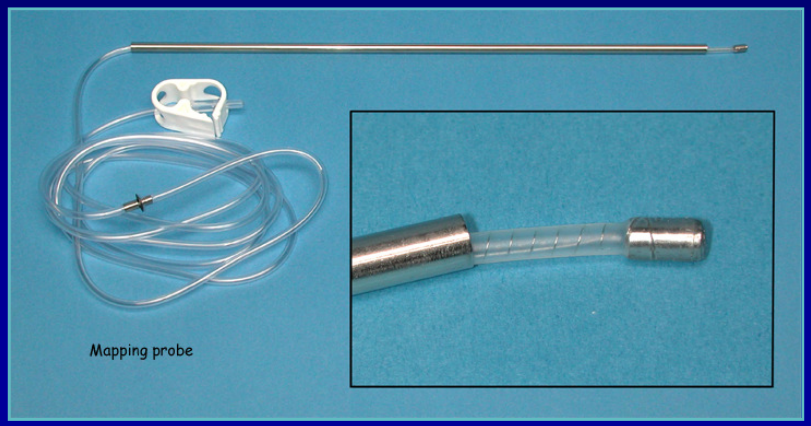
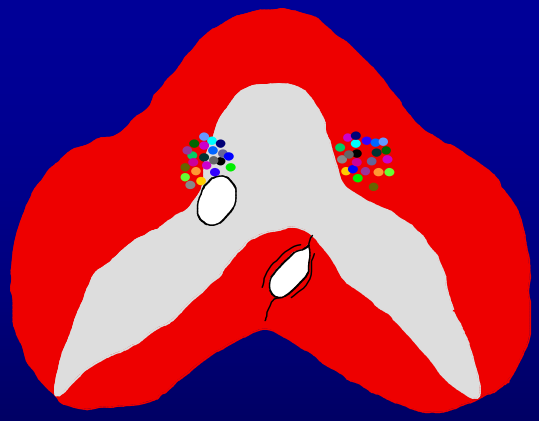
Methods: Laparoscopic Mapping of the Motor Point- Where Maximum Contraction Occurs

The key to finding the spot to implant electrodes





Onders, Aiyar, Mortimer. Am Surg 2004;70:241-7

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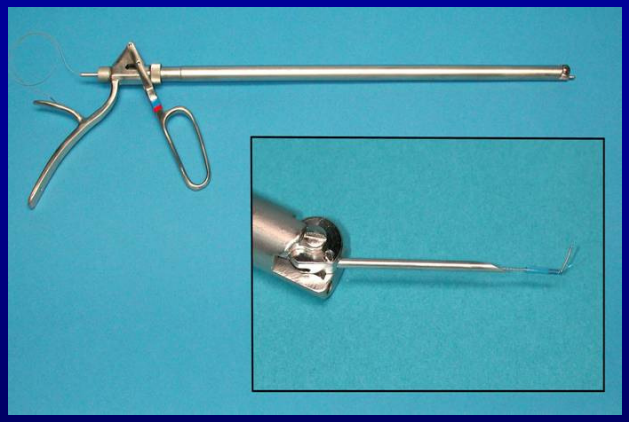
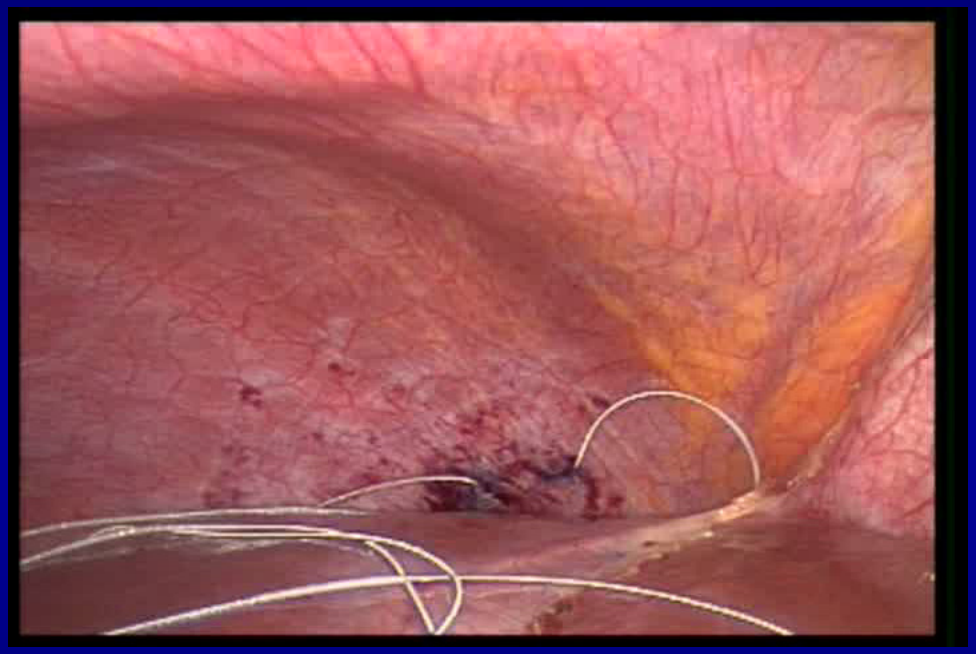
Implanting Electrodes and Stimulating the Diaphragm





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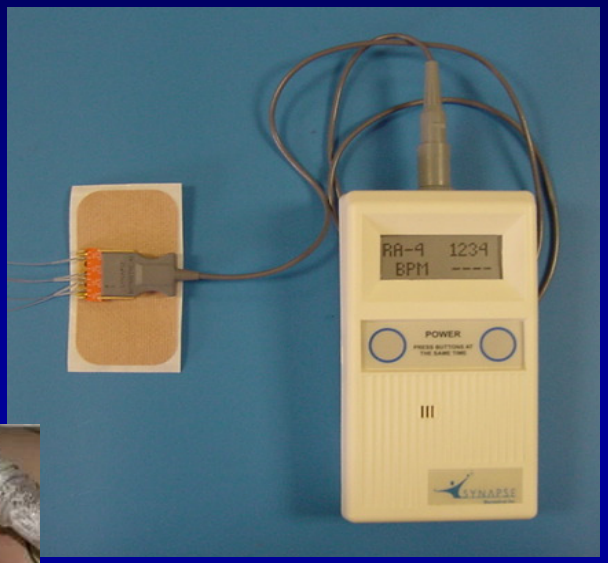
Programming Settings

- Setting optimized for each patient
  - Comfortable tidal volume with frequency less than 20
- Each diaphragm and electrode different settings
- Control options
  - Amplitude
  - Frequency
  - Rate
  - Pulse Width
  - Pulse Modulation



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Conditioning and Weaning from the Ventilator

