UNDERSTANDING THE CAUSE OF REVERSE TRIGGERING
BEYOND BREATH STACKING

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Breath Stacking

TWO DISTINCTLY DIFFERENT FORMS
Breath Stacking

Diaphragm contraction

Additional stacked breath
20 patients enrolled for 3 days undergoing low tidal volume ventilation

Mean RASS score -4

2 stacked breaths per minute

Low tidal volume ventilation associated with frequent breath stacking

Breath stacking results in significantly larger tidal volumes than set

Did not differentiate between types of breath stacking
67 Patients from 3 ICUs

-Occurs in all patients

-Double cycling is infrequent overall but occurs in clusters

-Breath stacking results in large tidal volumes (at times doubling the set tidal volume)

-Roughly 1/3 of events were caused by reverse triggering
33 patients

Improve identification of breath stacking dyssynchrony with objective criteria

- Ventilator cycling, interval expiratory volume, cumulative inspiratory volume, expiratory time, and inspiratory time.
Breath Stacking– Two flavors

Reverse triggering secondary to entrainment

Double triggering with ↑ respiratory effort/time
Reverse Triggering without Breath Stacking
Mechanical Ventilation-Induced Reverse-Triggered Breaths

A Frequently Unrecognized Form of Neuromechanical Coupling

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- 8 deeply sedated patients with ARDS monitored
- RT frequency relative to ventilator delivered breaths.
- Thought secondary to sedation unmasking neuro-mechanical coupling secondary to entrainment
What is Respiratory Entrainment?

- Evolutionary response to optimize breathing during locomotion
  - Recorded in rabbits, dogs, horses, and humans
- Quadruped species synchronize locomotor and respiratory cycles at constant ratio of 1:1 (strides per breath)
- Humans employ several patterns while running (4:1, 3:1, 2:1, 1:1, 5:2, and 3:2)
Neuro-Mechanical Coupling

- Mechanical ventilation external oscillator (instead of locomotion)
  - Vagally mediated pulmonary reflexes (Hering-Breuer reflex)
- Animals and healthy humans:
  - Respiratory rhythm can be entrained or phase locked to extrinsic periodic mechanical inflations imposed during controlled mechanical ventilation
- “Unconscious” response to make the breath more comfortable

Figure 1. Stable temporal relationship between inspiratory efforts and machine inflations, with the diaphragm contractions occurring at a consistent time relative to the ventilator cycle. This example shows a 1:1 entrainment pattern, i.e., for each machine cycle there is one inspiratory effort.

Reverse Triggering: Neuromechanical Coupling

Coupling of Diaphragm Contraction to Vent Delivered Breath

During breath holds no diaphragm contraction. Entrainment resumes with next breath.

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Reverse Triggering: Neuromechanical Coupling

Coupling of Diaphragm Contraction to Vent Delivered Breath: No Spontaneous Breaths

During expiratory breath hold diaphragm contractions continue at the same rate

During inspiratory breath hold diaphragm contractions stop and then resume with next vent delivered breath

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Reverse Trigger Timing

Reverse Trigger Initiation

1. Gastric/Esophageal Pressure
2. Corrected Volume
3. Airway Pressure
4. Flow

Reverse Trigger Initiation

1. Gastric/Esophageal Pressure
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Inspiratory and Expiratory Phases
Reverse Triggering Phenotypes

HOW TO DIFFERENTIATE
Campbell Diagram: Lung Volume vs Pleural Pressure

- $P_{\text{alveoli}}$
- $P_{\text{pleura}}$
- $P_{\text{transpulmonary}}$
- $P_{\text{airway opening}}$

- Lung Elastic Recoil
- Relaxed Chest Wall
- FRC
- $V_L$
- $V_{\text{rel}}$
- $P_{\text{mus}}$
- $P_{\text{Pi}}$
Same Pes can be either an inspiratory effort or expiratory effort depending on lung volume.
Early Reverse Trigger

- Early RT event, with MAX contraction during inspiratory phase
- Rapid relaxation back to passive chest wall curve
- Passive Expiration Along Passive Chest Wall Compliance Curve
- Inspiration Along Passive Chest Wall Compliance Curve

Volume (ml) vs. Esophageal Pressure (cmH2O)
Early Reverse Triggering

Very brief passive inspiration

Early Diaphragm Contraction During Inspiratory Phase

Rapid Relaxation

Termination of the reverse trigger

Passive Expiration

Very brief passive inspiration

Pmus
Early Reverse Trigger with Slight Delayed Relaxation

- Early RT event, with MAX contraction during inspiratory phase
- Rapid relaxation back to passive chest wall curve

