

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.



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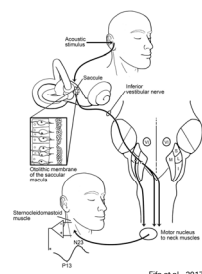
Outline of Talk

- 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



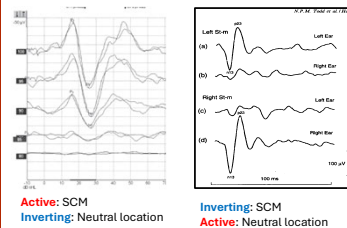
- **cVEMPs** reflect myogenic activity in the sternocleidomastoid muscles, driven by saccular response and inferior vestibular nerve
 - Cervical
 - Saccular
 - Inferior nerve, Ipsilateral, Inhibitory

File et al., 2017



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cVEMPs: Typical response

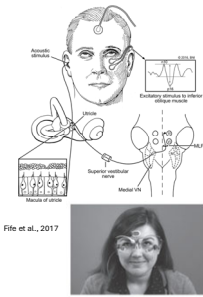


- **Ipsilateral** to stimulus
- **Biphasic waveform:**
 - First peak: P1 at ~13 ms
 - Second peak: N1 at ~23 ms
- **Inhibitory response:** moving from increased EMG activity to decreased EMG activity
- Some variability in preferred polarity of VEMP responses



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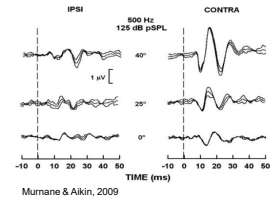
oVEMPs: Quick Refresher



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

oVEMP: Typical Response

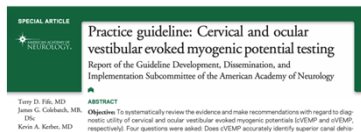
- **Contralateral** to stimulation
- **Multipeak waveform**
 - Focus on N1-P1 component
- **Excitatory response:**
- Strongest response seen with eyes tilted up to view static target @ ~30 deg above horizontal (Govender et al., 2016a)



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VEMPs: Applications



- 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

VEMPs: Diagnostic Test Battery

Central Vestibular Function		Saccade, Pursuit, OPK
Supportive Findings for Central or Peripheral		Gaze, Spontaneous Positionals, Positioning
Superior Nerve	Horizontal SCC	Calorics (low frequency) Rotary chair (low to mid F) vHIT (high F)
	Anterior SCC	vHIT
	Utricle	oVEMP
Inferior Nerve	Posterior SCC	vHIT
	Saccule	cVEMP

- 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 ACL, B81, and IH for each age group

Group (age range)	ACL (%)	B81 (%)	IH (%)
1 (10-19 yrs)	100	100	100
2 (20-29 yrs)	100	100	100
3 (30-39 yrs)	100	100	100
4 (40-49 yrs)	95	100	100
5 (50-59 yrs)	95	100	100
6 (60-69 yrs)	85	100	100
7 (70+ yrs)	80	75	100
All subjects	92	98	100

ACL = air conduction stimuli; B81 = bone conduction stimuli; IH = impulse hammer stimuli

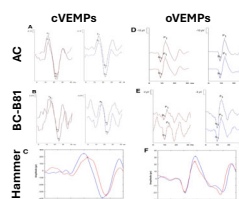
Patterson et al., 2021

TABLE 4. oVEMP response rates for ACL, B81 and IH for each age group

Group (age range)	ACL (%)	B81 (%)	IH (%)
1 (10-19 yrs)	100	100	100
2 (20-29 yrs)	95	100	100
3 (30-39 yrs)	100	100	100
4 (40-49 yrs)	95	100	100
5 (50-59 yrs)	95	100	100
6 (60-69 yrs)	85	100	100
7 (70+ yrs)	67	83	100
All subjects	90	98	100

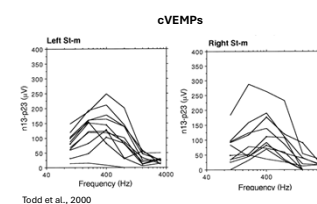
ACL = air conduction stimuli; B81 = bone conduction stimuli; IH = impulse hammer stimuli

