Current and Prospective Evaluation Methods of the Vestibular Labyrinth: Video OCR, VEMPs, Galvanic Vestibular Stimulation

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Learning Objectives

- Evaluate diagnostic information provided by masseter vestibular evoked myogenic potentials
- Discuss sensitivity and specificity of the video Ocular Counter-Roll Test (OCR) and correlations to other tests of vestibular function
- Describe how galvanic vestibular stimulation (GVS) can be implemented in vestibular diagnostics and vestibular rehabilitation.

Outline of Talk

- Vestibular evoked potentials (VEMPs)
  - Brief review
  - Updates on emerging techniques:
    - Frequency tuning
    - Masseter VEMPs
- Ocular counter roll (OCR)
  - Brief overview of relevant physiology
  - Potential applications:
    - Peripheral vestibular disorders
  - Limitations
- Galvanic vestibular stimulation (GVS)
  - Brief overview of relevant physiology
  - Potential applications:
    - Vestibular diagnostics
    - Rehabilitation
  - Limitations

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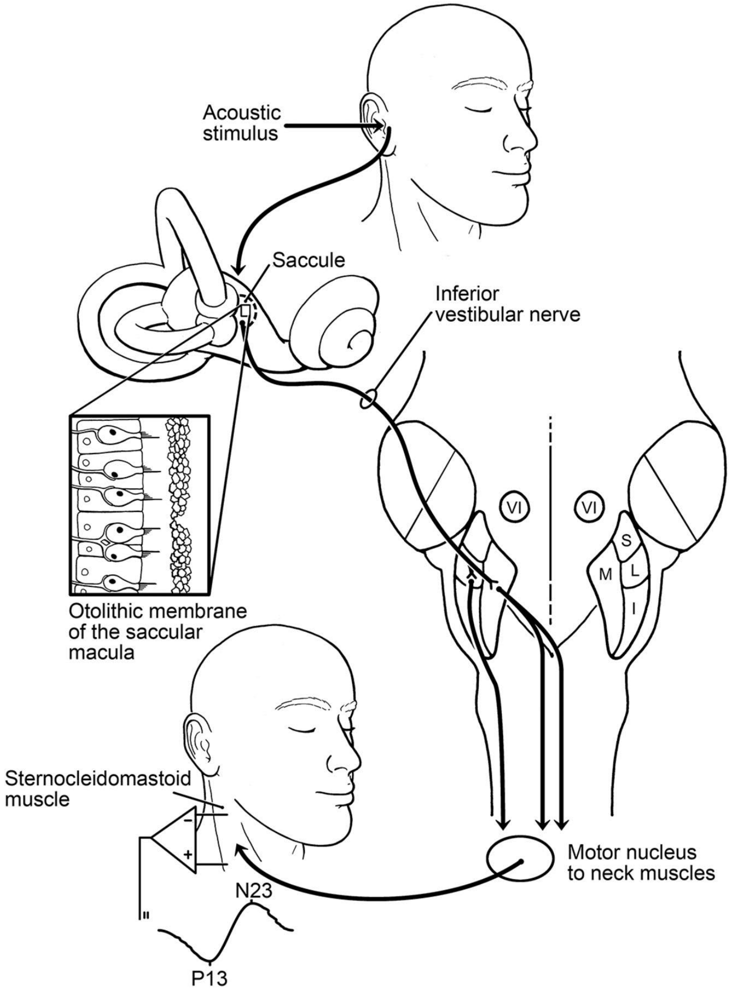
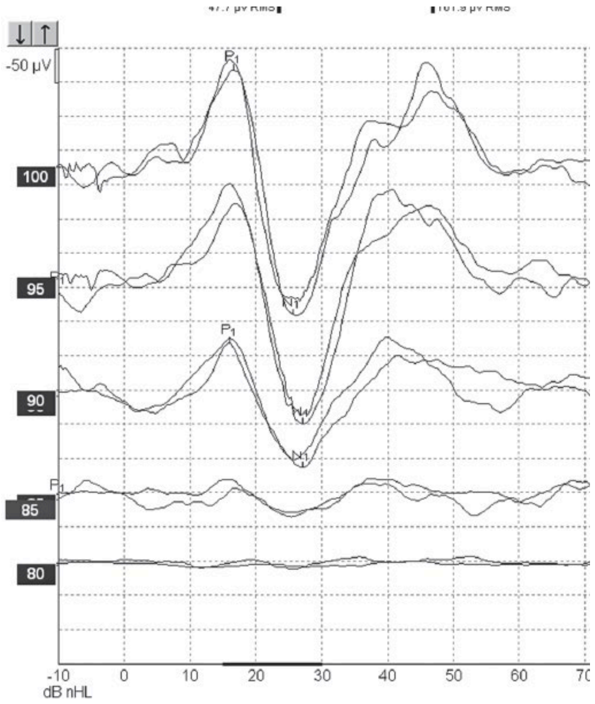
cVEMPs: Quick Overview



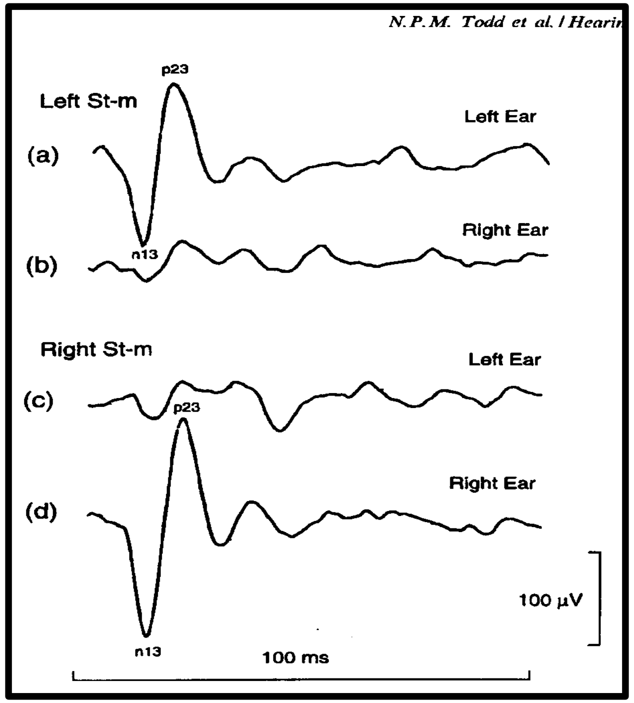
Fife et al., 2017

- **cVEMPs** reflect myogenic activity in the sternocleidomastoid muscles, driven by saccular response and inferior vestibular nerve
  - **C**ervicial
  - **S**accular
  - **I**nferior nerve, **I**psilateral, **I**nhibitory

cVEMPs: Typical response



Active: SCM
Inverting: Neutral location



Inverting: SCM
Active: Neutral location

- **Ipsilateral** to stimulus
- Biphasic waveform:
  - First peak: P1 at ~13 ms
  - Second peak: N1 at ~23 ms
- **Inhibitory response**: moving from increased EMG activity to decreased EMG activity
- Some variability in preferred polarity of VEMP responses

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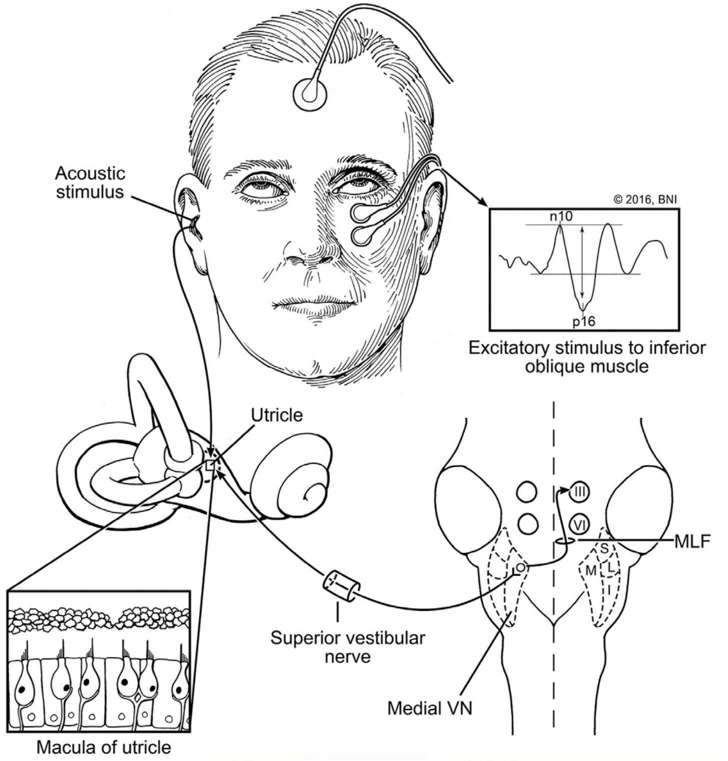
oVEMPs: Quick Refresher

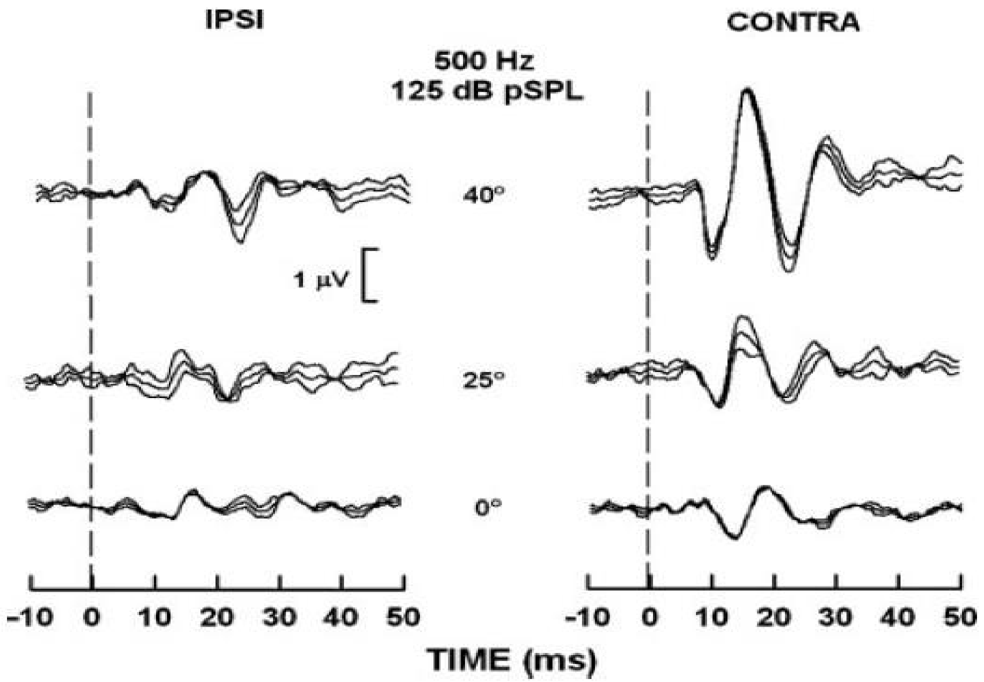


Fife et al., 2017

- **oVEMPs** reflect extraoccular muscle response driven predominantly by utricular, superior vestibular nerve
  - Ocular
  - Utricle
  - Superior nerve, contralateral, excitatory

oVEMP: Typical Response

- **Contralateral** to stimulation
- **Multipeak** waveform
  - Focus on N1-P1 component
- **Excitatory response**:
- Strongest response seen with eyes tilted up to view static target @ ~30 deg above horizontal (Govender et al., 2016a)



Murnane & Aikin, 2009

VEMPs: Applications

SPECIAL ARTICLE

AMERICAN ACADEMY OF NEUROLOGY.

Practice guideline: Cervical and ocular vestibular evoked myogenic potential testing

Report of the Guideline Development, Dissemination, and Implementation Subcommittee of the American Academy of Neurology

Terry D. Fife, MD
James G. Colebatch, MB, DSc
Kevin A. Kerber, MD

ABSTRACT

Objective: To systematically review the evidence and make recommendations with regard to diagnostic utility of cervical and ocular vestibular evoked myogenic potentials (cVEMP and oVEMP, respectively). Four questions were asked: Does cVEMP accurately identify superior canal dehis-

- American Academy of Neurology practice guidelines (2017)
- Support VEMPs for distinguishing canal dehiscence from controls :
  - cVEMP threshold or corrected amplitude
  - oVEMP amplitude or threshold
- Evidence is insufficient to determine whether cVEMP and oVEMP:
  - Accurately identify vestibular function specifically related to the saccule/utricle
  - Useful in diagnosing vestibular neuritis, Ménière disease, or vestibular migraine

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VEMPs: Diagnostic Test Battery

<table>
<tr><td colspan="2">Central Vestibular Function</td><td>Saccade, Pursuit, OPK</td></tr>
<tr><td colspan="2" rowspan="2">Supportive Findings for Central or Peripheral</td><td>Gaze, Spontaneous</td></tr>
<tr><td>Positionals, Positioning</td></tr>
<tr><td rowspan="3">Superior Nerve</td><td>Horizontal SCC</td><td>Calorics (low frequency)
Rotary chair (low to mid F)
vHIT (high F)</td></tr>
<tr><td>Anterior SCC</td><td>vHIT</td></tr>
<tr><td>Utricle</td><td>oVEMP</td></tr>
<tr><td rowspan="2">Inferior Nerve</td><td>Posterior SCC</td><td>vHIT</td></tr>
<tr><td>Saccule</td><td>cVEMP</td></tr>
</table>

- cVEMPs provide saccule & inferior nerve information
  - **Innervation**: Align with posterior SCC
- oVEMPs provide utricle and superior nerve information:
  - **Innervation**: Align with horizontal and anterior SCC

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VEMPs: Stimuli

TABLE 3. cVEMP response rates for ACS, B81, and IH for each age group

Group (age range)	ACS (%)	B81 (%)	IH (%)
1 (10–19 yrs)	100	100	100
2 (20–29 yrs)	100	100	82
3 (30–39 yrs)	100	95	90
4 (40–49 yrs)	95	90	85
5 (50–59 yrs)	95	100	75
6 (60–69 yrs)	83	88	83
7 (70+ yrs)	80	74	53
All subjects	92	92	79

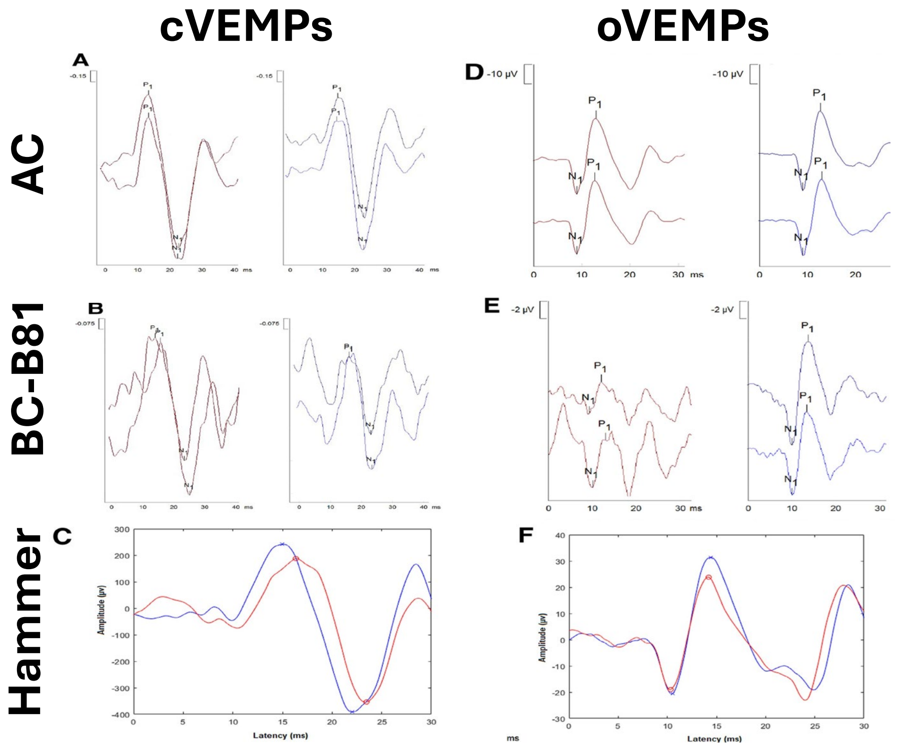
ACS, air conduction stimuli; IH, impulse hammer.

