Aerodynamic Assessment of Velopharyngeal Function: A Primer for Clinicians

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Disclosure

• The presenter has no financial or non-financial interest relevant to the presentation.
Seminar Topics

• Justification for aerodynamics
• Review of low tech methods
• Fundamental principles of the pressure-flow technique
• Instrumentation & clinical protocols
• Normal VP function and dysfunction
• Modifications for children and toddlers
Why Use Aerodynamics?

• A comprehensive evaluation of VP function must include both
  – Perceptual techniques
  – Instrumental techniques
(Peterson-Falzone et al., 2001)
Why Use Aerodynamics?

• While perceptual assessment is the “gold standard”
  – The ear can be fooled (e.g., McGurk Effect)
    • Hypernasality can be masked by hoarseness
    • Nasal air emission can be masked by articulatory distortions
  – Clinicians may be biased
    • Expect good outcomes post secondary procedures?
  – Aerodynamics helps to “keep us honest”
Why Aerodynamics?

• Advantages of Pressure-Flow as an instrumental technique
  – Non-Invasive
  – Relatively inexpensive
    • > $ than Nasometry but < $ than endoscopy
  – Provides objective information
  – Can be used with children as young as 2 years of age (but typically 5 to 6)
  – No physician oversight required
Why Aerodynamics?

• **50%** of traditional VPI speech characteristics are **aerodynamic** by definition
  – Nasal air emission
  – Reduced oral air pressure (Po)
  – Hypernasality
  – Compensatory articulations

• Hypernasality and compensatory articulations also may have aerodynamic components
Why Aerodynamics?

• Velopharyneal (VP) port essentially functions as an aeromechanical valve to separate the oral and nasal cavities during speech production.

• Given the primary goal of initial and secondary palatal surgeries is to restore structural and aeromechanical integrity of the VP mechanism, aerodynamics should be a primary procedure to assess surgical outcomes.
Why Aerodynamics?

• Disadvantages of Pressure-Flow
  – Relatively expensive (> Nasometry)
  – Techniques relatively complicated
    • Calibration of pneumotachograph (flowmeter)
    • Calibration of pressure transducers
    • Orifice area equation
  – Few “commercial” vendors
    • Microtronics, Inc. (PERCI-SARS)
    • Glottal Enterprises, Inc. (Nasal Emission System)
Low Tech Assessment

- Obligatory symptoms of VPI
  - Hypernasality
  - Reduced oral air pressure (Po)
  - Nasal air emission
    - Visible – laminar airflow (no turbulence)
    - Audible – turbulent airflow (sound of forceful exhalation; large VP gap – nose produces turbulence)
    - Audible with Rustle – raspberry-like sound due to a small VP gap (tissue vibration)
Mirror Testing
Listening Tube
(from Kummer)
See-Scape
(from Kummer)
Low Tech Assessment

• Caveats
  – Inadequate temporal resolution to distinguish
    • Utterance onset and offset nasal airflow (affected by speaking rate)
    • Nasal airflow due to velar bounce
    • Nasal airflow in nasal-plosive phonetic contexts (e.g., “jumping”, “hamper”)
Low Tech Assessment

• Caveats
  – See-Scape
  “I always thought that it was good to make the float rise. I always tried to make it rise.”

Adult patient commenting on the See-Scape when tested as a child
Pressure-Flow Technique: Fundamental Principles

- Developed by Warren and colleagues (1960s)
- Method to calculate the minimum cross-sectional area of VP orifice
- Based upon Bernoulli’s principle (i.e., hydrokinetics)
Pressure-Flow Technique: Fundamental Principles

• 3 Basic Elements of Standard Approach
  – Vocal tract pressure measurements
    • Oral (Po)
    • Nasal (Pn)
      (to derive differential pressure)
  – Nasal airflow measurement (Vn)
  – VP area calculation
Flow Through an Orifice
Pressure-Flow Technique: Historical Development

- Warren & DuBois (1964)
  - Plastic model of upper vocal tract
  - Used thin plates with varying cross-sectional areas from 2.4 to 120.4 mm$^2$ to model VP port
  - Determined need for correction factor, $k=0.65$
    - Dimensionless value used to correct for turbulent flow through orifice
Sharp-edged plates create turbulence and pressure loss, $k$ corrects for loss.
Hydrokinetic Orifice Equation

\[ \text{VP Area (mm}^2\text{)} = \left( \frac{V_n}{\sqrt{\Delta P}} \right) (.11) \]