Patterson et al., 2021



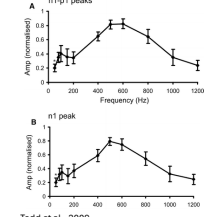
- Air conduction, bone conduction (B81), or skull taps/impulse hammer can be used
 - Largest response amplitudes from impulses (Patterson et al., 2021; Rosengreen et al., 2011)
 - AC cVEMP response rates comparable to BC and IH across age span
 - AC oVEMP response rates lower for adults 70+ years (Patterson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

VEMPs: Stimuli



Todd et al., 2000

oVEMPs



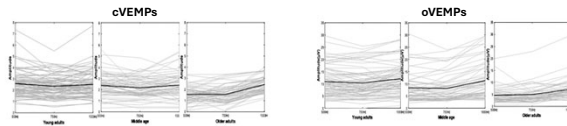
Todd et al., 2009

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

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VEMPs: Frequency Tuning and Age



- 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	40%	43% *	13%	21% *
Present response(s) at least one ear	70%	57% *	33%	23% *
Present response(s) both ears	40%	30% *	10%	13%
All tested frequencies present (500-2000 Hz)	13%	N/A	2%	N/A

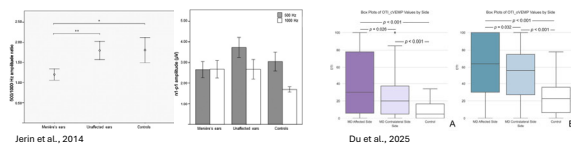
*All tested frequencies present (500-2000 Hz). N/A, not applicable. *Significant difference between multi-frequency testing and only testing at 500 Hz (one-sided value of $p < 0.05$).

- 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



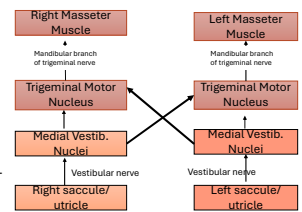
- Shift in c/oVEMP tuning seen in Meniere's Disease (MD) to 750 or 1000 Hz (Jerin et al., 2014; Singh et al., 2016; Angeli et al., 2022)
- Some have proposed metrics incorporating amplitude ratios and presence of responses (Du et al., 2025)



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Masseter VEMPs: Background

- Masseter VEMPs (mVEMPs) are a bilateral symmetrical response of the vestibulo-masseteric pathway (Deriu et al., 2003; Deriu et al., 2010; Giaconini 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 (90–100 dB nHL)
 - Auditory portion** (p16-n21)—longer latency, low threshold (<80/90 dB nHL) (Deriu et al., 2005)

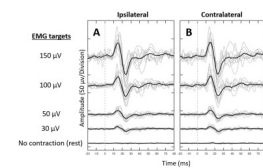
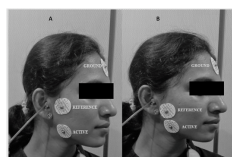


(Deriu et al., 2005)



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mVEMPs: Recording



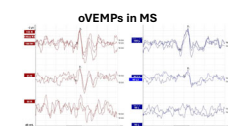
(Romero et al., 2020)

- 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)

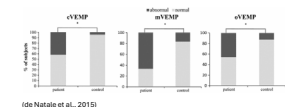


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VEMPs: Non-Vestibular Disorders



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)



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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	BI: absent	BI: absent	RPM	71.60	60.11	9
13	R: absent	Not done	RPM	53.25	42.90	10
14	BI: absent	BI: absent	RPM	0	41.80	100
15	AR-SS-N	435 L	LPM	32.02	0	100
16	R: absent	525 R	RPM	0	37.26	100
17	R: absent	BI: absent	RPM	50.70	41.69	10
18	L: absent	BI: absent	LPM	26.83	0	100
19	375 R	R: absent	RPM	0	46.21	100
20	AR-SS-N	AR-525-L	LPM	49.44	0	100