- Increasing diaphragm muscle strength and converting the muscle fibers.
- DP turned on and ventilator turned off
- Patients returned to ventilator when O2 saturation drops or dyspnea develops
- Sessions can be repeated in 45 minutes
- Time for conditioning depends on time from injury and amount of training done per day

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Results- Age and Length of Time on Ventilator Effects on Reaching 4 Continuous Hours of DPS

Onders et al Spinal Cord Medicine 2007

- 18-20 yo on MV < 1 yr: 1 week
- 40-50 yo on MV > 5 yr: 14 weeks
- >65 years old 21 weeks
- Required Scoliosis Rx 30 weeks

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SCI Results at UHCMC

- 81 patients implanted
- Age 2- 74
- Time From Injury 11 days to 25 years
- Median Hospital stay less than 24 hours
- All patients –surpassed basal respiratory needs
- First implant 2000- over ten years continuous use
  - Removed tracheostomy 2009

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SCI Results IDE trial – 50 patients
Median Hospital stay < 24 hours

	SCI Subjects (n=50)
Peri-operative Mortality	0
Device Related Mortality	0
Long Term Mortality	5(10%)
Morbidity	
Wound Infections	2
Diaphragm Injury	0
Diaphragm Laceration	0
Solid Organ Injury	0
Bleeding	0
Bowel Injury	0
Conversion to Open	0
Pneumothorax	0
Capnothorax	21 / 50 (42%)
Device	
Device Erosion	0
Device Migration	0
Lead Impedance Out of Range	0

- 68% Decreased Secretions
  - Less Suctioning
- Over 50% 24hours a day
- Longest 10 years

Surg Endosc
DOI 10.1007/s00464-008-0223-3

Complete worldwide operative experience in laparoscopic diaphragm pacing: results and differences in spinal cord injured patients and amyotrophic lateral sclerosis patients

Raymond P. Onders · MaryJo Elmo · Saeid Khansarinia · Brock Bowman · John Yee · Jeremy Road · Barbara Bass · Brian Dunkin · Páll E. Ingvarsson · Margrét Oddsdóttir

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Primary Endpoint Tidal Volume
Initial IDE trial

	Average	Stdev	Min	Max
Basal Metabolic Requirement (ml)				
Male (7ml/kg)	**575**	109	399	889
Female (6ml/kg)	**355**	79	240	504
Stimulated Tidal Volume (ml)				
Male	***816***	207	540	1500
Female	***528***	97	350	680
Minute Ventilation (liters / min)				
Male	10	3	6	18
Female	6	1	4	9

- **p<0.001 paired comparison of the stimulated tidal volume with the basal metabolic**

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Long Term Results
Over 200 Cumulative Years

- One internal electrode failures
- One patient superficial wire infection stopped pacing temporarily
- Causes of Death(11)- No Device Related deaths
  - 3 Urosepsis
  - 3 Cardiac(Elderly and long term injured)
    - 1 Endocarditis
  - 2 Complications from Decubiti
    - 1 Systemic Mastocytosis
  - 1 Aspiration- Sepsis
  - 1 recurrence of tumor and sepsis
  - 1 Heat Stroke

Decreasing Pneumonias

Historically average 2 per year

- No deaths from pneumonias
- 5 hospitalizations for pneumonias
- Patients and Caregivers report 60% less secretions with DP

Spinal Cord (2008), 1–5

www.nature.com/sc

ORIGINAL ARTICLE

Mechanical ventilation or phrenic nerve stimulation for treatment of spinal cord injury-induced respiratory insufficiency

S Hirschfeld[1], G Exner[1], T Luukkaala[2,3] and GA Baer[4]

[1]BG-Trauma Hospital, Hamburg, Germany; [2]Research Unit, Pirkanmaa Hospital District, University of Tampere, Tampere, Finland; [3]Tampere School of Public Health, University of Tampere, Tampere, Finland and [4]Department of Anaesthesiology, Medical School, University of Tampere, Tampere, Finland

Mode of ventilation	*Period 1*	*Period 2*
PNS	1.43 (0.05–3.92)	0 (0–0.92)
MV	1.33 (0.89–2.21)	2.07 (1.49–4.19)
P_3	0.888	<0.001

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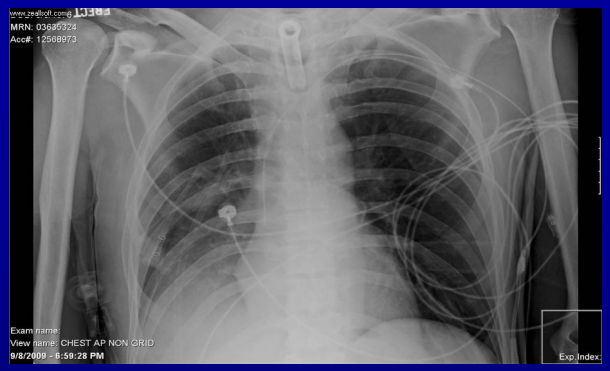
Improving Ventilation- Preventing Pneumonia

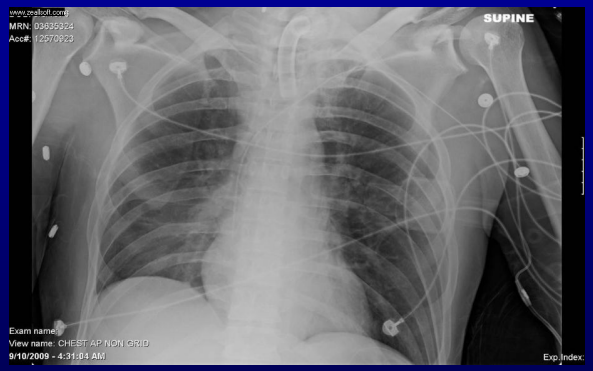
*Improve respiratory compliance- 18%**

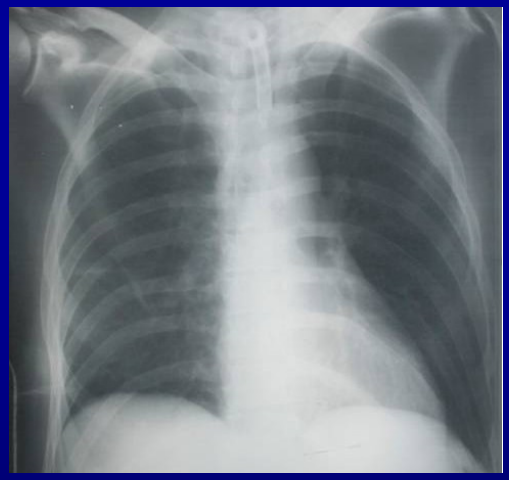
DP improves posterior lobe ventilation



Day before implantation
Incomplete SCI C3
Three previous pneumonias

One Day of Pacing





5 Months Later Recovered Diaphragm Control

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*Onders, Elmo et al , Chest 2007