Volume (ml) vs. Esophageal Pressure (cmH2O)

Passive Expiration Along Passive Chest Wall Compliance Curve

Inspiration Along Passive Chest Wall Compliance Curve
Early Reverse Trigger: Slight Delayed Relaxation

- Passive inspiration
- Active Contraction Completely During Inspiratory Phase
- Slight Delay in Relaxation Back to Passive Chest Wall
- Pmus
- Termination of the reverse trigger
- Passive expiration

[Graph showing various pressure and volume trends with labeled key points]
Early Reverse Trigger with Delayed Relaxation

- Early RT with MAX contraction completely during the inspiratory phase.
- Delayed relaxation to the passive chest wall compliance curve. Likely secondary to prolonged diaphragmatic activity.
- Inspiration Along Passive Chest Wall Compliance Curve.
Early Reverse Trigger: Delayed Relaxation

- Passive inspiration
- Active Contraction
- Completely During Inspiratory Phase
- Long Delay in Relaxation Back to Passive Chest Wall
- Pmus
- Termination of the reverse trigger
- Passive inspiration

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Mid Cycle Reverse Trigger

- **RT with eccentric contraction extending into expiratory phase**
- **RT with concentric contraction beginning in the inspiratory phase**
- **Delayed relaxation to the passive chest wall compliance curve.**
- **Inspiration Along Passive Chest Wall Compliance Curve**

### Graph:
- **Volume (ml)**
- **Esophageal Pressure (cmH2O)**
Mid Cycle Reverse Trigger

-被动

-主动收缩

-开始于吸气相

-放松到被动胸壁

-主动收缩

-延展到呼气相

-终止反向触发

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Late Reverse Trigger

Volume (ml)

Esophageal Pressure (cmH2O)

RT with contraction occurring completely during the expiratory phase

Delayed relaxation to the passive chest wall compliance curve.

Inspiration Along Passive Chest Wall Compliance Curve
Late Reverse Trigger

Passive inspiration

Delayed Relaxation to Passive Chest Wall

Active Contraction During Expiratory Phase

Pmus

Passive inspiration

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Reverse Trigger with Breath Stacking

RT with contraction occurring completely during the expiratory phase

Expiration Along Passive Chest Wall Compliance Curve

Sufficient contraction from RT to trigger a stacked breath

Inspiration Along Passive Chest Wall Compliance Curve

Delay relaxation to the passive chest wall compliance curve.

Expiration Along Passive Chest Wall Compliance Curve

Inspiration Along Passive Chest Wall Compliance Curve

Relaxation back to passive chest wall

Sufficient contraction from RT to trigger a stacked breath

RT with contraction occurring completely during the expiratory phase

Volume (ml)

Esophageal Pressure (cmH2O)

Volume (ml)

Esophageal Pressure (cmH2O)
Reverse Trigger With and Without Breath Stacking
Clinical Implications
Reverse Trigger with Breath Stacking

- Very common: occurring in many patients infrequently
  - Su et al: 30% of patients
  - De Haro: All patients with double cycling, 1/3 of events RT
- May result in significantly higher tidal volumes than desired
  - Su et al: (588.5 ± 142.8 mL vs. 404.8 ± 71.1 mL, p=0.00016)
  - Up to 10cc/kg in many patients
- Large transpulmonary pressure swings
- Frequency and Magnitude Likely Important
  - Isolated RT with breath stacking could act as a “sigh” and either be harmless or even serve as a mini recruitment maneuver
  - Frequent events may be harmful

Intensive Care Med. 2019 Aug;45(8):1161-1162
Crit Care Med. 2018 Sep;46(9):1385-1392.
Reverse Trigger Effects During Inspiratory Phase

- Increased tidal volumes
- Increased end-inspiratory transpulmonary pressures
- Increased mean inspiratory transpulmonary pressures

Increased tidal volume compared with adjacent passive breath

Small Airway pressure and flow deviations are a clue for RT

Higher mean and end-inspiratory transpulmonary pressures

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Reverse Trigger Induced Lung Injury?