L: absent c/o VEMP
B: Present mVEMPS

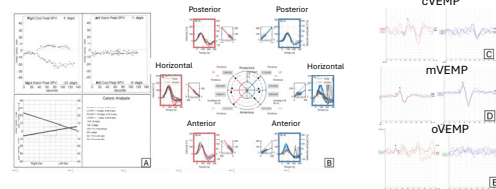
R: absent c/o VEMP
R: absent mVEMPS

- 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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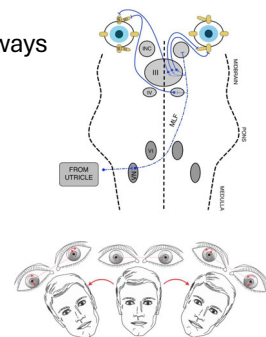
Video Ocular Counter Roll



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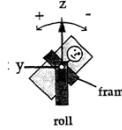
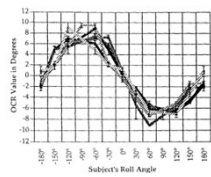
Background: Anatomic Pathways

- 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



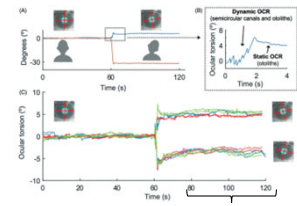
- Ocular counter roll (OCR) has been routinely measured in research settings using scleral search coils
- Gain of the OCR (in healthy adults) is ~ 0.1 - 0.2 depending on tilt angle (Bucher et al., 1992)



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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

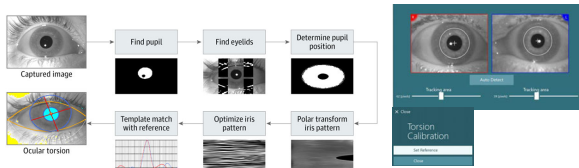


Otero-Millan, 2017



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Background: Measuring OCR

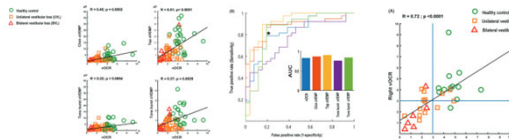


- Algorithm used in current clinical system focuses on determining changes in pupil position relative to reference (Otero-Millan, 2015; 2017; Yang, 2025)
- Static response assessed over 3 head tilts in each direction



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vOCR: Validation in Peripheral Loss

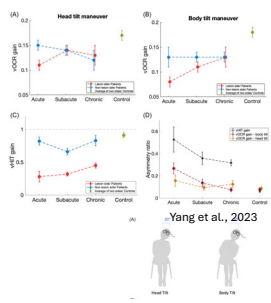


- Assessed vOCR to 30 degree head tilt and c/o VEMPs in HC, ULV, and BVL patients (Otero-Millan, 2017)
- vOCR correlated to oVEMP & cVEMP amplitude but not asymmetry ratio
- Best threshold to detect vestibular loss was 3 degrees (Otero-Millan, 2017) and 3.5 degrees (Tessier et al., 2025)
 - Sensitivity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



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vOCR: Peripheral Loss & Neck Input



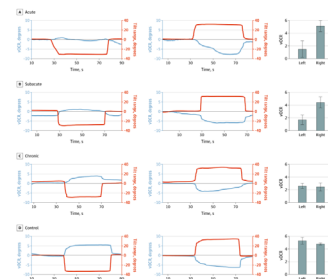
- Assessed vOCR in patients with acute (<4 wk), subacute (4wk-6mo), and chronic (6mo) UVL
- Head tilt maneuver:** abnormalities toward lesion side only for acute patients
- Body tilt maneuver:** abnormalities for subacute and acute patients
- vOCR can recover and neck inputs can enhance response

Yang et al., 2023



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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

Sadeighpour 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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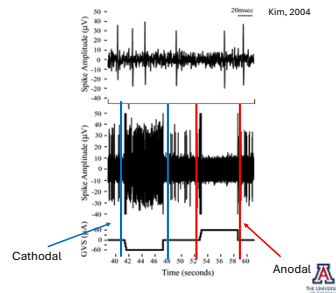
Galvanic Vestibular Stimulation



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Background: Galvanic Vestibular Stimulation