Diaphragm Pacing Stimulation System for Tetraplegia in Individuals Injured During Childhood or Adolescence

Raymond P. Onders, MD[1]; Mary Jo Elmo, ACNP[1]; Anthony R. Ignagni[2]

[1]Department of Surgery, Case Medical Center of University Hospitals and Case Western Reserve University, Cleveland

- 10 SCI children
- Age at injury avg 13 (range 1-17)
- Injury to DPS average 9 years (range 1-19)
- All Successful
- Scoliosis delays success

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First reported experience with intramuscular diaphragm pacing in replacing positive pressure mechanical ventilators in children☆,☆☆

Raymond P. Onders[a,*], Todd A. Ponsky[b], MaryJo Elmo[a], Karen Lidsky[c], Edward Barksdale[b]

Journal of Pediatric Surgery

- Age 5-17, weight as low as 15 Kg
- Time on MV 11 days to 7 years
- Two full time, 4 conditioning

Patient	Injury	Time on Ventilator (months)	Age at Implant	Weight (kg)	Pacing Achieved (hours)
1	MVA	50	9	39	12*
2	MVA	28	5	19	8*
3	Brain Stem Tumor	13	7	31	Fulltime
4	MVA	92	10	24	22
5	MVA	48	7	15	14*
6	Football	0	17	68	Fulltime

Similarities and Differences from Adults

- Surgery/Anesthesia
  - No difference from adult implantation
    - You may use one less port dependant on size
  - Four patients sent home same day as implantation
- Programming
  - Lower settings – higher breaths per minute
  - Adjust with growth/weight gain
- Conditioning
  - More anxiety in younger children
  - TLSO braces “feel tight” – harder to breathe
  - Early implantation = faster/easier conditioning
  - Parental Encouragement -KEY

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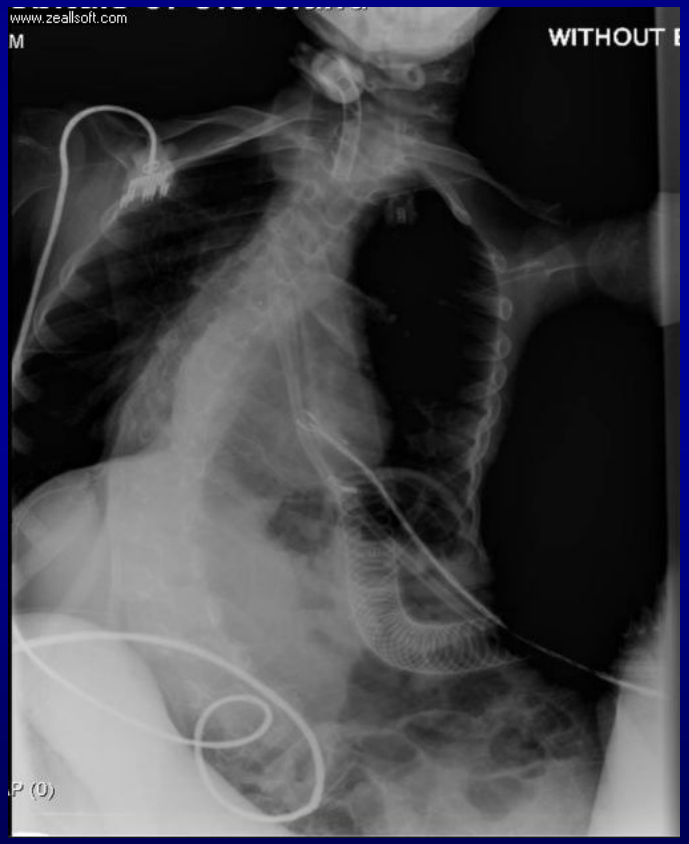
Scoliosis Significantly Impedes Breathing

Worsening Scoliosis made DP less effective



Improved breathing with pacing post surgery

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Multicenter analysis of diaphragm pacing in tetraplegics with cardiac pacemakers: Positive implications for ventilator weaning in intensive care units

Raymond P. Onders, MD,[a] Saeid Khansarinia, MD,[b] Todd Weiser, MD,[c] Cynthia Chin, MD,[c] Eric Hungness, MD,[d] Nathaniel Soper, MD,[d] Alberto DeHoyos, MD,[d] Tim Cole, MD,[e] *and* Christopher Ducko, MD,[f] *Cleveland, OH, Atlanta, GA, New York, NY, Chicago, IL, Lincoln, NE, and Boston, MA*

- 10 in IDE trial 06-07/ 10 post HDE 09
- No device to device interactions
  - Over 40 cumulative years
  - All with adequate tidal volumes
- 70% use DP 24 hours a day
  - No mechanical ventilation

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EARLY USE OF DIAPHRAGM PACING IN SPINAL CORD INJURY TO WEAN FROM VENTILATORS: DECREASING INTENSIVE CARE UNIT STAYS AND COSTS

Onders, Lottenberg, Cheatam et al AAST 2010

AMERICAN ASSOCIATION FOR THE SURGERY OF TRAUMA

- 5 Patients during initial trauma admission
  - 7 days to 8 weeks post injury
  - 2 no health insurance
  - Weaning one day to 4 weeks
- 4 transferred to rehabilitation center
- 2 patients weaned from DP
  - Temporary use

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SCI Quality of Life "Stories"

- No need for continuous electricity
  - Hurricanes or Snowstorms concerns alleviated
- Silence of the pacer enabled sleeping
- Increased ability to attend school or church
- Transfer from ventilator nursing ward to home
- Increased ability for air travel
- One patient had not left her house for 7 yrs
  - First trip Disney World