Where:

- \( V_n \) is nasal airflow in mL/s
- \( \Delta P \) is oral-nasal air pressure in cm H\(_2\)O
- .11 is constant (includes k factor .65, pressure unit conversions, and density of air)
Pressure-Flow Technique: Historical Development

• Warren & DuBois (1964)
  – Accuracy of model tests?
  – Error between known and calculated VP orifice areas was no greater than \( \approx 10\% \)
    • Relatively small errors for smaller orifices
    • Relatively large errors for larger orifices
Pressure-Flow Technique: Historical Development

• Warren & DuBois (1964)
  - Initial clinical application
    • Tube inserted into nose for nasal airflow
    • Balloon-tipped catheter inserted through nose into oropharynx to detect Po
      – Little interference from balloon during speech
      – But, differential pressure included both VP and nasal cavity components; therefore, correction needed
A

Cork to Plug Nostril and Secure Tubing

To Flowmeter

To Pressure Transducer

B

Cork

Posterior Pharyngeal Wall

Soft Palate

Balloon in Pharynx

Tongue
Pressure-Flow Technique: Historical Development

• Warren (1964)
  – Modified clinical application
    • Open-ended catheter held in mouth (Po)
    • 2nd open-ended catheter inserted into nose (Pn)
  – Allowed direct determination of differential oral-nasal pressure across VP port
  – But, limited speech samples to bilabial consonants
Pressure-Flow Technique: Accuracy of VP Area Estimates

• Zajac and Yates (1991)
  – Inserted 18.1 mm² tube into nasopharynx of non-cleft speaker
  – Recorded pressure and flow during /pa/
  – Calculated “VP” area (used k=.67)
  – Obtained ≈7% error between known and calculated areas
Pressure-Flow Technique: Accuracy of VP Area Estimates

- Accuracy depends upon value of $k$
- Yates et al. (1990)
  - Questioned value of $k = 0.65$
  - $k$ varies as function of inlet geometry of orifice
  - Rounded inlets may be more representative of human VP port, if so, then $k = 0.97$
Yates et al: Rounded inlet orifices create less turbulence and pressure loss, therefore, k value may approach .97

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<th>Orifice Type</th>
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<th>Coefficient</th>
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<tr>
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<td>Short Tube, Sharp Corner</td>
<td><img src="image" alt="Short Tube, Sharp Corner" /></td>
<td>0.50, 0.67, 0.79</td>
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</table>
Pressure-Flow Technique: Accuracy of VP Area Estimates

• Effect of $k = .65$ for human speakers
  • May over estimate VP area up to 30% compared to $k = .97$
  • Why not change $k$?
    • Geometry not known for a given speaker
    • Normative data collected with $k = .65$

• VP area estimates should be considered as relative, not absolute
Pressure-Flow Technique: Instrumentation

- Two air pressure transducers
  - Bidirectional (positive & negative pressures)
  - Pressure range of at least ± 15 inches water (≈ ± 38 cm H₂O)
  - Built-in signal amplifier
- Heated pneumotachometer (flow meter)
  - Bidirectional pressure transducer (± 0.5 or 1.0 inch water pressure range)
Pressure-Flow Technique: Instrumentation

- A/D converter
- Signal processing software
- Additional equipment for calibration
  - Manometer (either fluid-filled or digital)
  - Rotameter or large volume syringe
This PERCI-SAR system connected for VP measurement using MTST-3 transducers.
Equipment
Questions?
Clinical Protocol

Standard Pressure-Flow Technique:

1) Requires patency of both nostrils
2) Po detected behind lips (bilabials)
3) Pn detected by occluding one nostril
   • Creates stagnation pressure that is continuous with downstream VP port
   • Eliminates resistance of nasal cavity
4) Nasal airflow detected by flow tube
Standard Pressure-Flow Technique
Pressure Measurement
Location is Everything!