TABLE 6. oVEMP response rates for ACS, B81 and IH for each age group

Group (age range)	ACS (%)	B81 (%)	IH (%)
1 (10–19 yrs)	100	100	100
2 (20–29 yrs)	96	100	100
3 (30–39 yrs)	100	85	100
4 (40–49 yrs)	95	100	90
5 (50–59 yrs)	95	80	90
6 (60–69 yrs)	92	83	96
7 (70+ yrs)	67	80	87
All subjects	90	89	93

ACS, air conduction stimuli; IH, Impulse hammer.

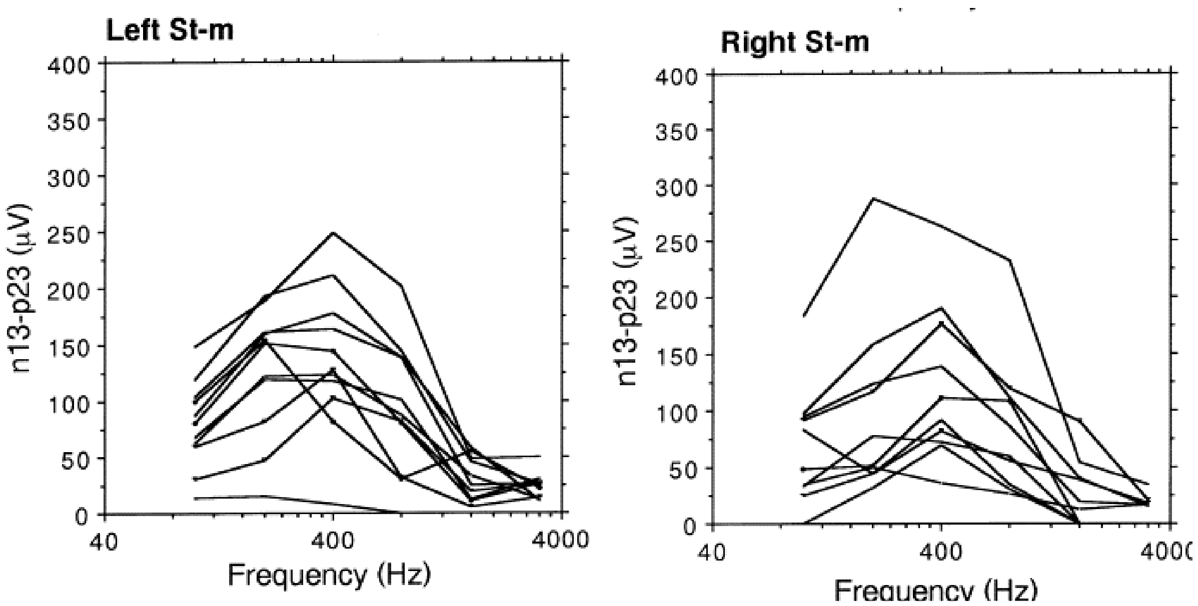
Patterson et al., 2021



- Air conduction, bone conduction (B81), or skull taps/impulse hammer can be used
  - Largest response amplitudes from impulses (Patterson et al., 2021; Rosengreen et al., 2011)
  - AC cVEMP responses rates comparable to BC and IH across age span
  - AC oVEMP response rates lower for adults 70+years (Patterson et al., 2021)

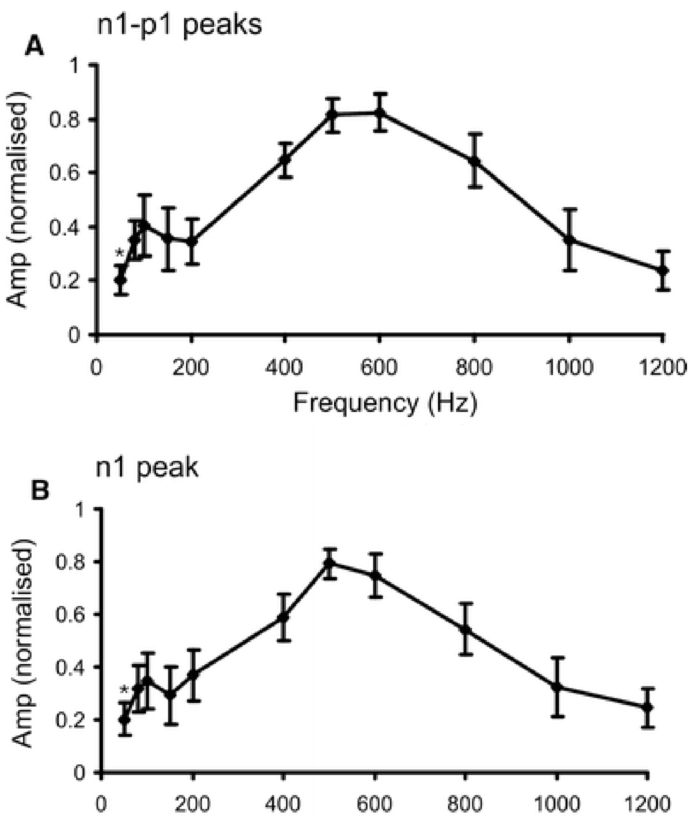
VEMPs: Stimuli

cVEMPs



Todd et al., 2000

oVEMPs

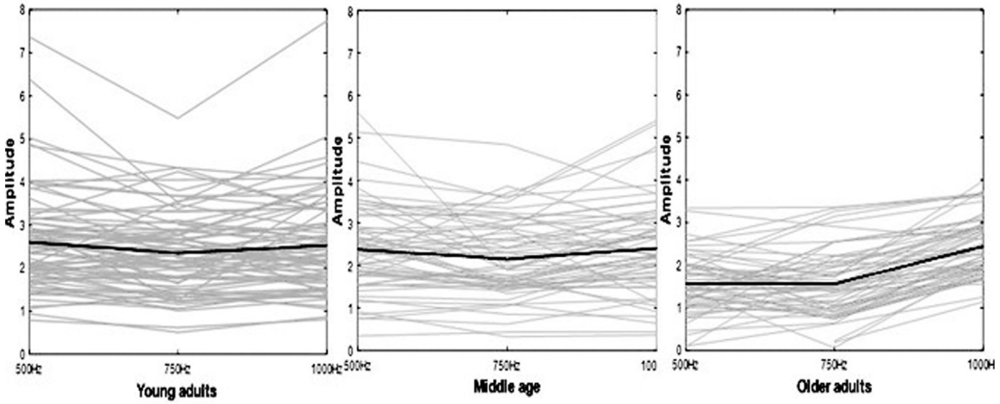


Todd et al., 2009

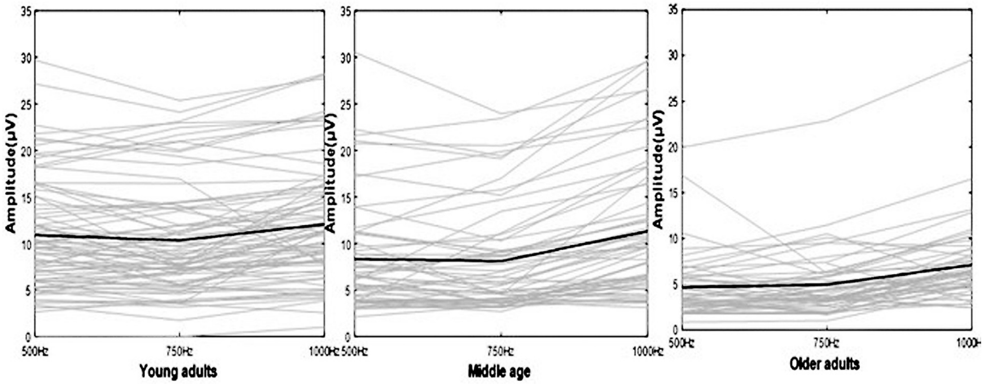
- Traditionally, 500 Hz tone burst used as generates most robust responses in healthy adults (Todd et al., 2000; Todd 2009a; Todd et al., 2009b; Donnelan et al., 2010)

VEMPs: Frequency Tuning and Age

cVEMPs



oVEMPs



- Both c/oVEMPs shift in tuning with age to exhibit a best frequency at 750 or 1000 Hz (Piker et al., 2014; Singh et al., 2018)
    - Shift seen for cVEMP in older (60-79 years) adults and oVEMPs for middle (40-58 years) and older adults (Jha et al., 2022)
- Shifts may represent increased stiffness or reduced mass in the macula
    - Aging results in morphological changes in otoconia and mass of the otoconia particles (Jang et al., 2006; Walther et al., 2007)

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VEMPs: Frequency Tuning in BVL

TABLE 1 Present VEMP responses: multi-frequency vs. only the 500 Hz stimulus in BV patients.

	cVEMP (n = 47)		oVEMP (n = 48)	
	Multi-frequency	*500 Hz*	*Multi-frequency*	*500 Hz*
Present response(s): right ear	51%	43%	21%	15%
Present response(s): left ear	60%	45% *	33%	21% *
Present response(s): at least one ear	70%	57% *	35%	23% *
Present response(s): both ears	40%	30% *	19%	13%
All tested frequencies present (500–2,000 Hz)	15%	N/A	2%	N/A

Multifrequency VEMP response(s) are classified as present, in case at least one tested frequency demonstrated a present response. Multi-frequency included VEMP testing at 500, 750, 1,000, and 2,000 Hz. N/A, not applicable. *Significant difference between multi-frequency testing and only testing at 500 Hz (one-sided value of $p < 0.05$).

- In patients with diagnosed BVL, multi-frequency (500, 750, 1000, and 2000 Hz) testing of oVEMPs and cVEMPs showed increases in response rate (Lucieer et al., 2024)
    - Can assess residual function using off-frequency VEMPs

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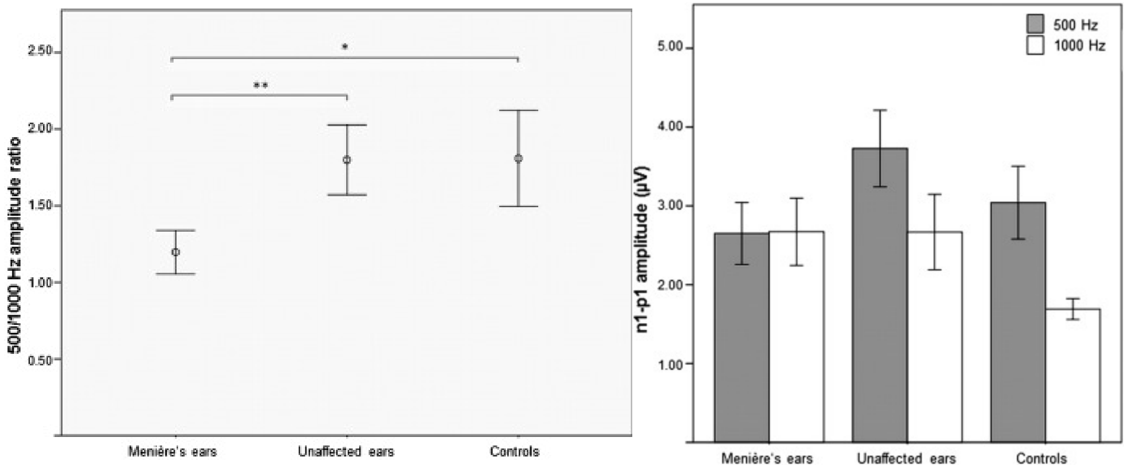
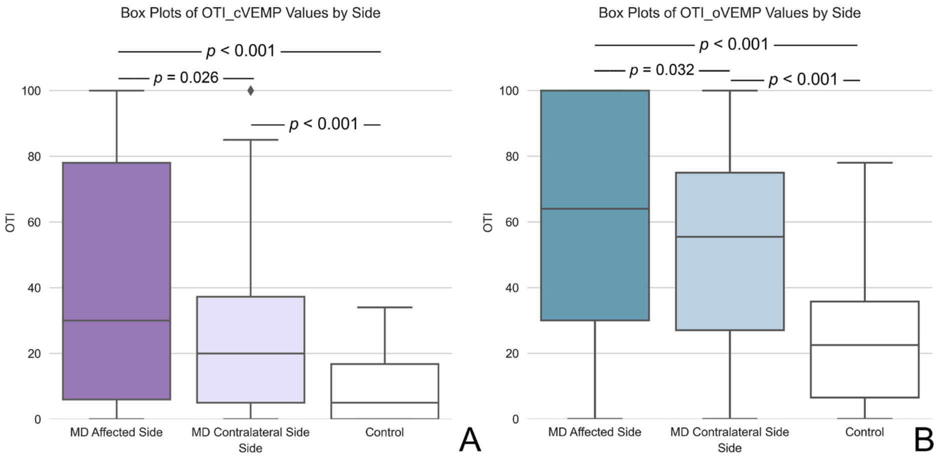
VEMPs: Frequency Tuning in MD