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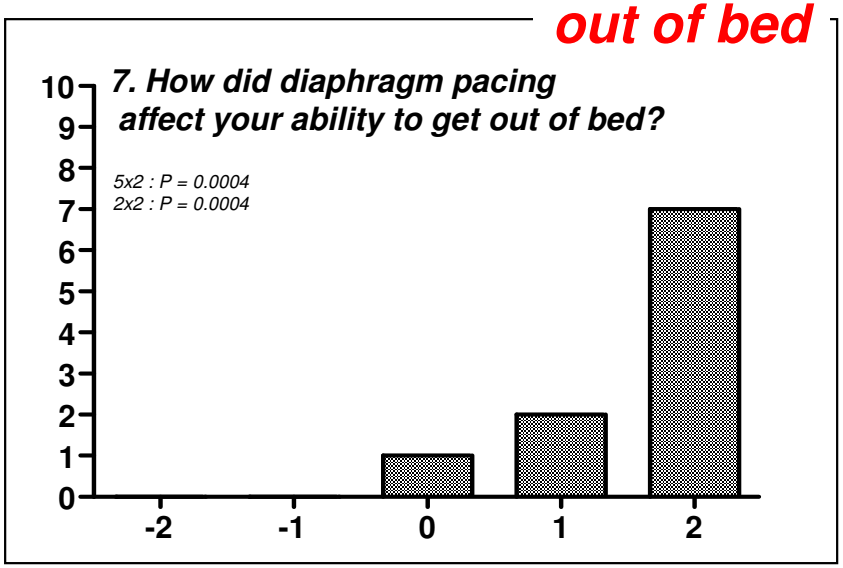
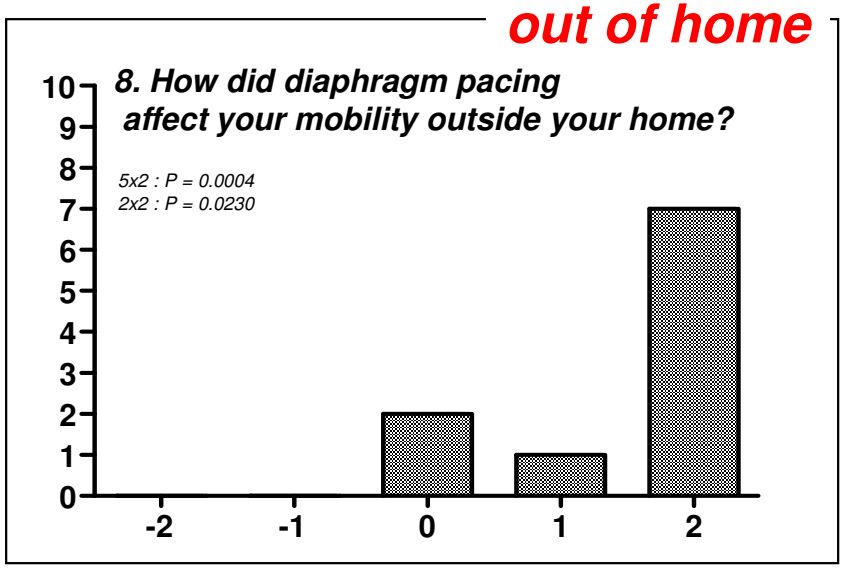
Similowski et al 2009 Quality of Life post pacing