- Similar to spontaneous breathing?
- Could large tidal volumes and transpulmonary pressure changes be injurious?
- Forces generated by respiratory muscles: regional injurious effects
  - Dependent regions
  - Regional transpulmonary pressure magnified by stress raisers and diaphragm shape
- Pendelluft from Reverse Triggering?
- Could the effect vary depending on severity of lung injury?

Yoshida et al. Am J Respir Crit Care Med. 2017 Sep 1;196(5):590-601
Reverse Trigger Effects During Expiratory Phase

- Increased mean expiratory transpulmonary pressures
- Increased end-expiratory transpulmonary pressure

Contraction during expiration results in volume loss “knee”

The transient decrease in expiratory flow can be used as a clue with standard waveforms

Transpulmonary pressures are significantly higher during expiration

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Reverse Triggering Effects During Expiratory Phase

- Early RT with delayed relaxation
  - Increased transpulmonary pressure during expiration compared to expected (passive chest wall)
  - Could this act as an “expiratory brake”? 

Expiratory transpulmonary pressures is passive based upon the passive chest wall

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Expiratory Brake

- ARDS induced in 10 anesthetized, spontaneously breathing pigs.
- Diaphragmatic electric activity during expiration, dynamic computed tomographic scans, and respiratory mechanics.
- Five pigs, protocol repeated during mechanical ventilation after muscle paralysis.

Damage from Eccentric Contractions

- 6 dogs studied with triggered diaphragm contractions during elongation (eccentric contractions)
- Elongation of diaphragm via external abdominal pressure
- Deterioration of muscle function
- Structural muscle damage

Arch Bronconeumol. 2009 Feb;45(2):68-74
Reverse Triggering is Common
Not well recognized at the bedside
Challenging to detect using standard airway-time tracings
We should not lump all forms together
How can we modify?
- PEEP, sedation, ventilator mode
The timing of reverse trigger within the inspiratory or expiratory phases
- Different effects on transpulmonary pressures and lung volumes
- May have unique clinical consequences
Improved phenotyping needed to understand clinical consequences
- Which phenotypes may be tolerable, beneficial or harmful
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Discussion Slides
Important Clinical Questions

- Mechanical ventilation mode
- Effect of PEEP
- Effect of sedation
- Clinical correlations of each phenotype with and without breath stacking
- Aside from paralysis, how can we treat
Reverse Trigger Timing

- Phase angle $\theta = \frac{\text{Phase delay}}{\text{machine cycle duration}} \times 360^\circ$
- Entrainment delay from $0^\circ$ to $+180^\circ$
- Difficult to use at the bedside
- Does not account for duration of efforts and how efforts relate to the inspiratory/expiratory phases
RT With and Without Breath Stacking
Reverse Trigger Detection Challenges
Early vs. Passive: (n=26)
Vt: 452.1 +/- 112.6 vs. 392.8 +/- 73.3, \( p=0.0068 \)
Mid Inspiratory Cycle Entrainment

Diaphragm Contraction more concordant with ventilator – Primarily concentric

Entrainment occurs roughly halfway into the delivered breath

Mid-cycle vs. Passive: (n=23)

Vt: 435.5 +/- 105.8 vs. 396.7 +/- 93.3, p=0.019
Can you Differentiate the patterns of entrainment from these wave forms?
An unusual pattern of entrainment

- Pattern found in MANY patients of alternating patient initiated and then passive breaths
APV to CMV – Entrainment Decreases (then goes away)
Early Reverse Triggering
Mid Cycle Reverse Trigger

- Passive inspiration
- Active Contraction starting during Inspiratory Phase
- Delayed Relaxation to Passive Chest Wall
- Active Contraction extending into Expiratory Phase
- Passive inspiration

Pmus
Reverse Triggering with Breath Stacking
Reverse Trigger with Breath Stacking
How to Define Reverse Triggering Timing?

Inspiration Along
Passive Chest Wall
Compliance Curve

Sufficient contraction from RT to trigger a stacked breath

RT extending into expiration

Relaxation back to passive chest wall

Expiration Along Passive Chest Wall Compliance Curve

Inspiration Along Passive Chest Wall Compliance Curve

Volume (ml)

Esophageal Pressure (cmH2O)
The Breathing Pattern “Finger Print”
Early Reverse Trigger
Reverse Trigger Timing

Reverse Trigger Initiation

Gastric/esophageal Pressure
Corrected Volume
Airway Pressure
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Reverse Trigger Initiation

Gastric/Esophageal Pressure
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