Jerin et al., 2014

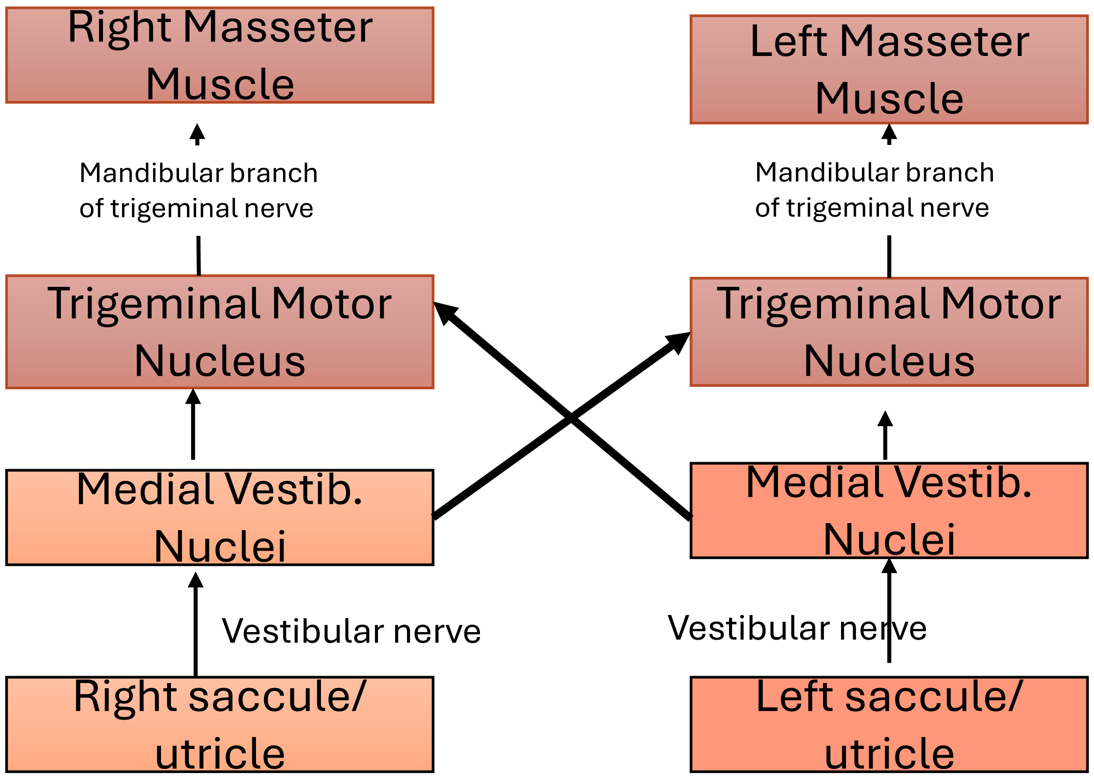


Du et al., 2025

- Shift in c/oVEMP tuning seen in Meniere's Disease (MD) to 750 or 1000 Hz (Jerin et al., 2014; Singh et al., 2016; Angeli et al., 2022)
- Some have proposed metrics incorporating amplitude ratios and presence of responses (Du et al., 2025)

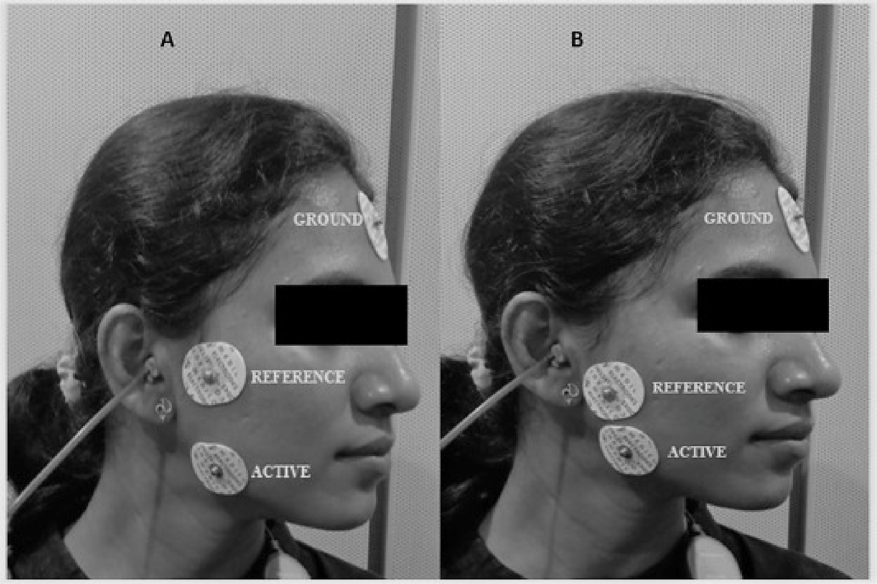
Masseter VEMPs: Background

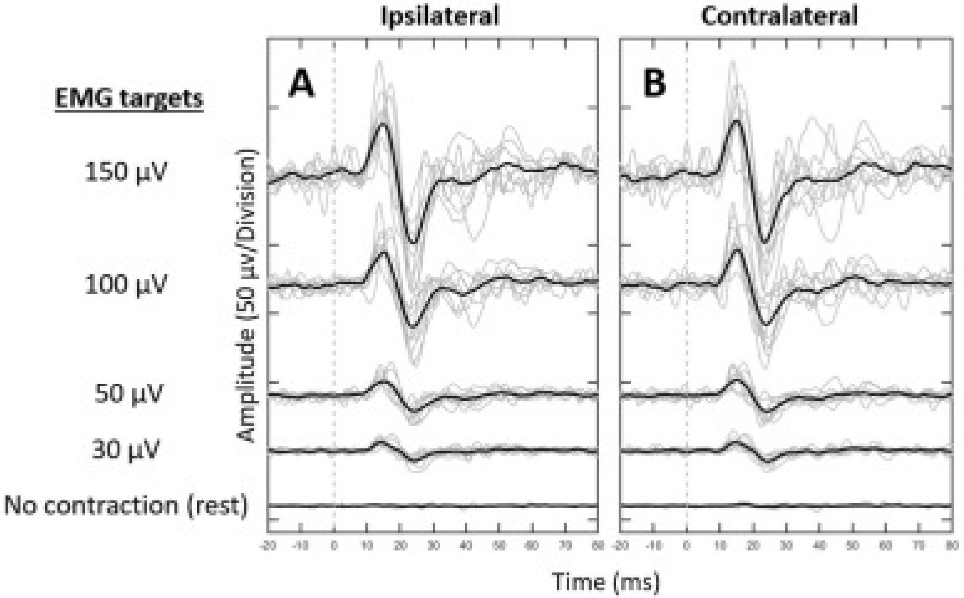
- Masseter VEMPs (mVEMPs) are a bilateral symmetrical response of the vestibulo-masseteric pathway (Deriu et al., 2003; Deriu et al., 2010; Giaconi et al., 2007; Cuccurazzo et al., 2007)
- Elicited using same stimuli as c/oVEMPs
  - Broad stimulation of otoliths
- Consists of two components
  - **Vestibular portion** (p11-n15)—short-latency, higher threshold (90–100dB nHL)
  - **Auditory portion** (p16-n21)—longer latency, low thresholder (<80/90dB nHL) (Deriu et al., 2005)



(Deriu et al., 2005)

mVEMPs: Recording





(Romero et al., 2020)

- Montage(s) for recording:
  - **Inverting**: Mandibular angle or medial point of zygomatic arch
  - **Active**: lower third of masseter muscle
  - **Ground**: Forehead (or other neutral location)
- Amplitude of response scales linearly to EMG (Romero et al., 2020)

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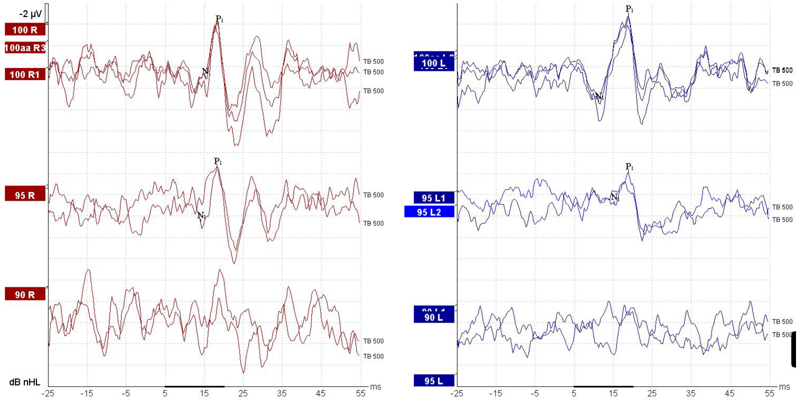
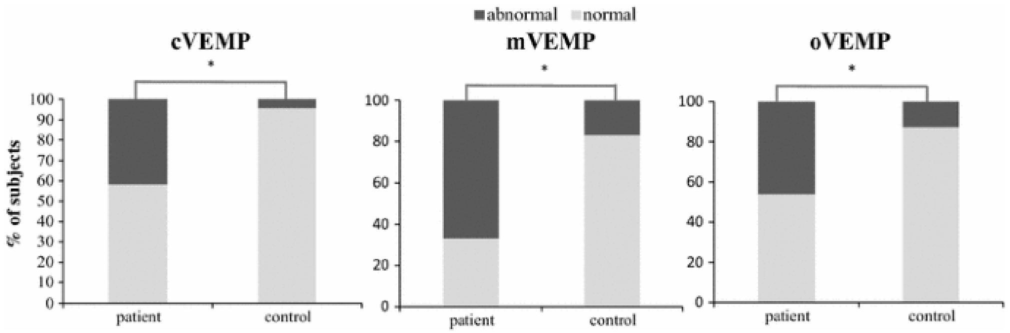
VEMPs: Non-Vestibular Disorders

oVEMPs in MS



Parkinson's Disease



(de Natale et al., 2015)

- VEMPs are altered (prolonged latency or absent) in ~65% of patients with MS-related vertigo (Di Stadio et al., 2019)
    - In patients with PD, absent responses and delayed latencies common (cVEMP: OR = 6.77; oVEMP: OR = 13.9; Cui et al., 2022)
- mVEMP abnormalities more frequently seen than c/oVEMPs in MS (de Natale et al., 2015) and Parkinson's disease (OR = 7.52) (Cui et al., 2022)
    - Latency prolongations occur less commonly than reduced or absent responses
- Number of VEMP abnormalities correlated to brainstem findings and MRI findings (Di Stadio et al., 2019; de Natale et al., 2015)

mVEMPs: Peripheral Vestibular Loss

Patient no.	cVEMP	oVEMP	Affected side	mVEMP right amplitude	mVEMP left amplitude	mVEMP amplitude asymmetry ratio
11	L: absent	L: absent	LPM	23.81	25.15	3
12	Bl absent	Bl absent	BlPM	71.60	60.11	9
13	R: absent	Not done	RPM	53.25	42.90	10
14	Bl: absent	Bl: absent	BlPM	0	41.80	100
15	AR:5%-N	43% L	LPM	32.02	0	100
16	R: absent	52%-R	RPM	0	37.26	100
17	R: absent	Bl: absent	RPM	50.70	41.69	10
18	L: absent	Bl: absent	LPM	26.83	0	100
19	37%-R	R: absent	RPM	0	46.21	100
20	AR:5%-N	AR: 52%-L	LPM	49.44	0	100

L: absent c/o VEMP
B: Present mVEMPS

R: absent c/o VEMP
R: absent mVEMPS

- mVEMP responses are asymmetric in Meniere's Disease (Behmen et al., 2023)
  - cVEMP and oVEMP responses also asymmetric supporting otolith contributions to mVEMPs
  - mVEMP responses do not always align with c/o VEMP responses

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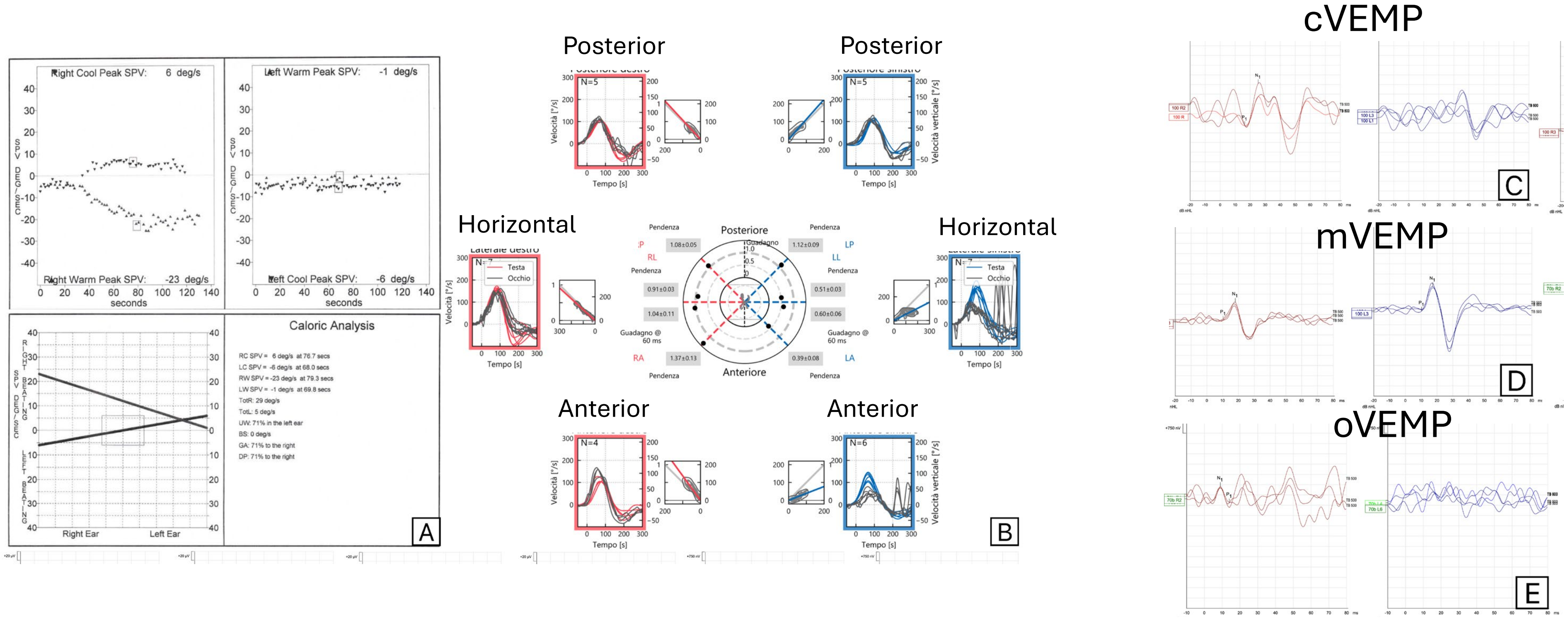
mVEMPs: Peripheral Vestibular Loss



- Response in vestibular neuritis do not strictly align with superior vs. inferior nerve involvement (Comacchio et al., 2022)

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c/oVEMPs: Take Home and Limitations

- **Take homes on VEMP tuning**:
  - Changes in tuning from 500 Hz to 750 or 1000 Hz may reflect MD or age
  - Assessing at other frequencies in middle age or older adults may reveal responses
  - In BVL patients, multi-frequency testing increases odds of capturing response
- **Limitations in VEMP tuning**:
  - May aid in MD identification but age effects tuning and changes in unaffected MD ears

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mVEMPs: Take Home and Limitations

- **Take homes on mVEMPs**:
  - Reflects vestibulo-masseter function
  - Can be more sensitive to changes in function in non-vestibular disorders
- **Limitations in mVEMPs**:
  - Alignment with other vestibular diagnostics is not well-defined