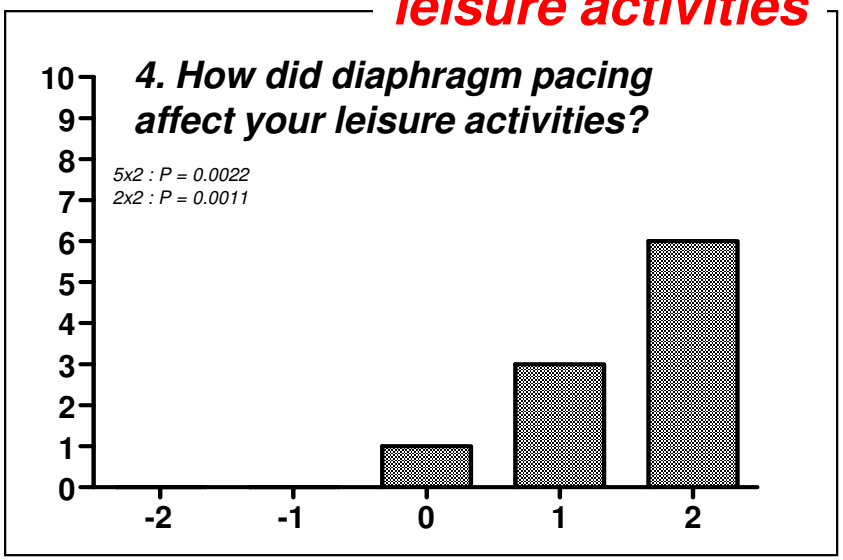
out of bed



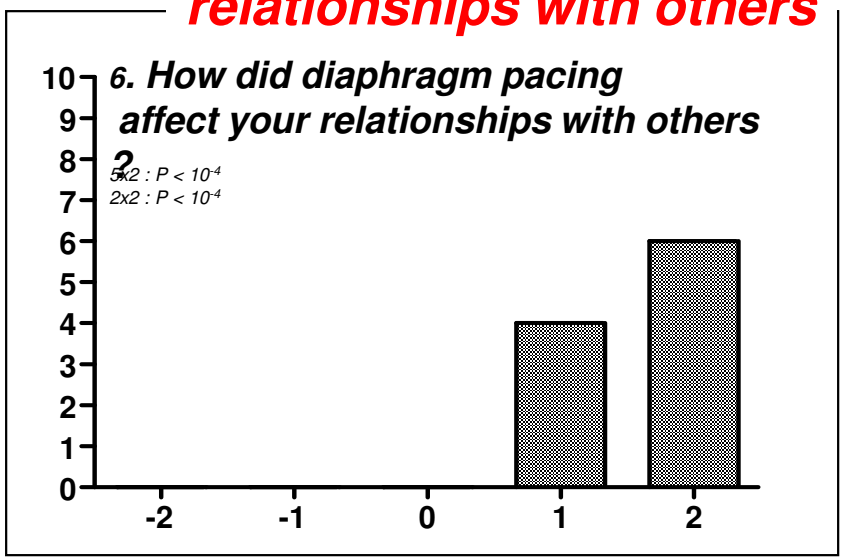
out of home



leisure activities

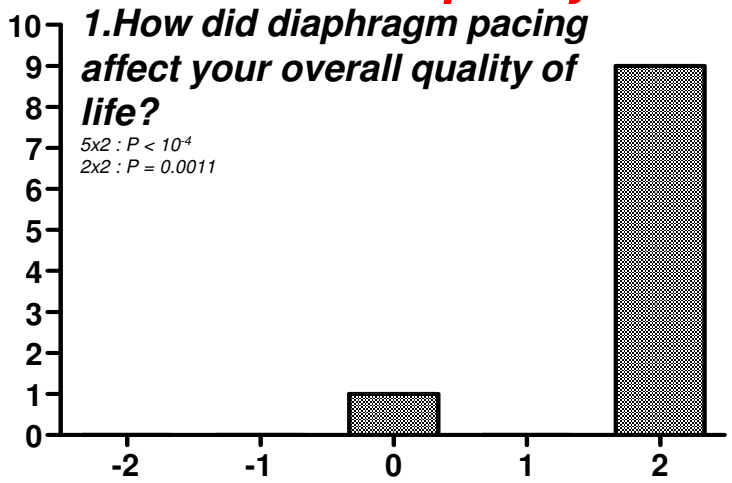


relationships with others

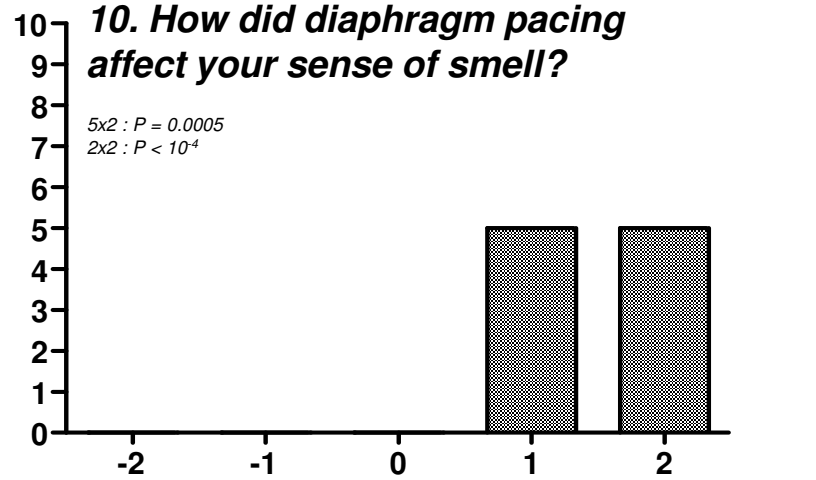


Similowski et al 2009 Quality of Life post pacing

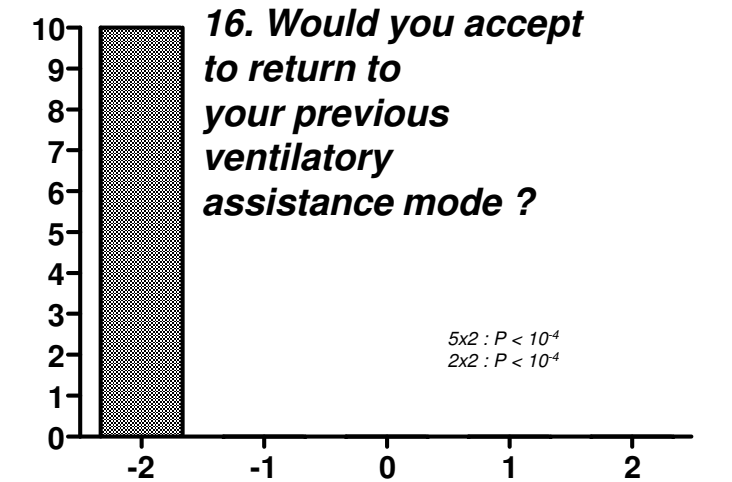
quality of life



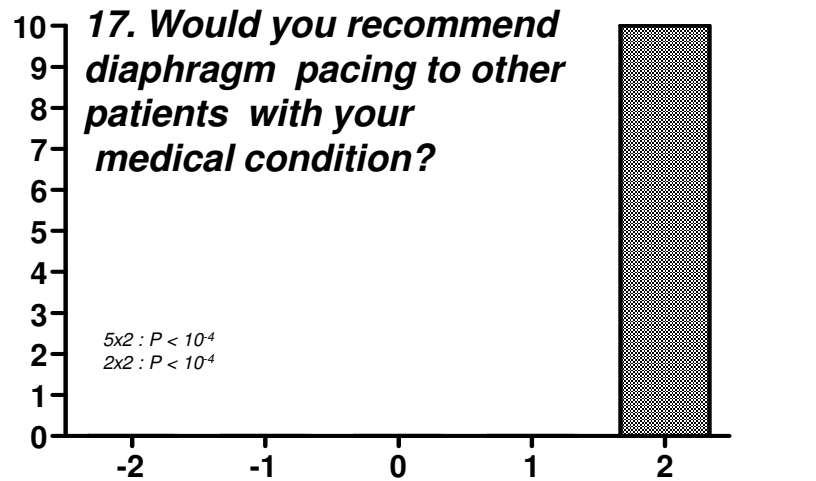
olfaction



back to MV



recommend



Simplifies Activities

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Improves Leisure Activities

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Relationships with others-Lived ON campus in dorm room with student caregivers

C1-2 SCI at age 18 – implanted 5 months post injury

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Tracheostomy Management

Onders, Elmo, Kaplan J Spinal Cord Medicine 2009

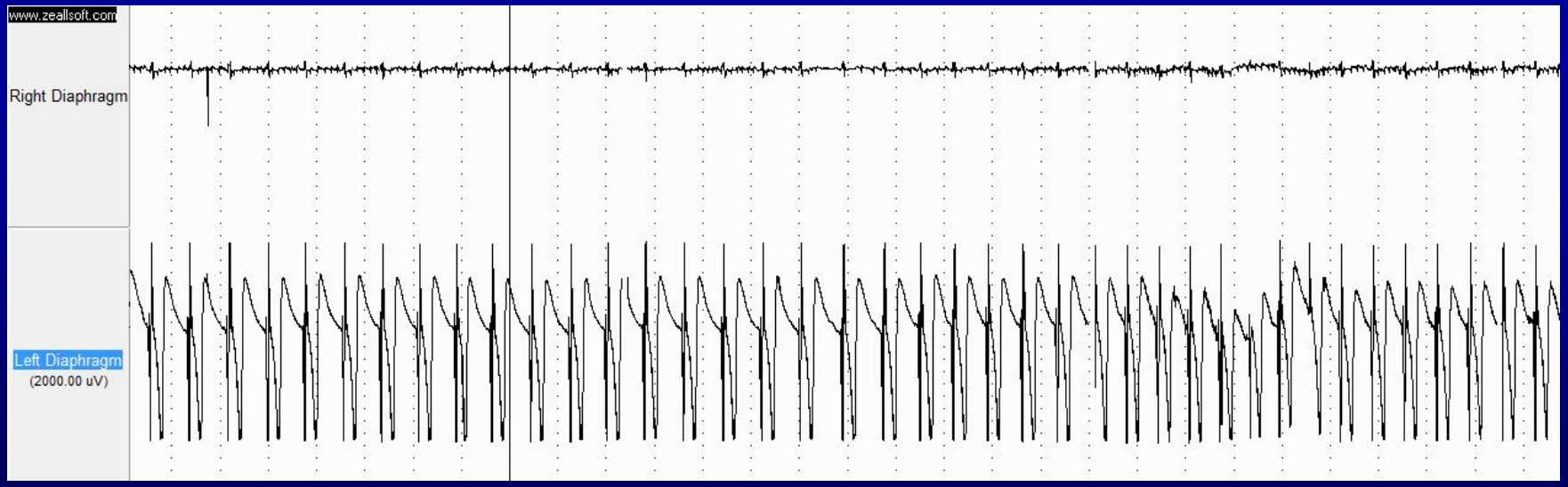
- 46 % Cuffed tracheostomy prior to DP
  - Affects natural ability of cilia to clear secretions
- 92% Cuffless post DP
- Routine downsizing of tracheostomies
- Tracheostomy plugs
- 4 Decanulations