• Vocal tract pressures can be easy or difficult to obtain

• Oral air pressure (Po)
  – Catheter must be behind structure of interest
  – Relatively easy for bilabial sounds
  – Somewhat easy for alveolar sounds
  – Relatively difficult for velar sounds
  – Orientation of catheter not critical for stops
Pressure Measurement

• Nasal air pressure (Pn)
  – Catheter must be downstream of VP orifice
  – Inserted into nostril via
    • Cork
    • Foam plug
    • Nasal olive
Nasal Airflow Measurement

- Requires
  - Pneumotachograph (flow meter)
  - Nasal flow tube
  - Should not use nasal olive

- Flow from most patent nostril
Speech Samples
www.unc.edu/~dzajac/UNC_Pressure_Flow_Lab.htm

• Zajac (2000)
  – 223 non-cleft speakers
  – Ages 6 to 37 years

• Speech samples
  – Syllables, words, & sentences
  – Produced 5 times
    • Habitual loudness and rate
    • Single breath group
Speech Samples

• /pi/
• /pa/
• /si/ *
• /mi/
• /hamper/
• “peep into the hamper” *

* Not reported by Zajac (2000)
/pi/ x5: Non-Cleft Speaker

Oral Pressure

Nasal Airflow

VP closure

Audio
/pa/ x5: Non-Cleft Speaker

Oral Pressure

Nasal Airflow

VP closure

Audio
/si/ x5: Non-Cleft Speaker

Oral Pressure

Nasal Airflow

Audio

VP closure
"hamper" x5: Non-Cleft Speaker

- Oral Pressure
- Nasal Airflow
- Audio

Graphs showing time in seconds (s) on the x-axis and various units on the y-axis.
"peep into the hamper" x3: Non-Cleft Speaker

Oral Pressure

Nasal Airflow

Audio
Hamper (adult): Normal VP Function

Oral Pressure

Nasal Airflow

cm H₂O

ml/s

time (s)
Normal VP Function
(no cleft)

Stop Consonants

- Po: 3 to 7-8 cm H₂O
  - Children > adults
- NO nasal airflow and complete VP closure, but beware of:
  - Onset/offset flow
  - Velar bounce
  - Tonsillectomy/Adenoidectomy
Normal VP Function
(no cleft)

Nasal Consonants

– Po: < 1 to 2 cm H$_2$O
– Nasal airflow: 70 to 130 mL/s
  • Varies with age and phonetic context
– VP area: 20 to 40 mm$^2$
  • Varies with age and phonetic context
/pi/: Cleft Speaker - Normal Closure

Oral Pressure

Nasal Airflow

cm H₂O

ml/s

(time (s))
/p/: Cleft Speaker - Marginal Closure

Oral Pressure

Nasal Airflow
/pi/: 4 yr-old CLP - Inadequate VP Closure

Oral Pressure

Nasal Pressure

Nasal Airflow
Hamper: Inadequate VP Function

Oral Pressure

Nasal Airflow

cm H₂O

ml/s

/time (s)/
Categories of VP Function
Warren et al. (1989)

- VP Area $< 5.0 \text{ mm}^2$
  - Adequate VP Closure
- VP Area $\geq 5.0$ but $\leq 9.9 \text{ mm}^2$
  - Borderline Adequate/Borderline Inadequate
- VP Area $\geq 10.0$ but $\leq 19.9 \text{ mm}^2$
  - Borderline Inadequate
- VP Area $\geq 20.0 \text{ mm}^2$
  - Inadequate VP Closure
Categories of VP Function
(Phonetic context of /p/ in CV syllables)

- VP Area $\leq 1.0 \text{ mm}^2$
  - Normal (complete) VP Closure
- VP Area $\geq 1.1$ but $\leq 4.9 \text{ mm}^2$
  - Adequate
- VP Area $\geq 5.0$ but $\leq 9.9 \text{ mm}^2$
  - Borderline Adequate/Inadequate (marginal)
- VP Area $\geq 10.0 \text{ mm}^2$
  - Inadequate
Categories of VP Function Related to Perceptual Symptoms

- Adequate (<5mm²): Closure is adequate to generate usable Po, but
  - Inconsistent nasal rustle
  - Perhaps mild nasality
- Marginal (<10mm²)
  - May have audible nasal emission
  - May have mild to moderate nasality
- Inadequate (>10mm²)
  - Audible nasal emission
  - Moderate to severe nasality
  - >20mm² - reduced Po
Temporal Measures

• Time that VP port is open may be as important as size of opening (Warren et al., 1993)

• High correlations reported between VP closing duration in nasal-plosive sequences and perceived nasality (Dotevall et al., 2002)
VP Closing Duration

• Duration of Vn declination in “hamper”
  – Beginning: peak Vn
  – End: point where Vn drops to 5% of baseline
    • Controls for VPI (i.e., flow never reaches zero)
• “Norms” reported by Dotevall et al. (2002)
  – Approximately 50 ms
• “Norms” reported by Zajac & Mayo (1996)
  – Approximately 80 ms (adults)
  – Used 10 mLs criterion
VP Closing Time Caveats