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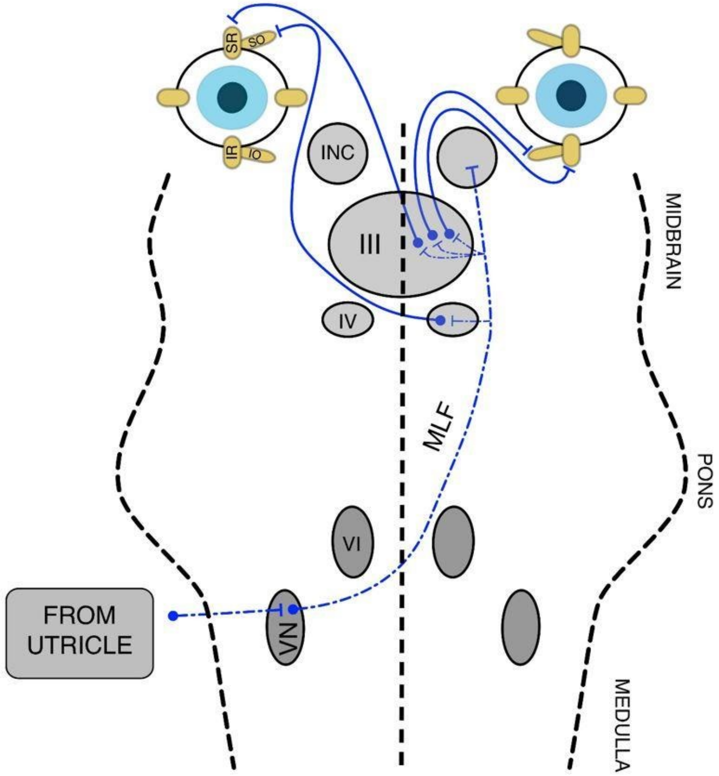
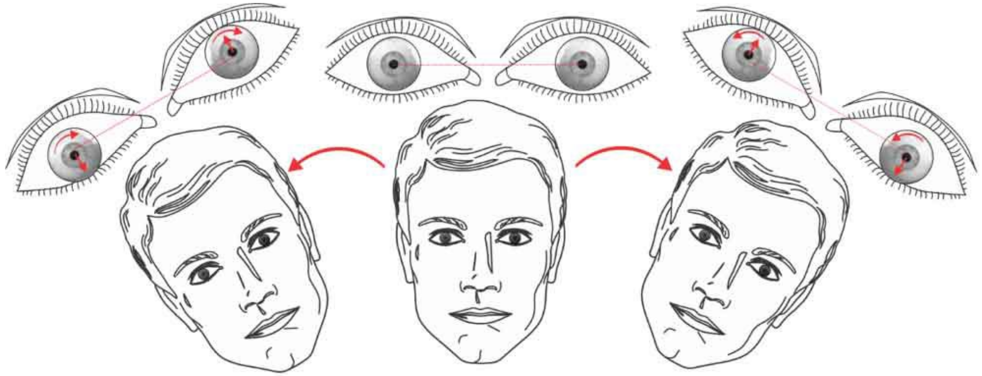
Video Ocular Counter Roll

Background: Anatomic Pathways

- Ocular counter roll (OCR) is a utricular-ocular reflex resulting in eyes rolling in opposite direction of head tilt
- For example, for a right head tilt:
  - Right eye elevates (**superior rectus)** and incycloducts (inward rotation; **superior oblique**)
  - Left eye depresses (**inferior rectus**) and excycloducts (outward rotation; **inferior rectus**)





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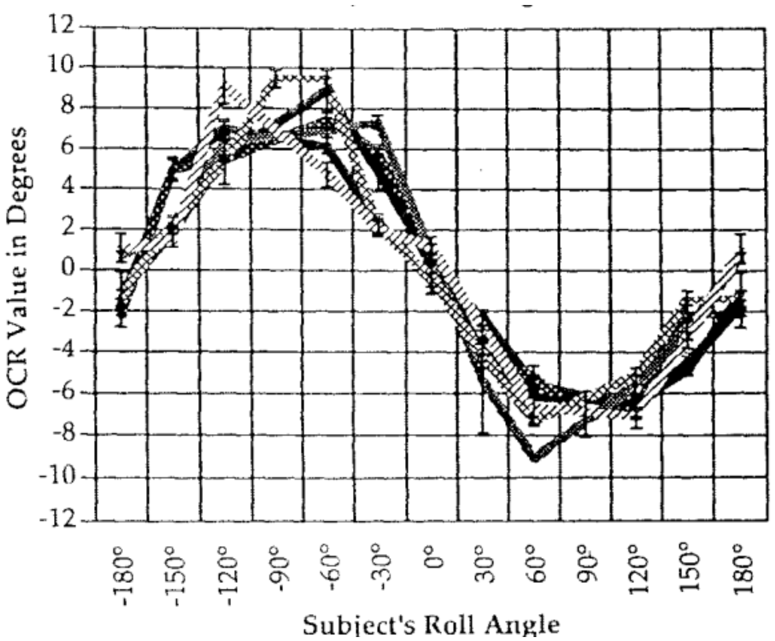
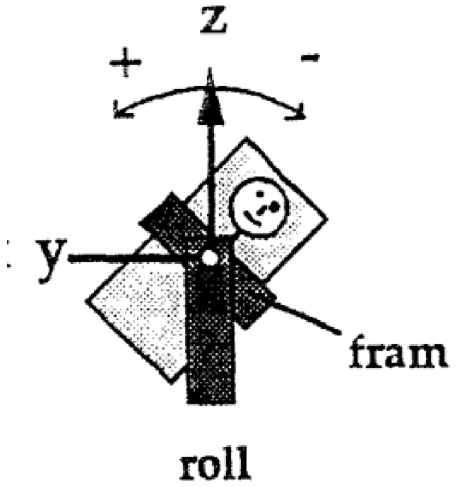
Background: OCR

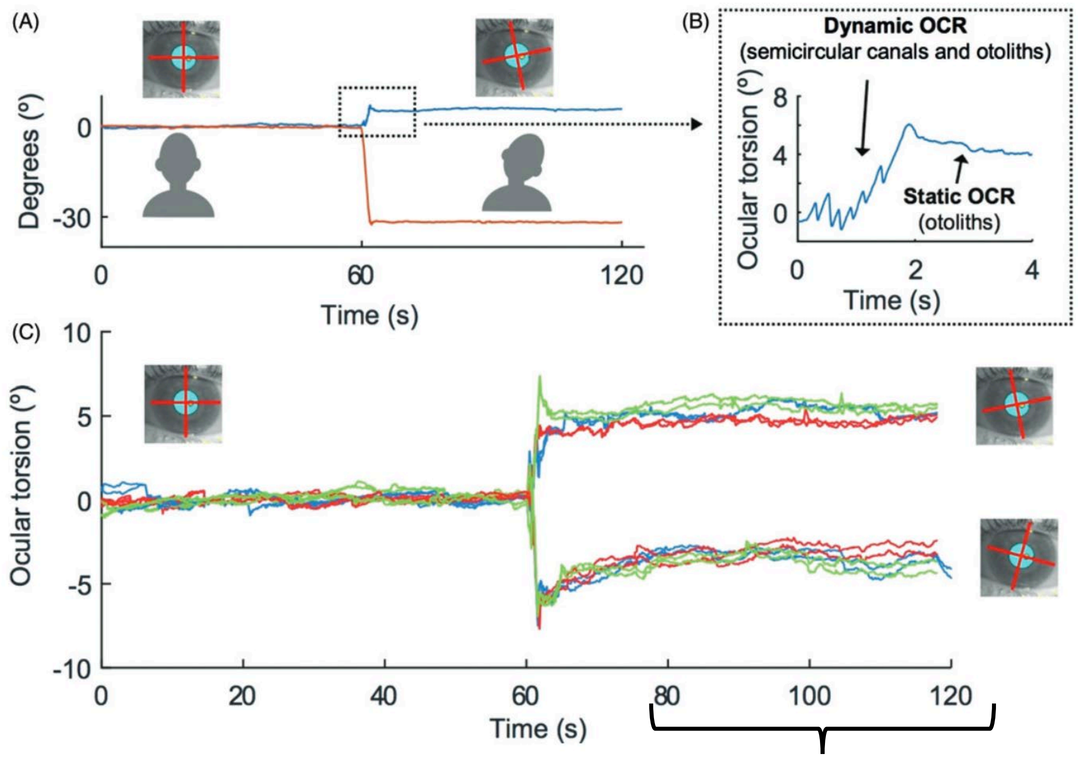




- Ocular counter roll (OCR) has been routinely measured in research settings using scleral search coils
- Gain of the OCR (in healthy adults) is ~0.1-0.2 depending on tilt angle (Bucher et al., 1992)

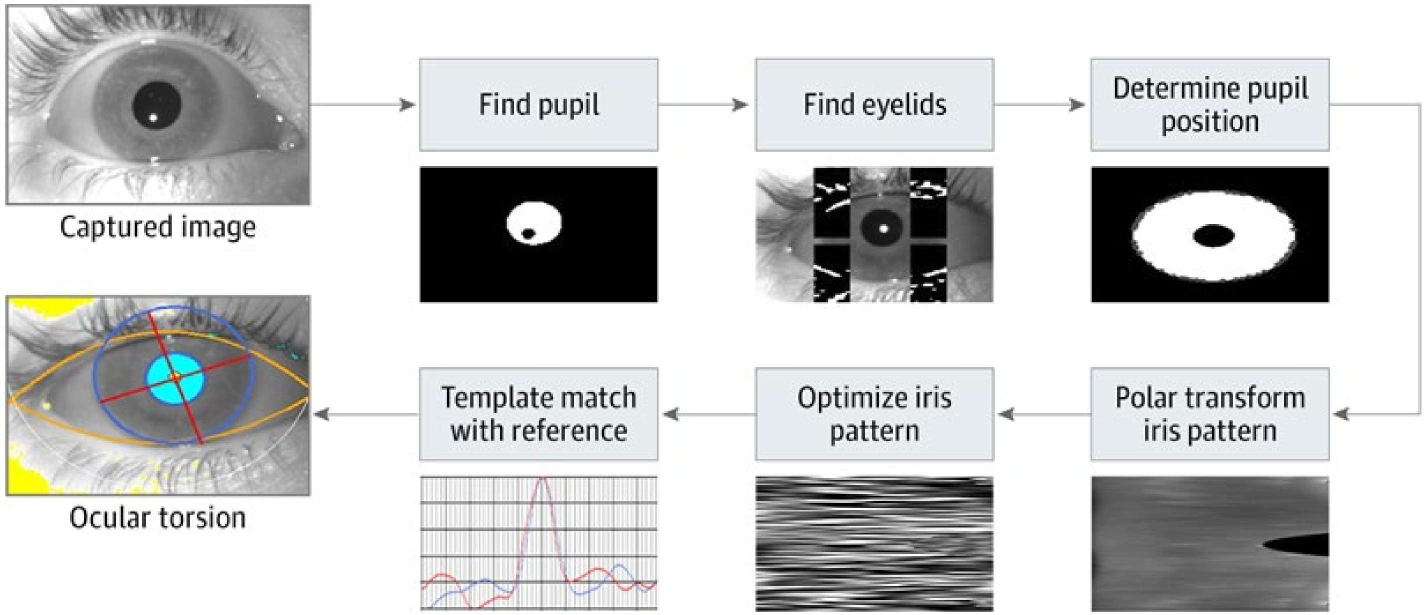
Background: OCR in Healthy Adults

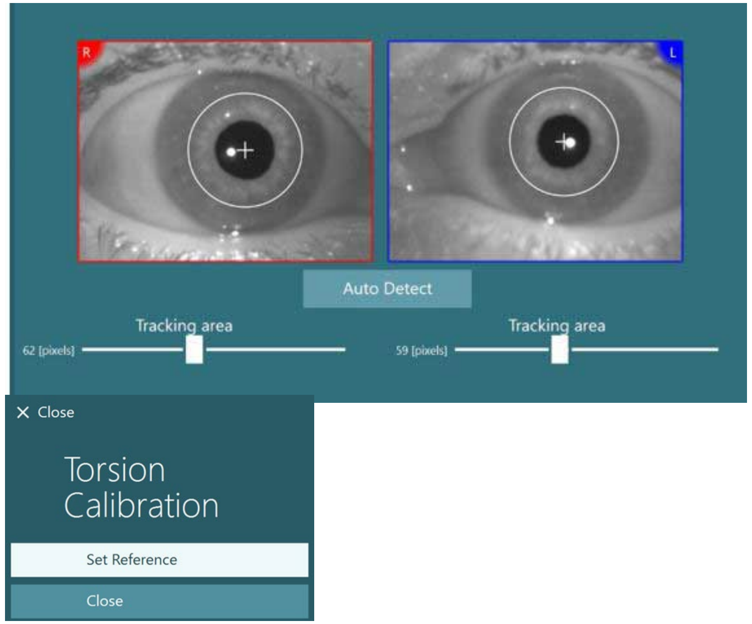
- **Dynamic OCR**:
  - Occurs during head tilt
  - Nystagmus reflecting SCC + otolith
- **Static OCR**:
  - Occurs after head tilt
  - Reflects otolith input
  - Measures typically looked at 20-60s post tilt to isolate otolith response



Otero-Millan, 2017

Background: Measuring OCR





- Algorithm used in current clinical system focuses on determining changes in pupil position relative to reference (Otero-Millan, 2015; 2017; Yang, 2025)
- Static response assessed over 3 head tilts in each direction

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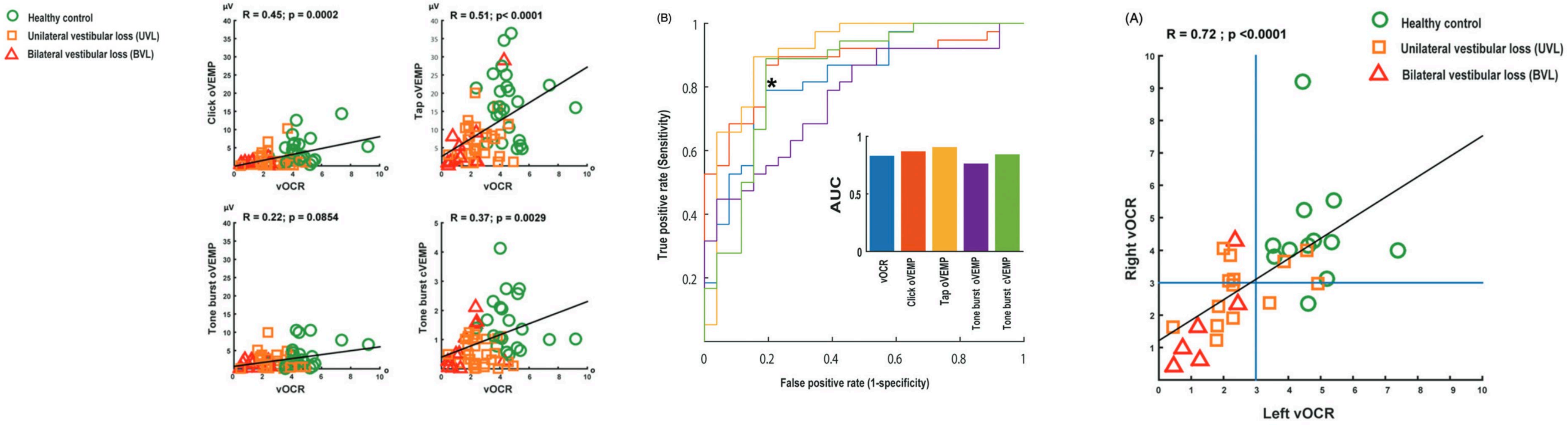
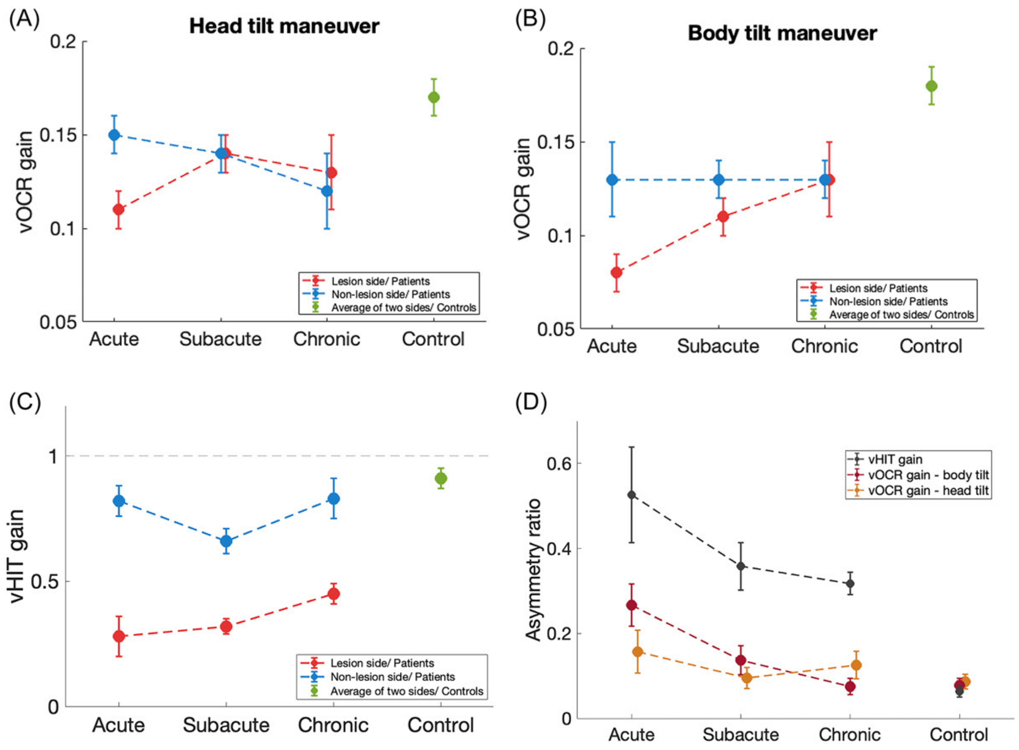
vOCR: Validation in Peripheral Loss