Mechanical Ventilation Stops Diaphragm Activity

Respiratory Instability in SCI- Acquired Central Sleep Apnea

Intermittent Weaning Leads to recurrent atelectasis and atrophy of diaphragm

Diaphragm EMG while on PPV



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Acquired Central Sleep Apnea in SCI

Onders et al J Spinal Cord Med 2009

- 4 patients 2006-2008
  - Age 18-59, post injury 3-24 years
  - All tracheostomy Ventilator Dependent at night
- Initially use DP during the day
  - All still do- "Do not have to think of breathing"
- Sleep with Passy- Muir at night
- All capped tracheostomy eventually with no obstructive symptoms
- One removed tracheostomy

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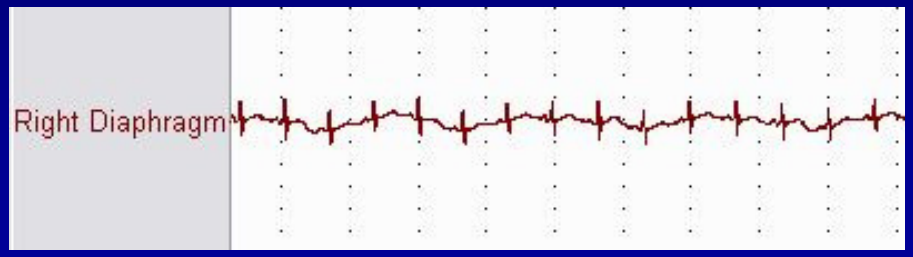
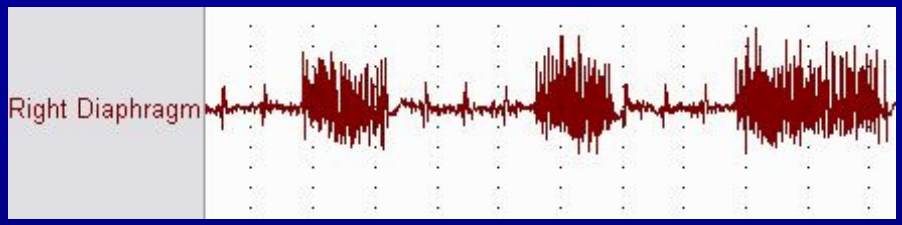
Implantation and Neuroplasticity

- Four patients have gone from Ventilators to DPS to volitional breathing
- DPS electrodes functions as EMG to assess recovery
- FES lead to recovery
- Can be used as a “biomarker” to assess other early aggressive therapies



Prior to DPS: NO EMG ACTIVITY



After DPS Conditioning:
Recovery of Natural Function

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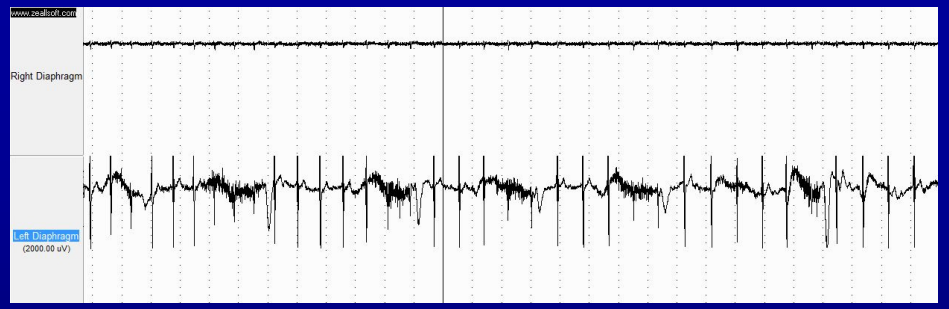
Neuroplasticity- Diaphragm Recovery First Middle East Implant- KKUH

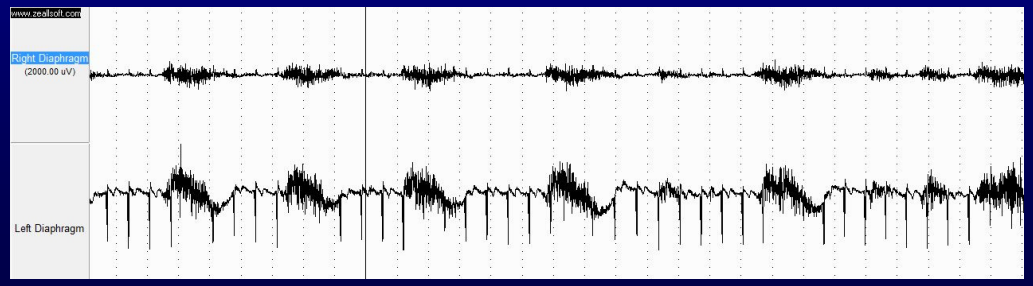
- 23 year old SCI
  - MV over a year
  - Cuffed trach
- Implanted Jan
- Weaned from Ventilator in 10 days
- Cuffless trach
- ***October evaluation recovered right diaphragm activity***

Diaphragm EMG on Ventilator

dEMG off Ventilator before DP



dEMG off Ventilator in October



DPS Replaces Mechanical Ventilation in Tetraplegics

- The DPS system is safe and effective
- ***In Ohio, save $13,000 dollars per patient per month***
- No patients stopped pacing and all would recommend it
  - *Adler et al Eur Resp J 2009*
- Earlier use and temporary use in weaning could decrease pneumonias

All patients with an intact phrenic nerves should be offered diaphragm pacing to allow natural diaphragm breathing

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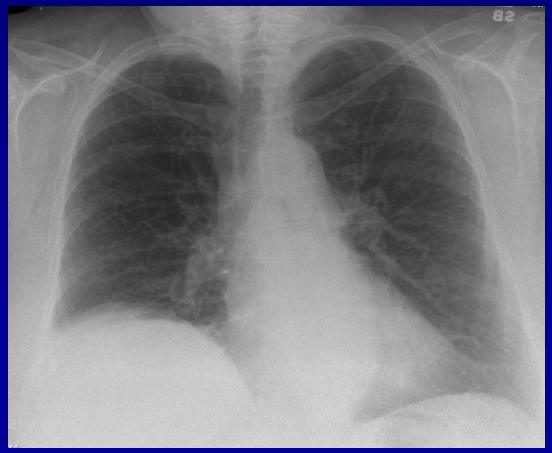
Idiopathic Diaphragm Dysfunction



- Negative phrenic nerve studies
- Paradoxical movement on flouroscopy
- Diaphragm stimulatable at surgery or plication done
- Five patients implanted
  - Early results positive

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Can DPS decrease Mechanical Ventilation in the ICU?