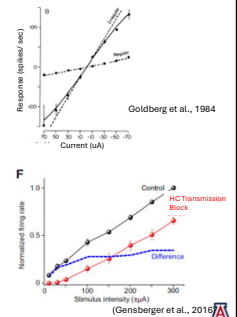
- GVS broadly refers to applying electrical current to stimulate the vestibular system
 - Typical applications are ~0.1–4 mA DC currents at the mastoid processes (Dlugacz et al., 2019).
- Anode and cathode current applied to skull
 - **Cathodal** current: increase in action potentials
 - **Anodal** currents: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



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Background: GVS Stimulation

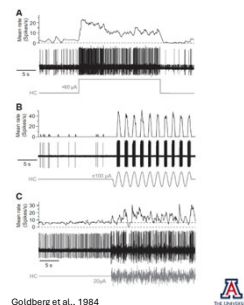
- GVS is broad vestibular stimulation with no specific direction
- GVS activates both canal and otolith afferents (Kwan et al., 2019; Forbes et al., 2022)
- GVS preferentially activates irregular afferent fibers (Goldberg et al., 1984; Minor, 1991)
- Evidence suggests that there is hair cell involvement
 - 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).



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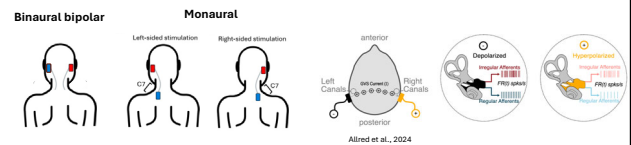
Background: GVS Waveforms

- **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



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GVS Montages

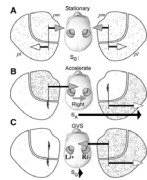
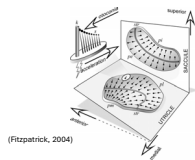


- **Binaural bipolar montage:** anode placed on one mastoid and the cathode on the other side
 - Used to excite cathode side and inhibit anode side
- **Monaural montage:** cathode or anode on the mastoid
 - Opposite polarity on the seventh cervical vertebra, the forehead, vertex, or forearm
 - Used to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



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Background: GVS Responses

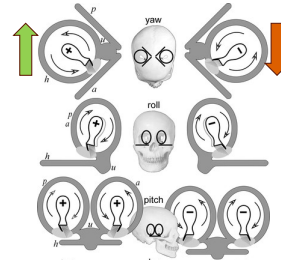


- Brain interprets binaural bipolar stimulation as predominant roll rotation and small yaw rotation and interaural translation toward cathode
- Otolith stimulation is complex and largely cancels out
 - Pars lateralis is slightly larger than pars medialis, the net signal from the utricular macula will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



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Overview GVS Responses

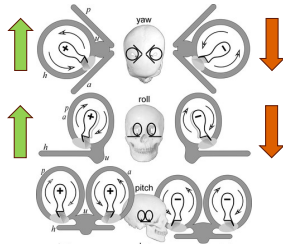


Right cathodal **Left anodal**
 Right HSCC excited Left HSCC inhibited
 Yaw rotation to right



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Overview GVS Responses



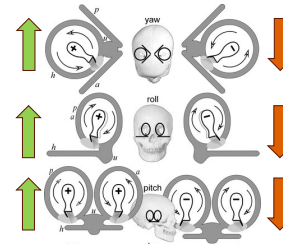
Right cathodal **Left anodal**
 Right HSCC excited Left HSCC inhibited
 Yaw rotation to right

Right ASCC excited **Left ASCC inhibited**
Right PSCC excited **Left PSCC inhibited**
 Right ear down roll



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Overview GVS Responses



Right cathodal **Left anodal**
 Right HSCC excited Left HSCC inhibited
 Yaw rotation to right

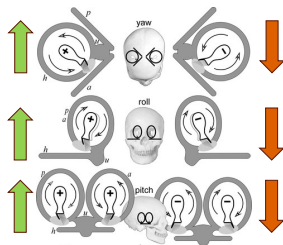
Right ASCC excited **Left ASCC inhibited**
Right PSCC excited **Left PSCC inhibited**
 Right ear down roll