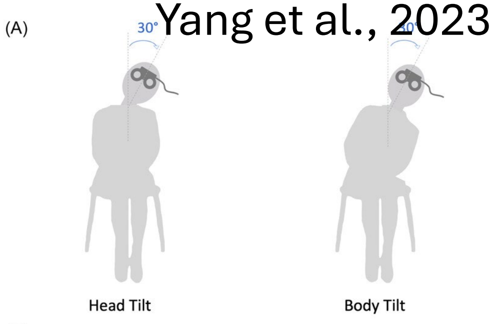


- Assessed vOCR to 30 degree head tilt and c/o VEMPs in HC, UVL, and BVL patients (Otero-Millan, 2017)
- vOCR correlated to oVEMP & cVEMP amplitude but not asymmetry ratio
- Best threshold to detect vestibular loss was 3 degrees (Otero-Milan, 2017) and 3.5 degrees (Tessler et al., 2025)
    - Sensitivity = 80%; Specificity = 81%
    - Area under the curve (AUC) similar between vOCR to c/oVEMPs

vOCR: Peripheral Loss & Neck Input

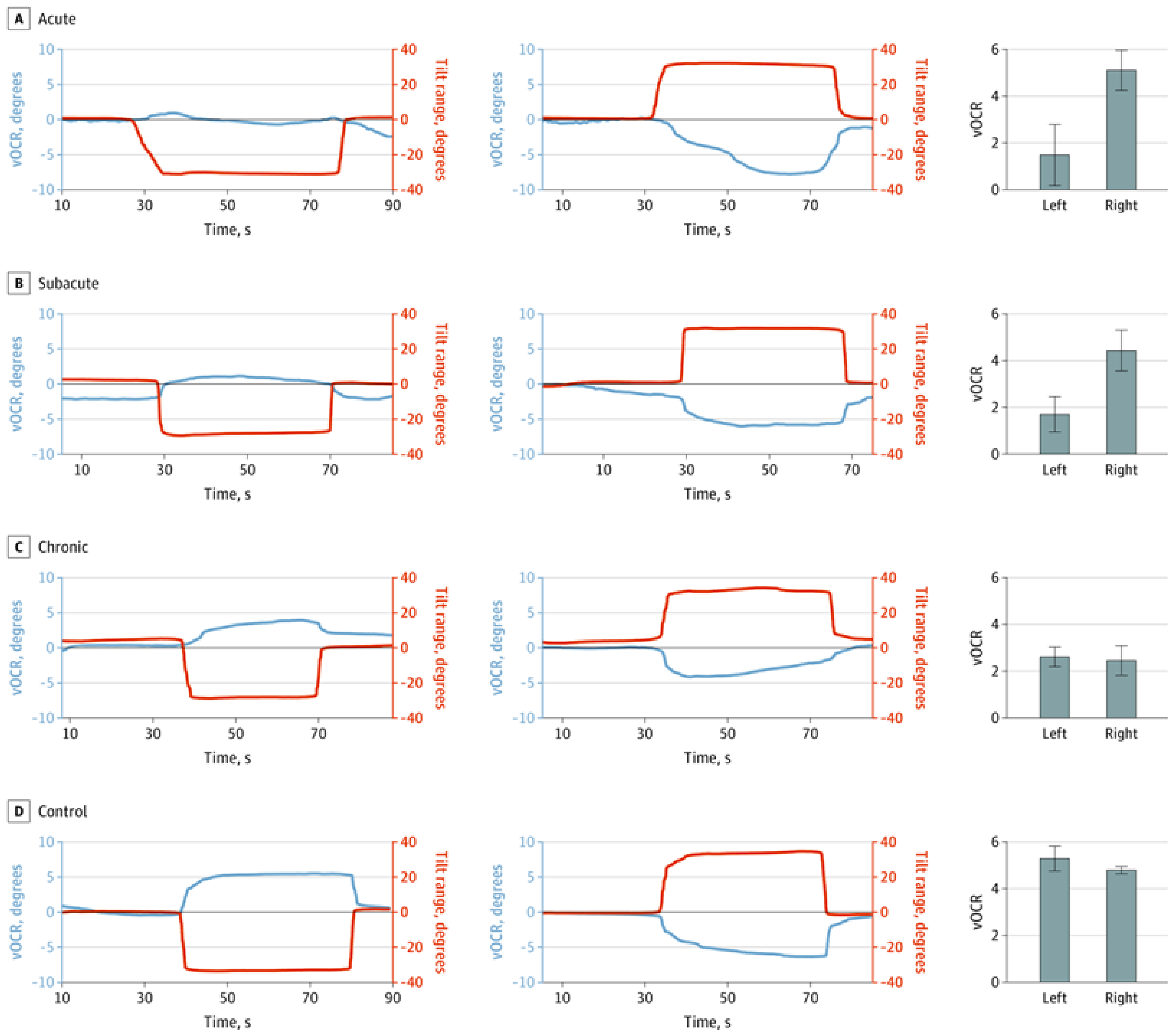


Yang et al., 2023



- Assessed vOCR in patients with acute (<4 wk), subacute (4wk-6mo), and chronic (6mo) UVL
    - **Head tilt maneuver:** abnormalities toward lesion side only for acute patients
    - **Body tilt maneuver:** abnormalities for subacute and acute patients
- vOCR can recover and neck inputs can enhance response

vOCR: Typical Responses



Acute left loss: reduced left amplitude, Significant asymmetry

Subacute left loss: reduced left amplitude, Significant asymmetry

Chronic right loss: reduced bilateral amplitude, no asymmetry

Sadeghpour et al., 2024

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vOCR: Take Home Messages and Limitations

- **Take home**:
  - vOCR can serve as test for otolith dysfunction with similar diagnostic sensitivity of VEMPs
  - vOCR reflects utricle function
  - Use of body tilt minimizes neck contributions and can maximize vestibular contributions
  - Cutoff of 3-4 degrees recommended
- **Limitations:**
  - vOCR asymmetry can normalize with recovery

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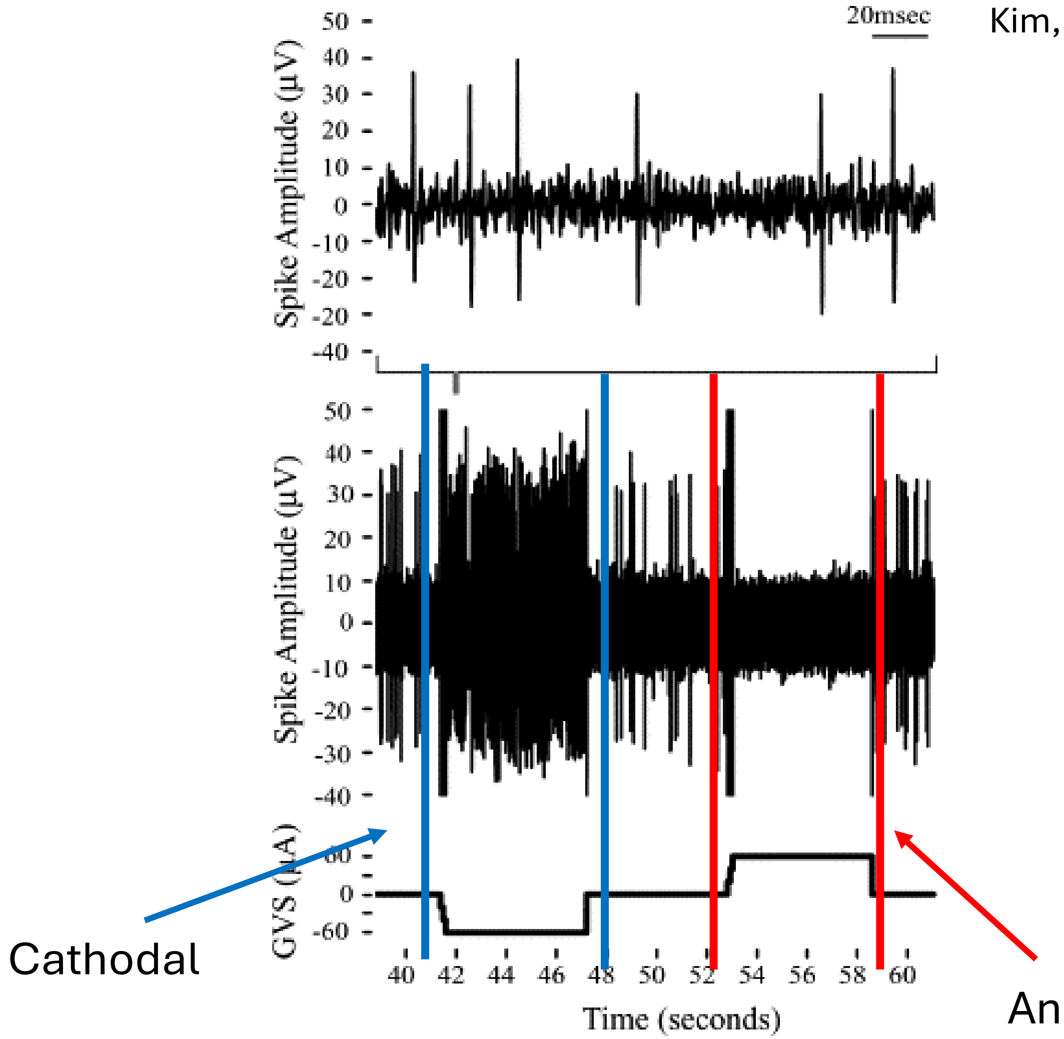
Galvanic Vestibular Stimulation

Background: Galvanic Vestibular Stimulation

- GVS broadly refers to applying electrical current to stimulate the vestibular system
  - Typical applications are ~0.1–4 mA DC currents at the mastoid processes (Dlugaiczyk et al., 2019).
- Anode and cathode current applied to skull
  - **Cathodal** current: increase in action potentials
  - **Anodal** currents: silences vestibular afferents

Kim, 2004



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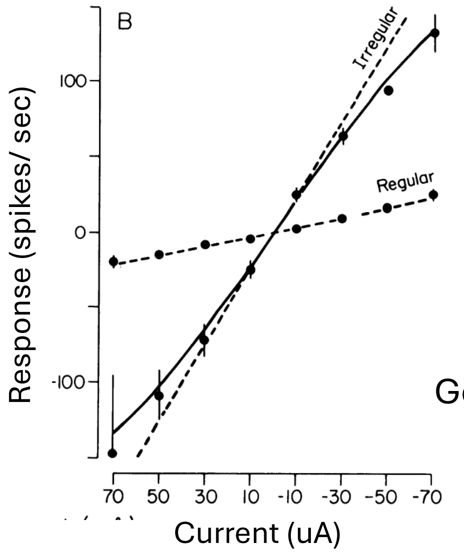
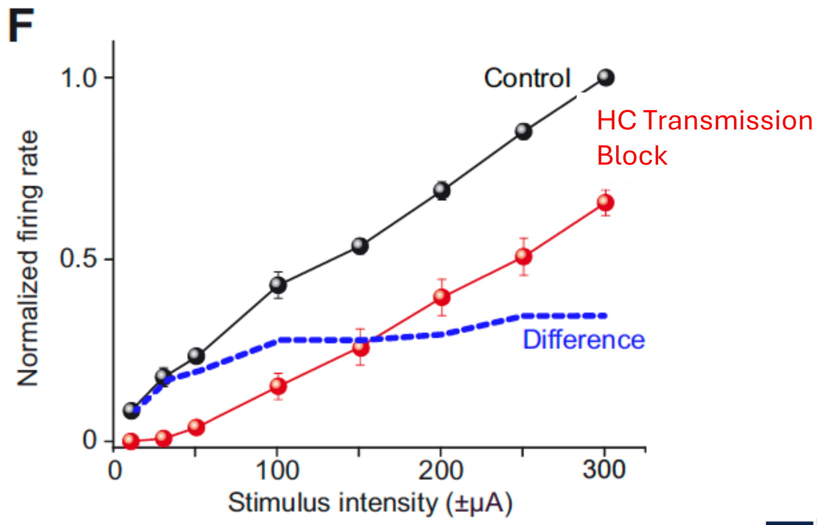
Background: GVS Stimulation

- GVS is broad vestibular stimulation with no specific direction
- GVS activates both canal and otolith afferents (Kwan et al., 2019; Forbes et al., 2022)
- GVS preferentially activates irregular afferent fibers (Goldberg et al., 1984; Minor, 1991)
- Evidence suggests that there is hair cell involvement
    - Blocks of HC transmission impacts GVS responses (Gensberger et al., 2016)
    - Gentamicin induced ototoxicity leads to reduced GVS responses (Aw et al. 2008; de Waele et al. 2002).