- 33-50% of ICU pts require mechanical ventilation
- 20% on ventilator > 7 days
- 40% time spent on weaning
- Over 100,000 tracheostomies performed yearly for failure to wean
- ICU costs $4000 per day

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Positive Pressure Ventilation Damages the Diaphragm

- One night of PPV causes marked atrophy
- 57% decrease Type 1 slow twitch
- Active muscles atrophy faster
- ***DP maintains Type 1 muscle fibers and prevents atrophy***

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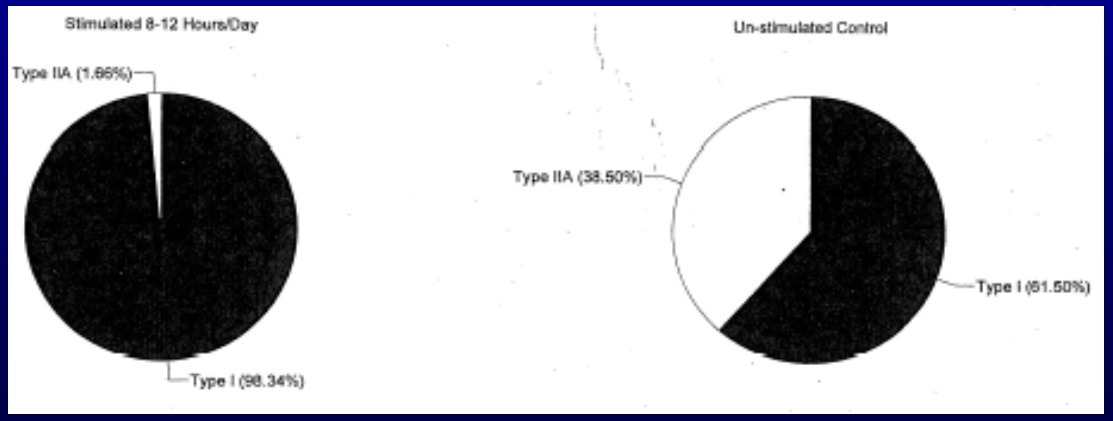
Rapid Disuse Atrophy of Diaphragm Fibers in Mechanically Ventilated Humans

Sanford Levine, M.D., Taitan Nguyen, B.S.E., Nyali Taylor, M.D., M.P.H., Michael E. Friscia, M.D., Murat T. Budak, M.D., Ph.D., Pamela Rothenberg, B.A., Jianliang Zhu, M.D., Rajeev Sachdeva, M.D., Seema Sonnad, Ph.D., Larry R. Kaiser, M.D., Neal A. Rubinstein, M.D., Ph.D., Scott K. Powers, Ph.D., Ed.D., and Joseph B. Shrager, M.D.

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 41, NO. 12, DECEMBER 1994 1115

Long-Term Intramuscular Electrical Activation of the Phrenic Nerve: Safety and Reliability

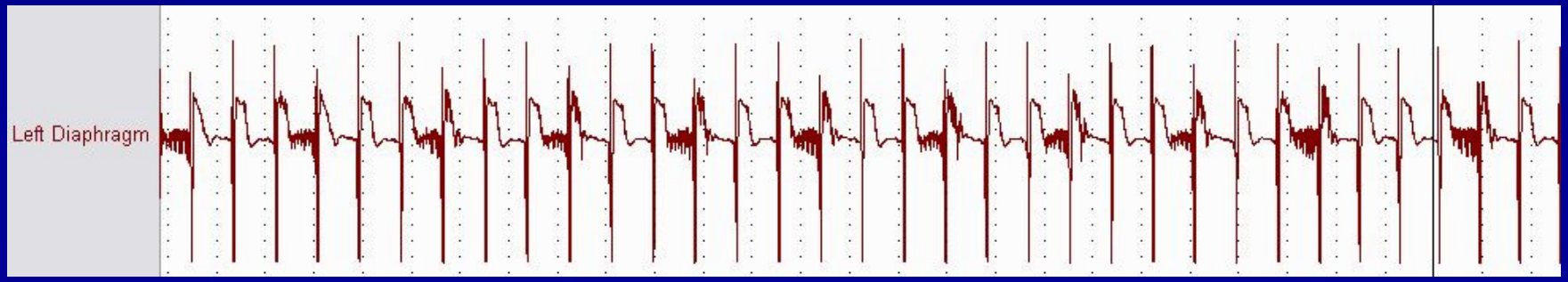
David K. Peterson, *Member, IEEE,* Michael L. Nochomovitz, Thomas A. Stellato, and J. Thomas Mortimer

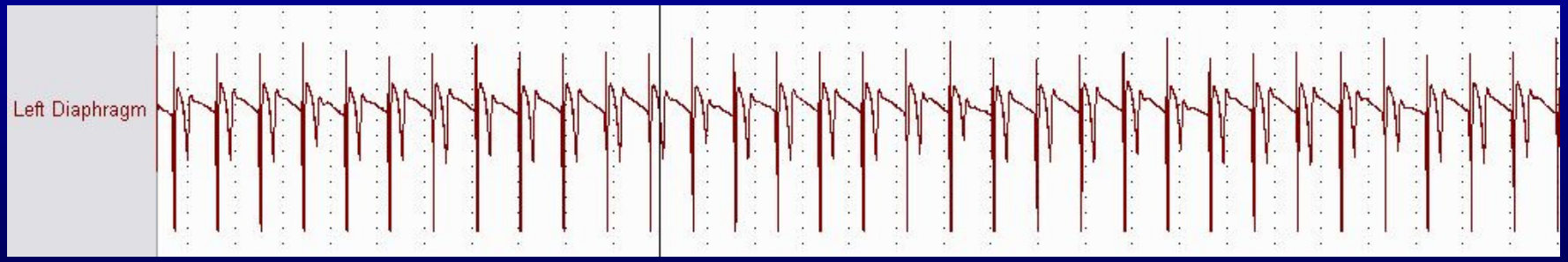


PPV Stops Diaphragm Activity

Sleep studies looking at diaphragm EMG shows no activity when on PPV- Making Diaphragm Weaker

Diaphragm EMG without PPV





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Problems of Mechanical Ventilation

Ventilator Induced Diaphragm Dysfunction (VIDD)

- Decreases Diaphragm Strength
  - Atrophy in 12 hours
  - Type I to Type IIb muscle conversion
- Increased Thoracic Pressure
  - Decreased cardiac output
  - Barotrauma
- Posterior Lobe Collapse
  - Atelectasis and Pneumonia