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



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Overview GVS Responses



Right cathodal **Left anodal**
 Right HSCC excited Left HSCC inhibited
 Yaw rotation to right

Right ASCC excited **Left ASCC inhibited**
Right PSCC excited **Left PSCC inhibited**
 Right ear down roll

Right ASCC excited **Left ASCC inhibited**
Left ASCC excited **Right PSCC inhibited**
 Nose down pitch Nose up pitch
 No pitch



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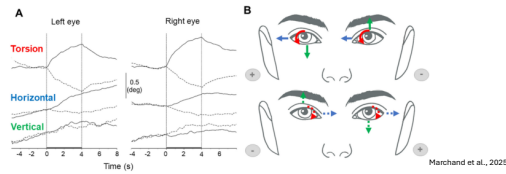
Background: Overview GVS Responses

- 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

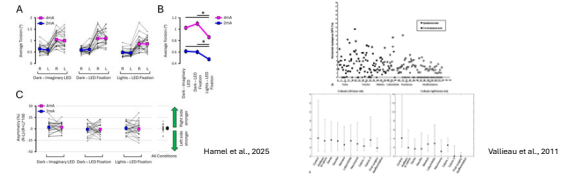


- **Torsion:** torsional toward the anode, away from cathode
- **Horizontal:** toward anode
- **Vertical:** hypertropia on cathodal side, hypotropia on anodal side (Aw et al., 2006; MacDougall et al., 2002, 2003; Severac Cauquil et al. 2003)



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Ocular Responses: Diagnostics



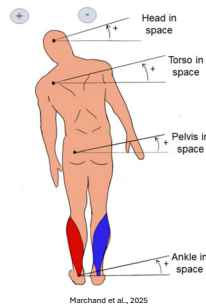
- Large inter-individual variability in healthy controls and patients with vestibular loss
- Asymmetry in ocular responses does not well correlate to asymmetry in calorics (Valleau et al., 2011)
- Impacted by target location and lighting (Hamel et al., 2025)



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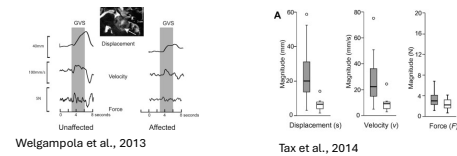
GVS: Postural Response

- 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



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Postural Responses: Diagnostics

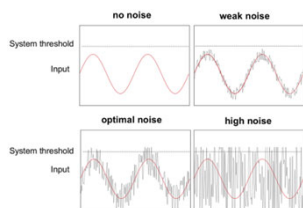


- GVS can be used to study vestibulospinal responses
- Asymmetry of body sway from unilateral stimulation can lateralize UVL (Welgampola et al., 2013)
- Bilateral VL show reduced evoked sway responses than healthy adults (Tax et al., 2014)



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Postural Responses: Rehabilitation

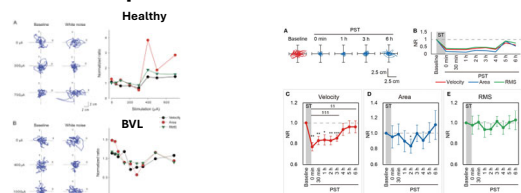


- Noisy GVS (nGVS) has potential rehabilitative applications
 - nGVS is a zero mean, noisy galvanic current over a fixed bandwidth
- **Stochastic resonance:** addition of random noise can enhance detection or response to a weak input signal



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Postural Responses: Rehabilitation in BVL

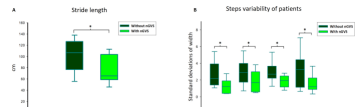


- Subthreshold nGVS during testing can improve postural stability in healthy controls and BVL (Iwaski et al., 2014)
- 30 minutes of nGVS prior to testing can lead to improvements in postural stability in BVL (Fujimoto et al., 2021)



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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