Goldberg et al., 1984



(Gensberger et al., 2016)

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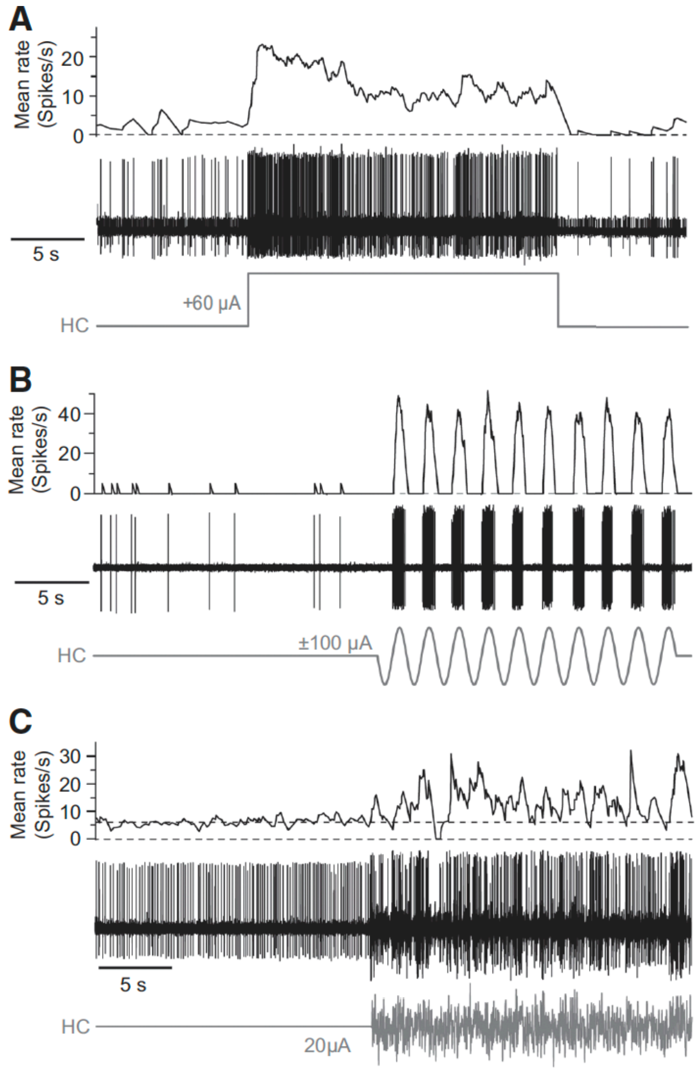
Background: GVS Waveforms

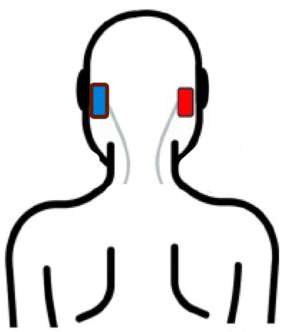
- **Current steps**: transient increase in discharge is followed by a sustained and variably elevated firing rate
- **Sinusoidal currents**: induce sinusoidal changes in afferent firing
- **Noisy stimulation:** band limited noisy current which increase spontaneous activity in afferent responses



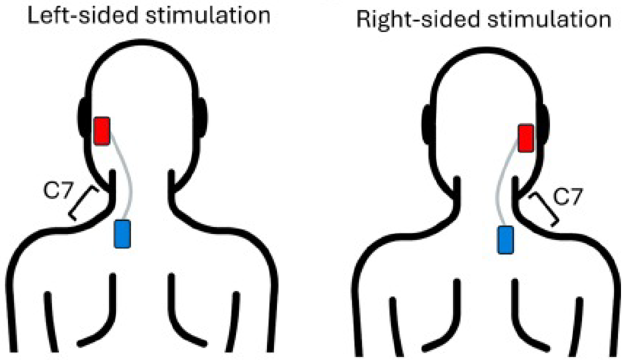
Goldberg et al., 1984

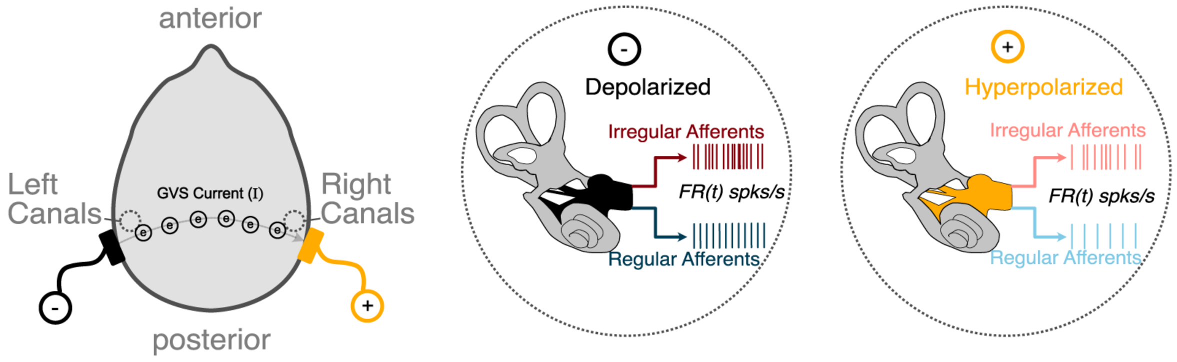
GVS Montages

Binaural bipolar



Monaural

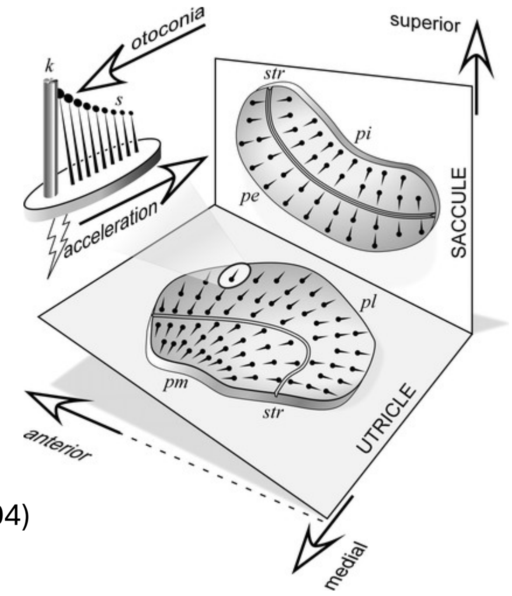




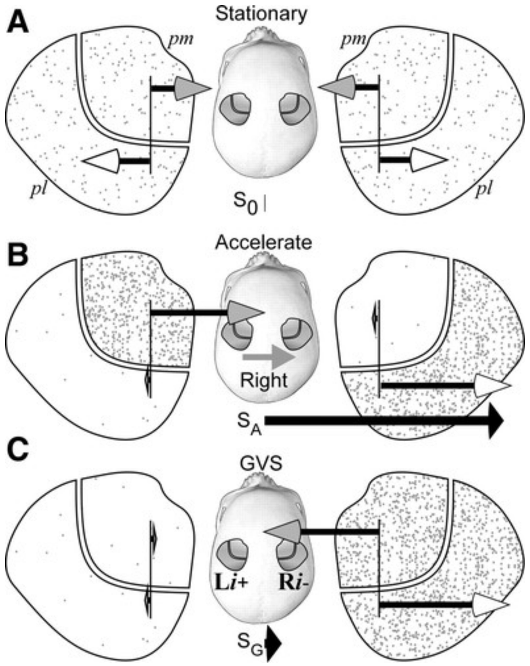
Allred et al., 2024

- **Binaural bipolar montage**: anode placed on one mastoid and the cathode on the other side
  - Used to excite cathode side and inhibit anode side
- **Monaural montage**: cathode or anode on the mastoid
  - Opposite polarity on the seventh cervical vertebra, the forehead, vertex, or forearm
  - Used to direct stimulation to one side

Background: GVS Responses



(Fitzpatrick, 2004)



- Brain interprets binaural bipolar stimulation as predominant roll rotation and small yaw rotation and interaural translation toward cathode
- Otolith stimulation is complex and largely cancels out
    - Pars lateralis is slightly larger than pars medialis, the net signal from the utricular macula will be a small lateral acceleration (Fitzpatrick, 2004)

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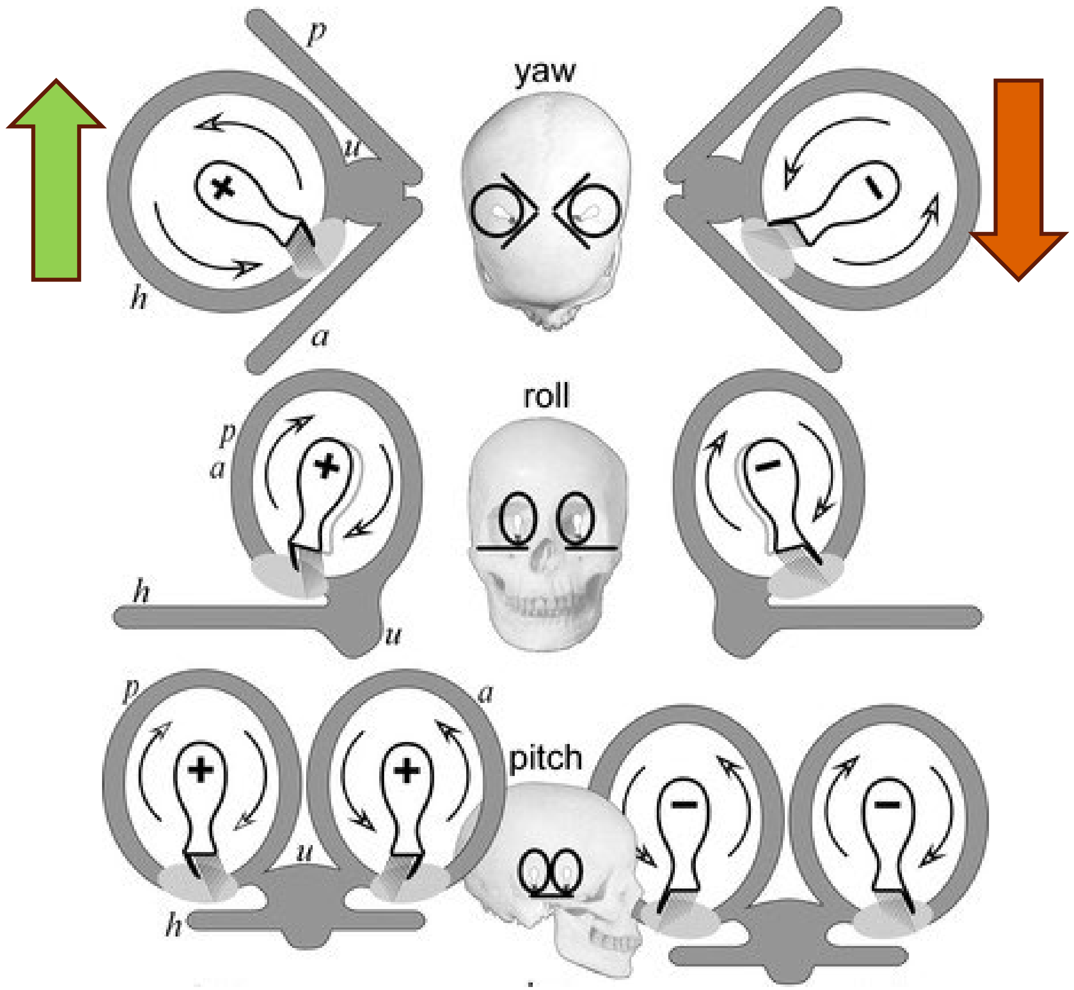
Overview GVS Responses