Diaphragm Pacing Counteracts all of these problems

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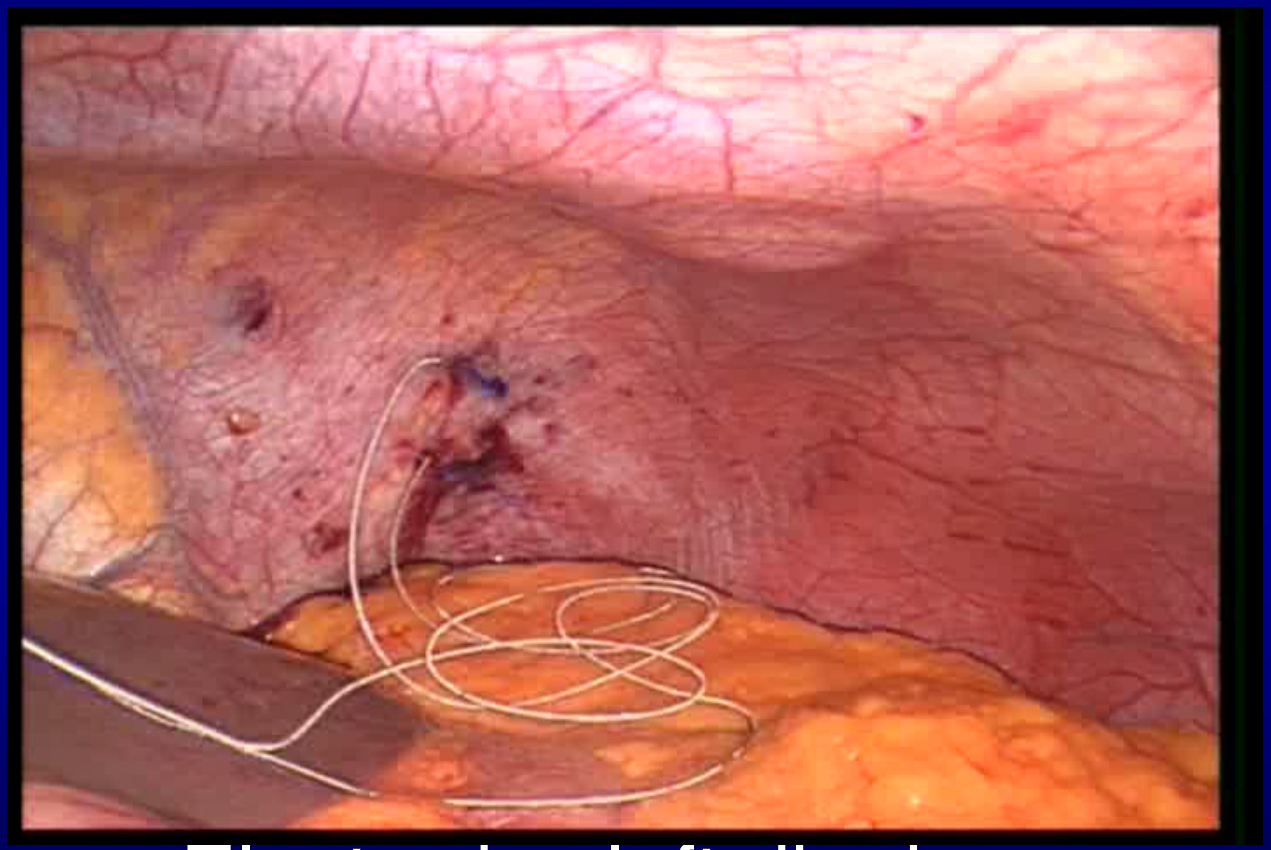
The Key Point: Stimulating the Diaphragm

The more it moves- the more you ventilate



Electrodes left diaphragm

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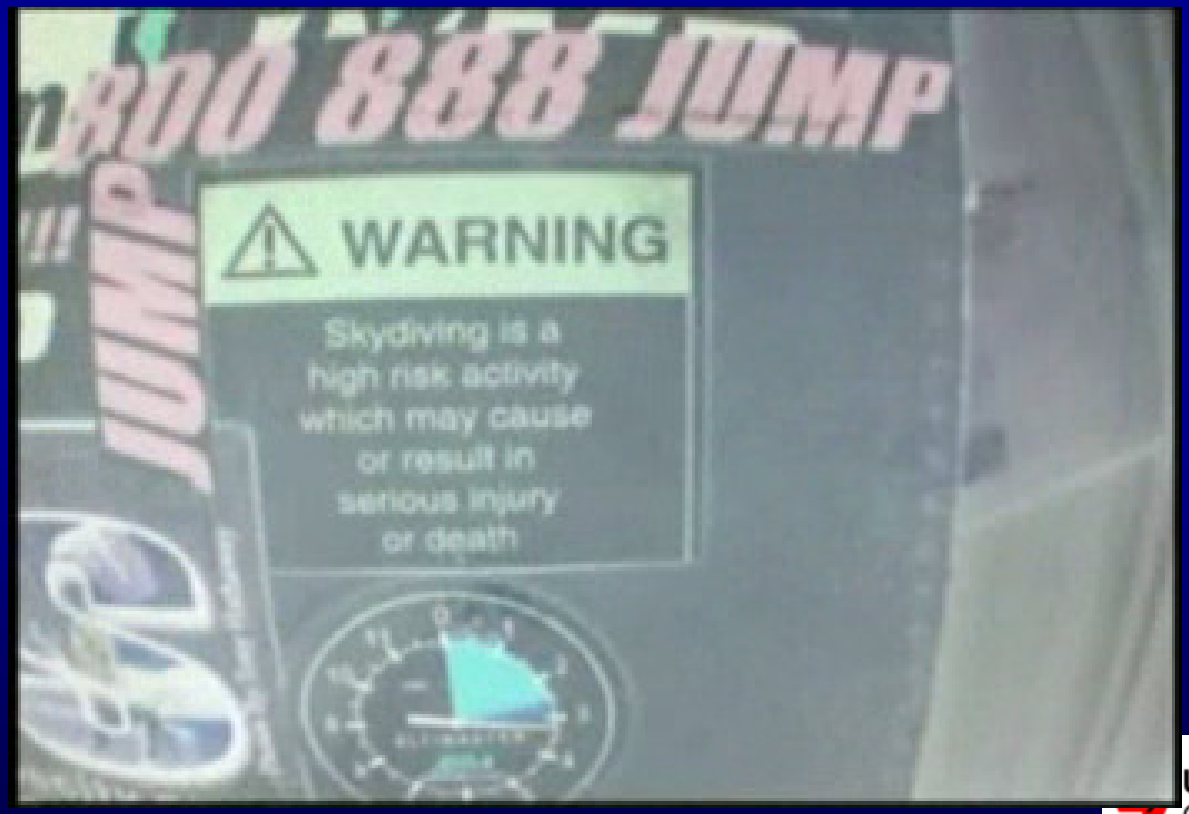
Replacing the Ventilators is the first step

- Cannot skydive with a ventilator



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Contact Information

Raymond P. Onders M.D.
Remen Chair of Surgical Innovation
Director of Minimally Invasive Surgery
University Hospitals Case Medical Center
11100 Euclid Avenue
Cleveland, Ohio 44106-5047
Phone: 216-844-5797
E-mail:
Raymond.Onders@uhhospitals.org

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