• Need consensus on procedures
• May need to **normalize** VP closing time to word duration
  – Controls for speaking rate
9 year-old girl, repaired CP: Mild nasality, marginal VP closure (adenoid involution?)
Same girl, 3\textsuperscript{rd} production – moderate nasality, inadequate VP closure (fatigue?)
15 year-old girl, LCLP, post maxillary advancement: Grossly inadequate VP closure
Same girl, “hamper”: Complete overlap of oral pressure and nasal airflow
20 year-old female, RCLP: Severe nasality, co-articulated glottal stops in “hamper”
5.6 year-old boy, VPI (no cleft): Moderate nasality, overlap of Po and Vn in “hamper”
Same boy: Post pharyngeal flap surgery
/hamper/: 10 yr-old post flap - Obstruction

Oral Pressure

Nasal Pressure

Nasal Airflow
Questions?
Modifications for Young Children
Differential Pressure Determination

• Requires
  – Oral catheter ("See mouth talk")
  – Nasal plug/olive ("See nose talk")

• Visual feedback (i.e., game)

• **No** nasal flow tube (no area calculation)
2/24/2005  pi (x5)  By: LEB  0.000 sq cm

Oral Press

Nasal Press

Time Axis

Arianna  141-27-13-8  Visit: 01  DX: 1  4Y 9M

no nasal flow
Categories of VP Function
(Phonetic context of /mp/, Warren et al., 1995)

• Diff. Pressure ≥ 3.0 cm H₂O
  ➢ Adequate VP Closure

• Diff. Pressure ≤ 2.9 but ≥ 1.0 cm H₂O
  ➢ Borderline or Marginal VP Closure

• Diff. Pressure < 1.0 cm H₂O
  ➢ Inadequate VP Closure
Modifications for Young Children

Nasal Mask Approach

• Requires
  – Nasal mask to obtain airflow and downstream pressure
  – Oral catheter to detect upstream pressure

• Avoids insertion of nasal plugs and tubes

• Useful when child
  – Has bilateral cleft lip/palate
  – Has unilateral nasal obstruction
  – Is fearful of nasal plug/tube
Modifications for Young Children
Nasal Mask Approach

• **Permits** calculation of VP area but
• Requires differential pressure **correction**
  – Differential oral-mask pressure includes VP pressure drop **and** nasal pressure drop (i.e., nasal resistance)
  – Must **subtract** nasal pressure drop to obtain true (larger) VP area
  – Nasal pressure drop obtained during breathing
Modifications for Young Children

Nasal Mask Only

- Nasal mask to obtain airflow
- No oral catheter
- Microphone to record audio
- Useful when child
  - Has lip incompetency
  - Fearful of oral catheter
Categories of VP Function
(Phonetic context of /p/ in CV syllables)

- Nasal Flow $\leq 20$ or $30$ mL/s
  - Normal (airtight) VP Closure
  - Includes “velar bounce”
- Nasal Flow $\geq 30$ but $\leq 150$ mL/s
  - Borderline or Marginal VP Closure
  - Influenced by respiratory effort/nasal resistance
- Nasal Flow $> 150$ mL/s
  - Inadequate VP Closure
Nasal Ram Pressure
aka Pressure-Flow Lite
Nasal Ram Pressure

VP status of stop consonants coded relative to NRP:

- Open VP port – Positive NRP
- Closed VP port – Atmospheric NRP
- No estimate of VP area
Male CLP (CA=21 mos.) - VP Closure

Breath Group
/t/ /p/ /t/

Audio (volts)

stop  play  toy

Time (s)
Male CLP (CA=22 mos.) - No VP Closure

Breath Group

/b/

ball

Audio (volts)

Time (s)
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<th>Cleft Type</th>
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<th>Age (mos.)</th>
<th># Stops</th>
<th>% Stops Closed</th>
<th>% Children</th>
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Pressure-Flow: Advantages

• Provides aerodynamic “image” of VP port
• Non-invasive
• Can be used with young children
• Objective data -- good norms
• Provides multiple information
  – Oral air pressure
  – Nasal air pressure
  – Nasal airflow
  – Estimates of VP area
Pressure-Flow: Disadvantages

• Technical
  - Calibration
  - Easy to make errors

• VP area is *relative* (due to k factor)

• May not correlate highly with perceived hypernasality on vowels
Thank-you!
&
Questions?