Right cathodal

Right HSCC excited

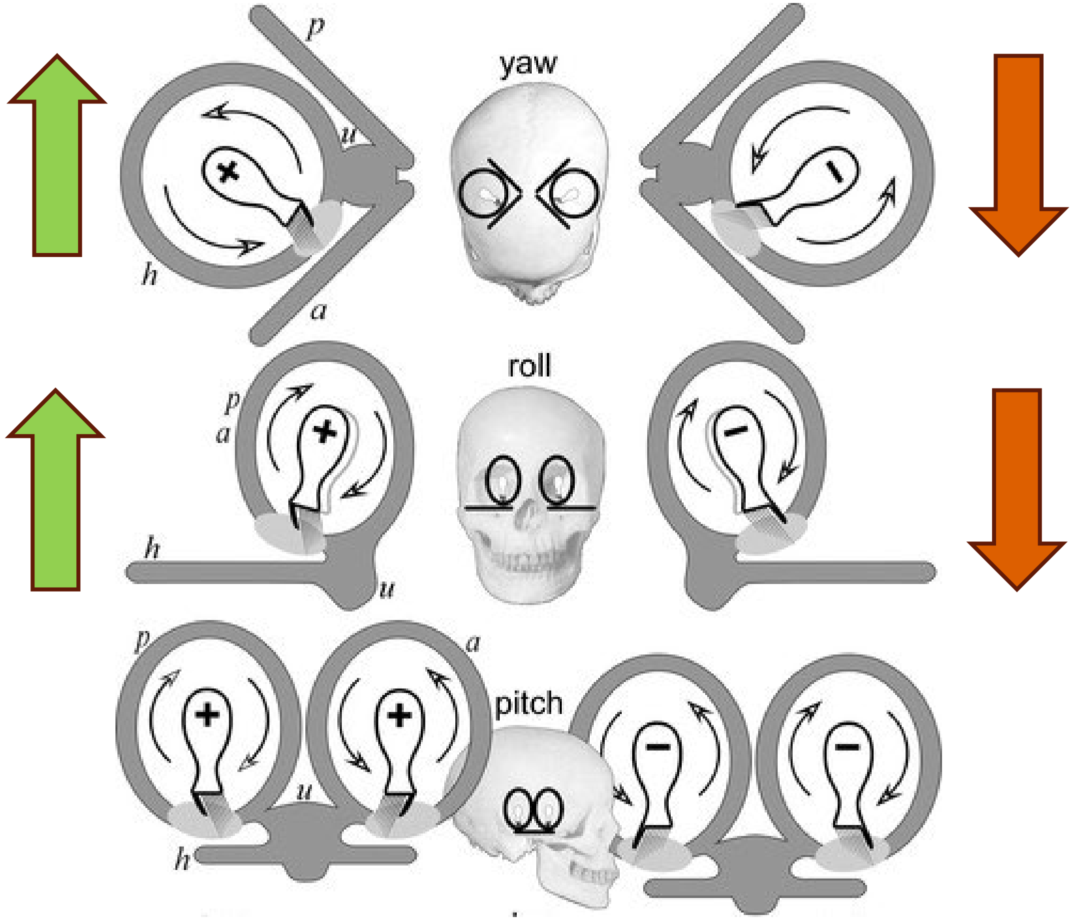
Left anodal

Left HSCC inhibited

+

Yaw rotation to right

Overview GVS Responses



Right cathodal

Left anodal

Right HSCC excited

Left HSCC inhibited

+

Yaw rotation to right

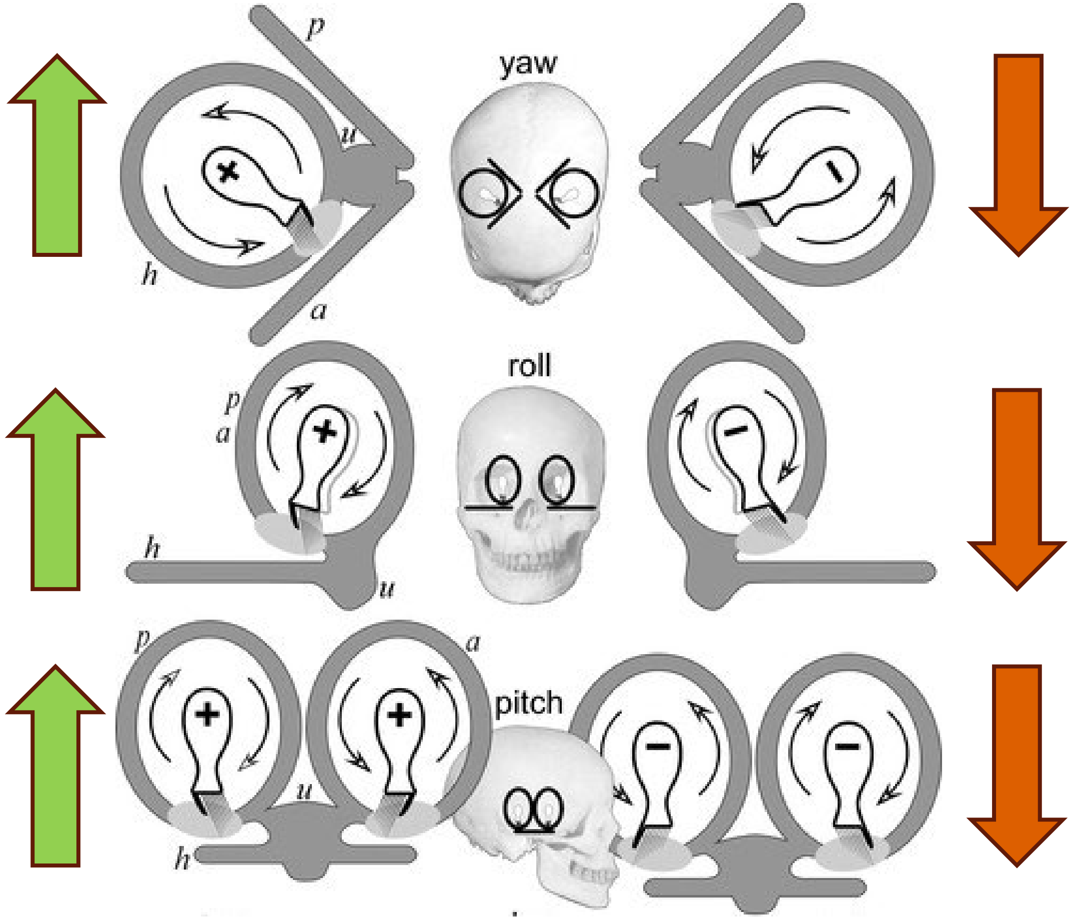
Right ASCC excited
Right PSCC excited

Left ASCC inhibited
Left PSCC inhibited

+

Right ear down roll

Overview GVS Responses



Right cathodal	Left anodal
Right HSCC excited	Left HSCC inhibited

+

Yaw rotation to right

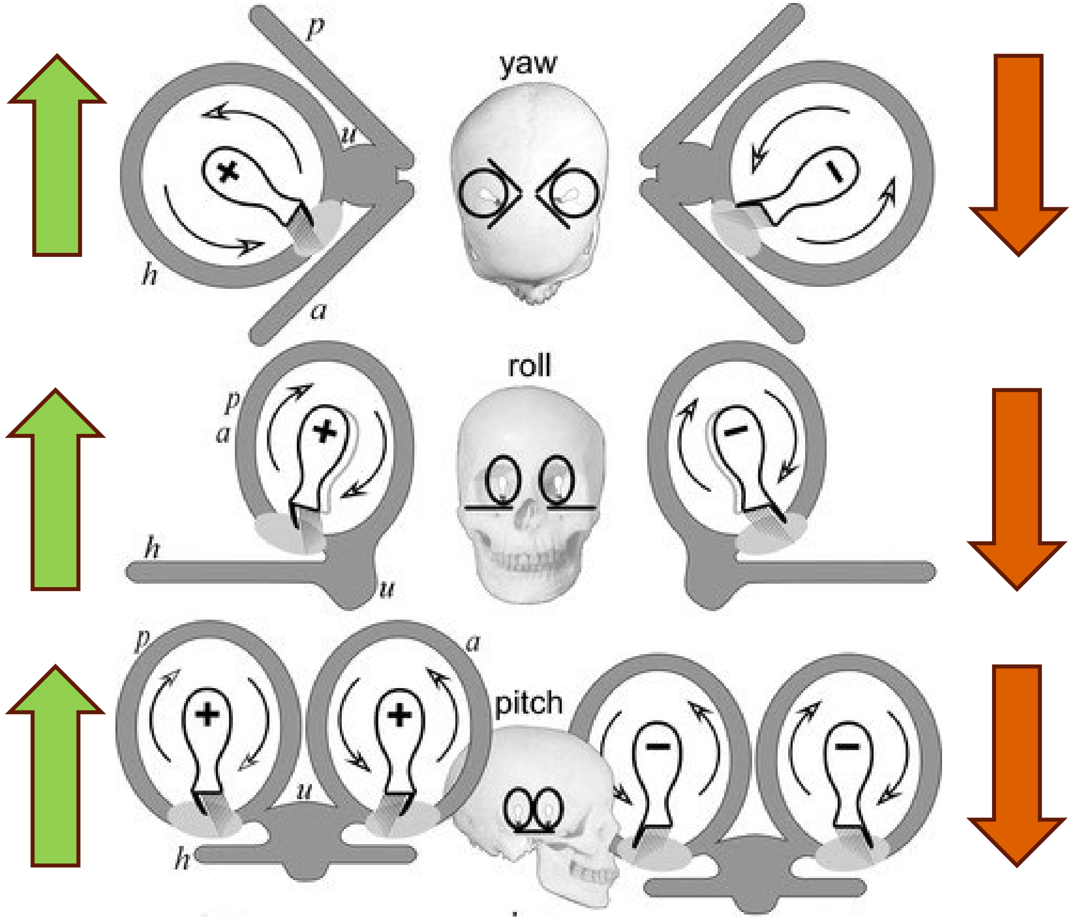
Right ASCC excited Right PSCC excited	Left ASCC inhibited Left PSCC inhibited

+

Right ear down roll

Right ASCC excited Left ASCC excited	Left PSCC inhibited Right PSCC inhibited
Nose down pitch	**Nose up pitch**

Overview GVS Responses



Right cathodal	Left anodal
Right HSCC excited	Left HSCC inhibited

+

Yaw rotation to right

Right ASCC excited Right PSCC excited	Left ASCC inhibited Left PSCC inhibited

+

Right ear down roll

Right ASCC excited Left ASCC excited	Left PSCC inhibited Right PSCC inhibited
Nose down pitch	**Nose up pitch**

-

No pitch

Background: Overview GVS Responses

- **Eye responses**: conjugate ocular torsion toward side of anode
- **Postural sway**: primary postural response is sustained sway directed toward the anode
- **Motion perception**: subjective sensations of roll, tilt or rotation

- All responses are context dependent and exhibit large inter-individual variability

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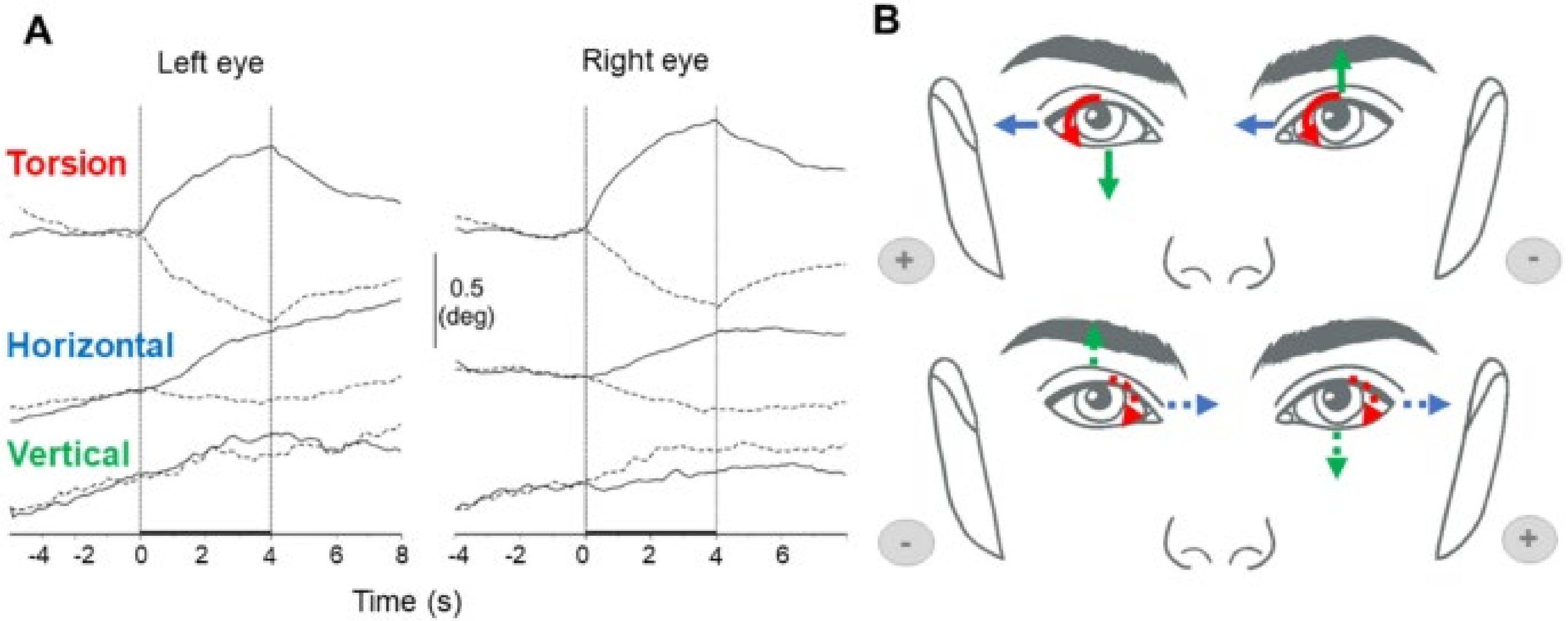
GVS: Ocular Responses

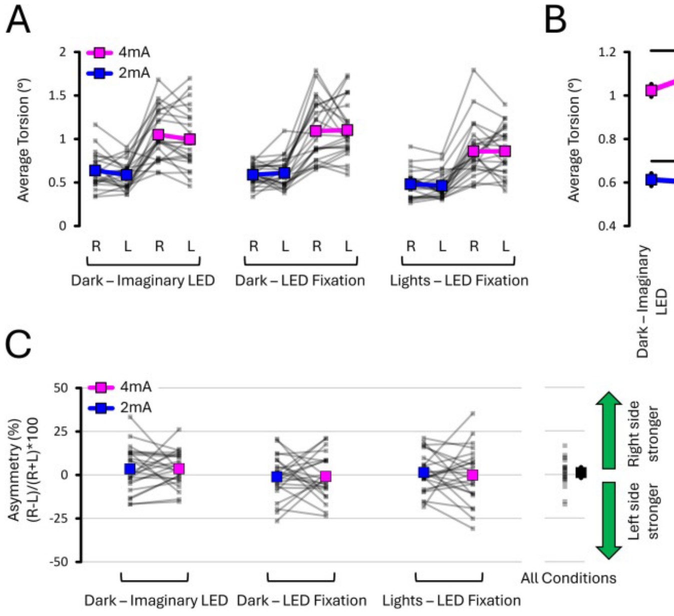


Marchand et al., 2025

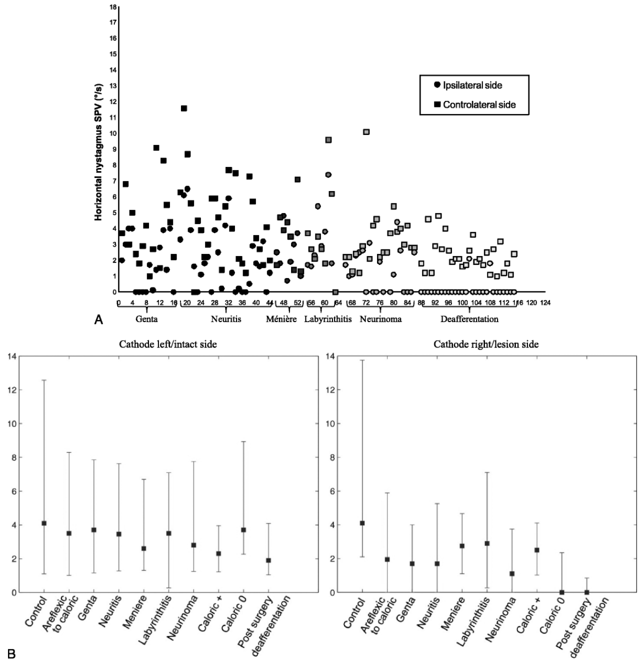
- **Torsion**: torsional toward the anode, away from cathode
- **Horizontal**: toward anode
- **Vertical**: hypertropia on cathodal side, hypotropia on anodal side

(Aw et al., 2006; MacDougall et al., 2002, 2003; Severac Cauquil et al. 2003)

Ocular Responses: Diagnostics



Hamel et al., 2025

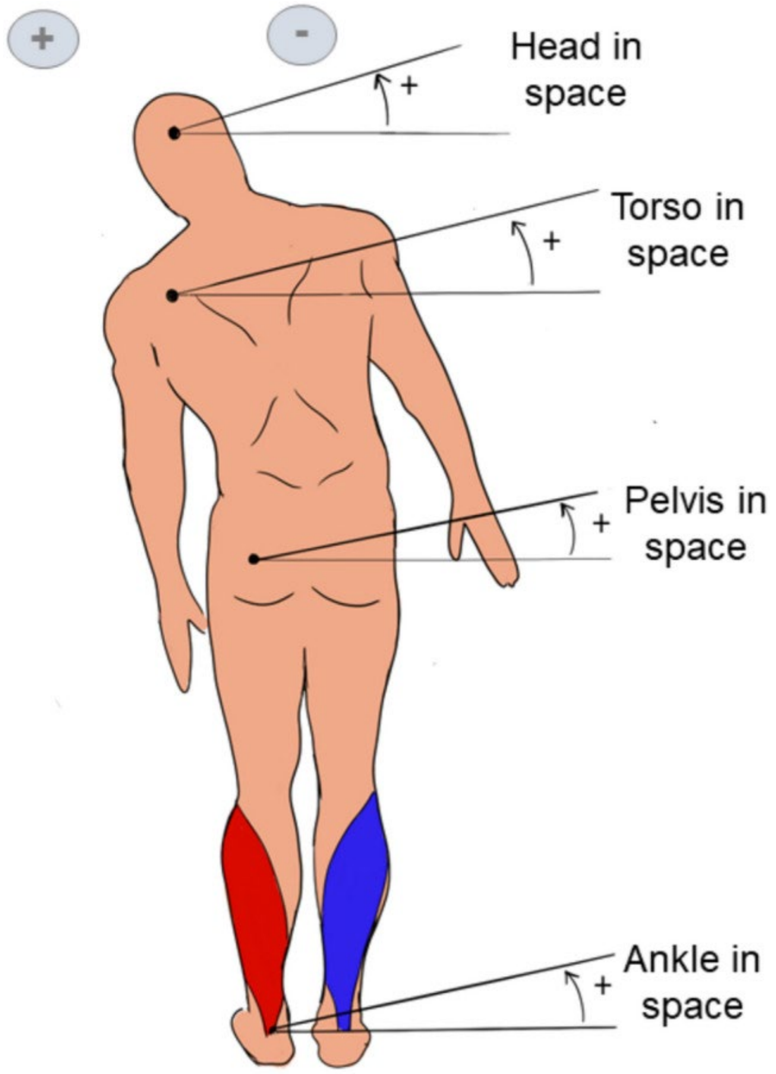


Vallieau et al., 2011

- Large inter-individual variability in healthy controls and patients with vestibular loss
  - Asymmetry in ocular responses does not well correlate to asymmetry in calorics (Vallieau et al., 2011)
  - Impacted by target location and lighting (Hamel et al., 2025)

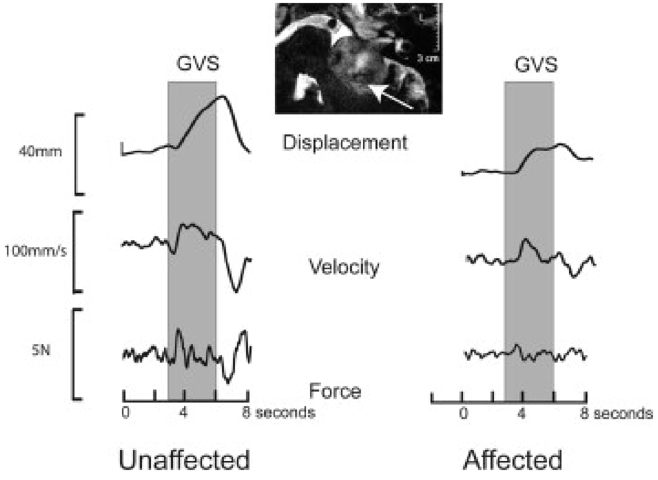
GVS: Postural Response

- Largest response is whole body sway directed toward anode
  - Loss of vision or proprioception causes larger sway magnitudes
- Muscle responses restricted to those that are involved in balance for specific experimental condition
- Two components of response:
  - Short latency: predominantly otolith
  - Medium latency: predominantly SCC

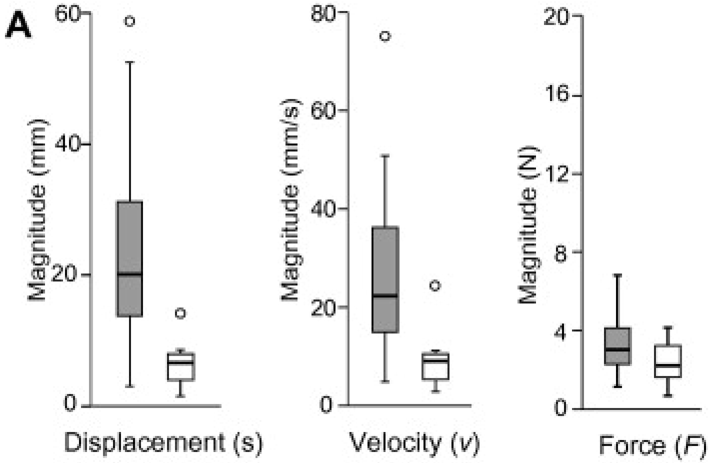


Marchand et al., 2025

Postural Responses: Diagnostics



Welgampola et al., 2013



Tax et al., 2014

- GVS can be used to study vestibulospinal responses
- Asymmetry of body sway from unilateral stimulation can lateralize UVL (Welgampola et al., 2013)
- Bilateral VL show reduced evoked sway responses than healthy adults (Tax et al., 2014)

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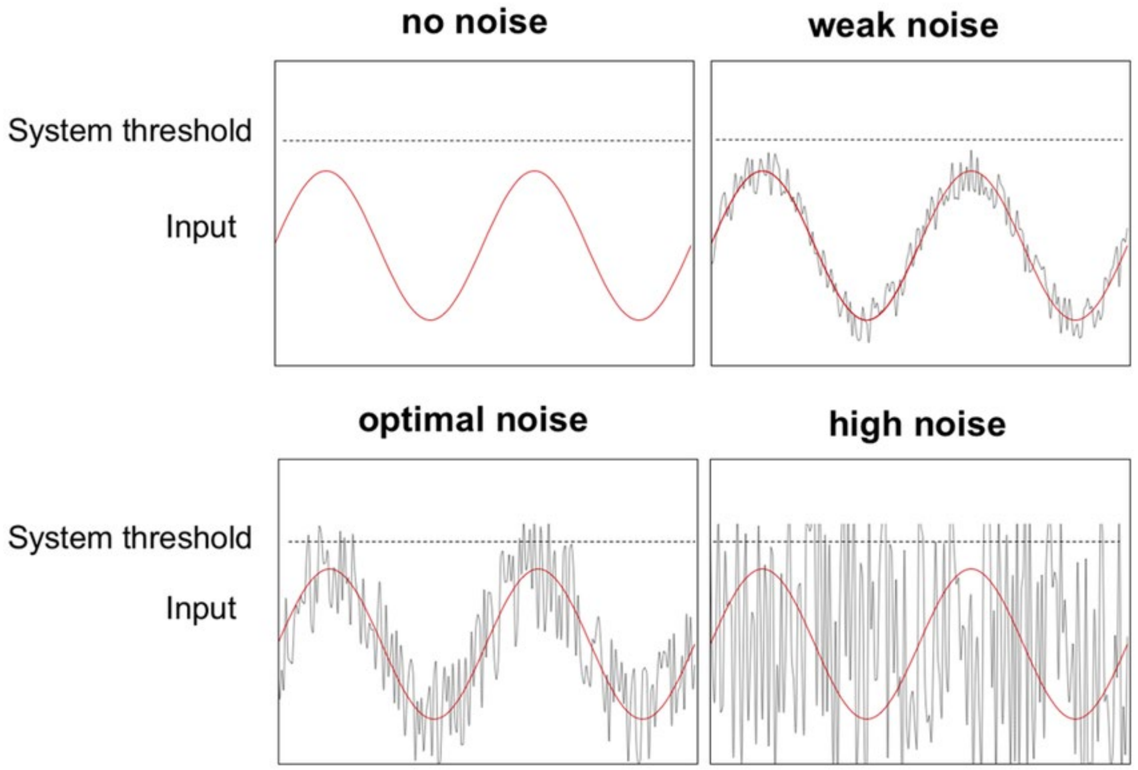
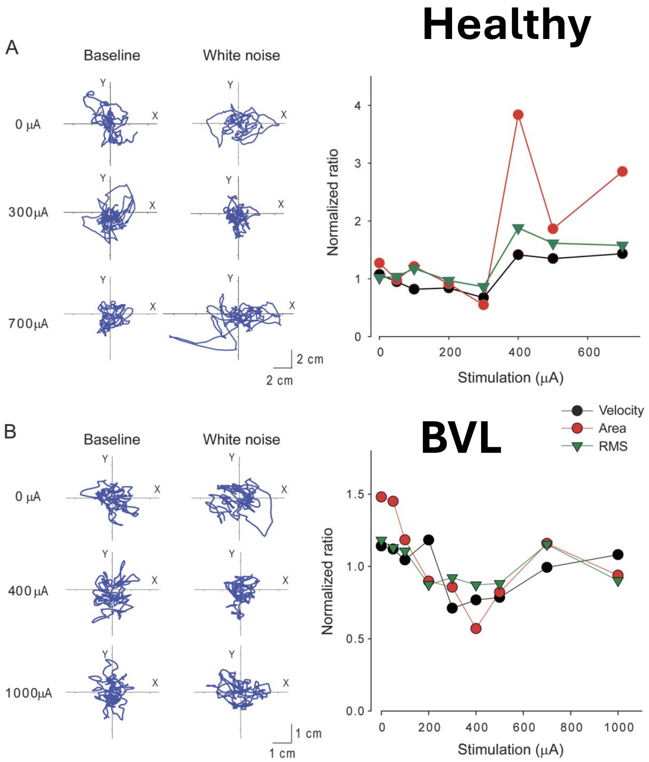
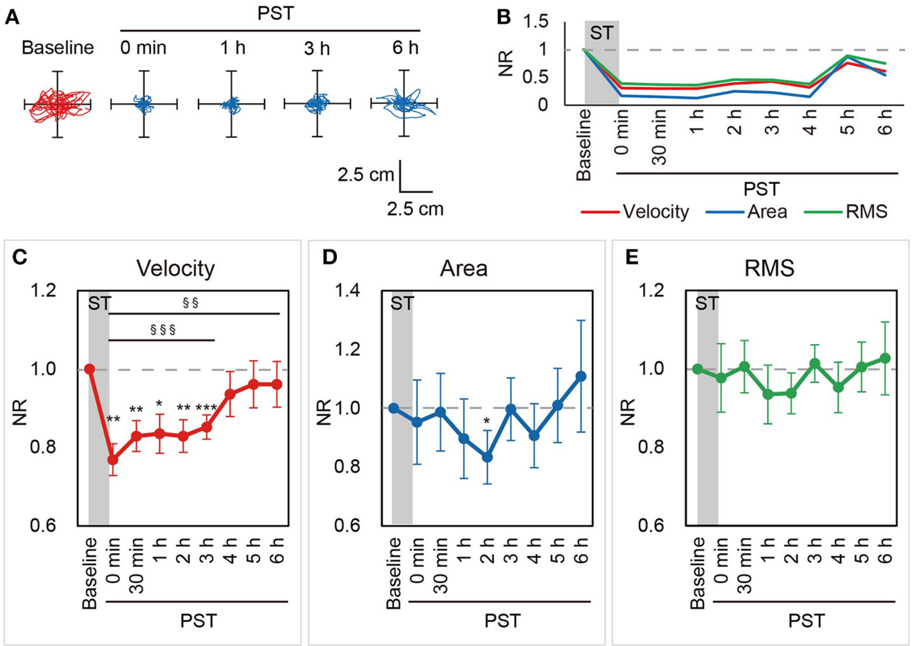
Postural Responses: Rehabilitation



- Noisy GVS (nGVS) has potential rehabilitative applications
  - nGVS is a zero mean, noisy galvanic current over a fixed bandwidth
- **Stochastic resonance**: addition of random noise can enhance detection or respose to a weak input signal

Postural Responses: Rehabilitation in BVL

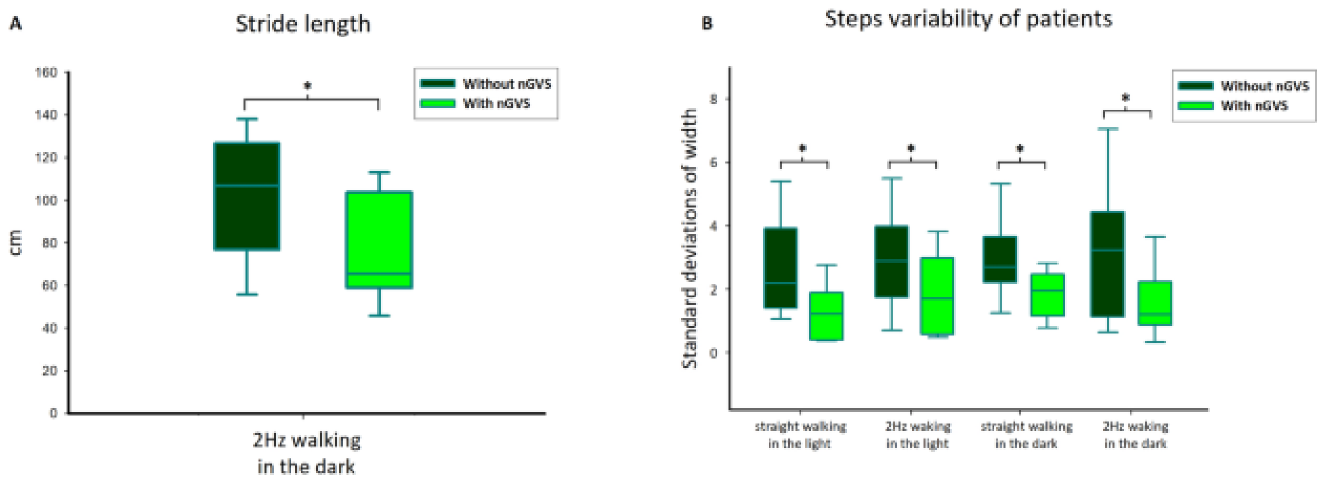




- Subthreshold nGVS during testing can improve postural stability in healthy controls and BVL (Iwaski et al., 2014)

- 30 minutes of nGVS prior to testing can lead to improvements in postural stability in BVL (Fujimoto et al., 2021)

Postural Responses: Rehabilitation in BVL



Chen et al., 2021

- Improvements in gait variability in BVL can be seen with nGVS (Chen et al., 2021)
- In BVL, changes seen in BVL patients with residual function but not those with complete loss (Chen et al., 2021; Schniepp et al., 2018)
- Meta-analysis revealed a moderate effect in favor of nGVS improving postural control during standing and walking [pooled SMD = 0.47 95% CI (0.25, 0.7)] (McLaren et al., 2022)

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Postural Responses: Rehabilitation in Neurodegenerative Disorders

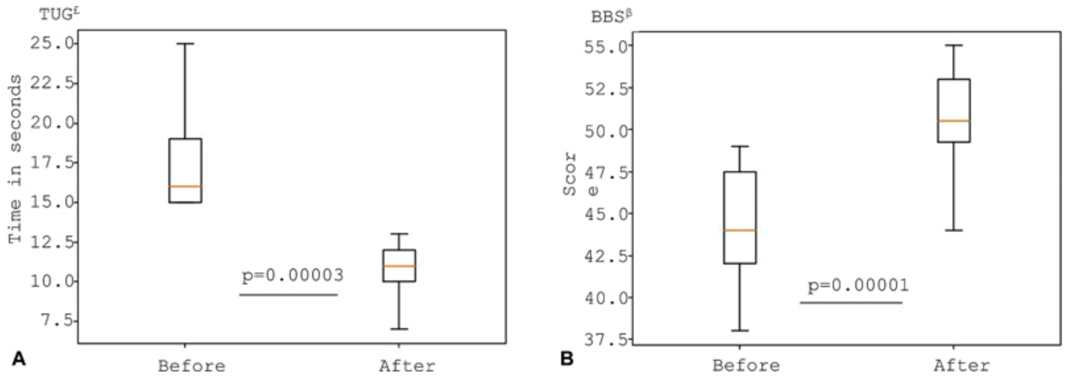

Table 4 Postural parameters of the stability limit area, confidence ellipse, path length, total mean velocity, and score for each condition in posturography before and after eight sessions of galvanic vestibular stimulation applied to 25 individuals with Parkinson's disease and instability

Condition	Parameter	Galvanic vestibular stimulation		*p*-value
		Before	After	
C1–eyes open with a fixed target on a stable surface	Confidence ellipse area	849 (384/2,041)	424 (237/1,143)	0.313
	Path length	626 (436/1,502)	549 (358/902)	0.276
	Mean velocity	16 (12/36)	15 (9/24)	0.518
	Score	94 (87/97)	97 (94/99)	0.032
C5–eyes closed on an unstable surface	Confidence ellipse area	4,378 (2860/5,963)	2,370 (1517/3,113)	< 0.001
	Path length	1,570 (1,190/2,433)	1,110 (970/1,513)	0.006
	Mean velocity	55 (38/85)	35 (28/48)	0.002
	Score	68 (31/84)	89 (76/93)	< 0.001

- Meta-analysis found that GVS has an overall pooled effect on the postural balance of PD patients ($g = 0.16$ $p < 0.05$; Mahmud et al., 2022)
- After 8 weeks of weekly nGVS, PD patients showed improvements in TUG, BSS, and balance for conditions with increased vestibular contributions (de Ávila Pires, 2025)

GVS: Take Home Messages and Limitations

- **Take Home:**
  - GVS is broad stimulation of the vestibular labyrinth
  - GVS yields a perceptual response, postural control response, and an ocular response
  - nGVS has promise for rehabilitative intervention
- **Limitations**:
  - Substantial inter-individual variability
  - Concerns about safety

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