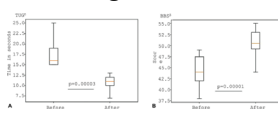


Table 4 Postural parameters of the stability limit area, confidence ellipse, path length, total mean velocity, and score for each condition in neurodegenerative patients and after eight sessions of galvanic vestibular stimulation applied to 25 individuals with Parkinson's disease and instability

Condition	Parameter	Before	After	p-value
1. Lateral sway area with a head turned to the right	Confidence ellipse area	849 (284.2-241)	524 (223.1-742)	0.013
	Path length	424 (245.1-502)	324 (170.9-502)	0.018
	Mean velocity	16.1 (10.3-21.9)	11.0 (6.8-15.2)	0.018
	Score	14.0 (10.0-18.0)	21.0 (16.0-26.0)	0.001
2. Lateral sway area with a head turned to the left	Confidence ellipse area	4,678 (2480.5-6861)	2,478 (1113.1-4118)	<0.001
	Path length	1,716 (1,062.4-2,369.5)	1,114 (650.1-1,578.9)	<0.001
	Mean velocity	17.1 (10.8-23.4)	11.1 (6.8-15.2)	<0.001
	Score	17.1 (10.8-23.4)	21.0 (16.0-26.0)	<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)



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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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References

- Alon, F. W., Munari, D. O., & Proffitt, T. M. (2003, October). The Effects of Click and Tone-Burst Stimulation Parameters on the Vestibular Evoked Myogenic Potential (VEMP) [Thesis]. American Academy of Audiology. <https://doi.org/10.3760/jaa.14.8.5>
- Angel, S. I., & Gonçalves, S. (2019). Cervical VEMP tuning changes by Meniere's disease stages. *Laryngoscope Investigative Otolaryngology*, 4(5), 543-548. <https://doi.org/10.1002/lary.2309>
- Aw, S. T., Todd, M. J., & Halmagyi, G. M. (2006). Latency and Initiation of the Human Vestibuloocular Reflex to Pulsed Galvanic Stimulation. *Journal of Neurophysiology*, 96(2), 505-520. <https://doi.org/10.1152/jn.01550.2005>
- Behnen, M. B., Kouksevitch, B. O., & Tak, A. Y. (2024). Masseter Vestibular-Evoked Myogenic Potential Result of Possible Meniere's Patients. *Journal of the American Academy of Audiology*, 36(3-04), 58-64. <https://doi.org/10.1055/a2255-7879>
- Bucher, U. J., Mast, F., & Bischof, N. (1992). An analysis of ocular counterrolling in response to body positions in three-dimensional space. *Journal of Vestibular Research: Equilibrium & Orientation*, 2(3), 219-220.
- Chen, P.-Y., Jiang, Y.-C., Wang, C.-C., Huang, S.-E., Yang, T.-H., Hsu, P.-C., Kuo, C.-H., Lin, Y.-Y., Lai, W.-Y., & Kao, C.-L. (2021). Effect of noisy galvanic vestibular stimulation on dynamic posture sway under visual deprivation in patients with bilateral vestibular hypofunction. *Scientific Reports*, 11(1), 4229. <https://doi.org/10.1038/s41598-021-83206-2>
- Comacchio, J., Zaffroni, G., Di Pasquale Pasqua, V. M., Magnavita, P., Bellemo, E., Fasanaro, E., & Poletto, E. (2025). Masseter Vestibular Evoked Myogenic Potentials (M-VEMPs) in Vestibular Neuritis. *Audiology Research*, 15(3), 83. <https://doi.org/10.3389/audi.15030063>
- Cuccuruzzo, B., Deriu, F., Tolu, E., Yates, B. J., & Billig, I. (2007). A monosynaptic pathway links the vestibular nuclei and masseter muscle motoneurons in rats. *Experimental Brain Research*, 176(4), 665-671. <https://doi.org/10.1007/s00221-006-0834-7>
- de Natale, E. R., Ginatempo, F., Paulus, K. S., Pes, G. M., Manca, A., Tolu, E., Agnelli, V., & Deriu, F. (2015). Abnormalities of vestibular-evoked myogenic potentials in idiopathic Parkinson's disease are associated with clinical evidence of brainstem involvement. *Neurological Sciences*, 36(6), 995-1001. <https://doi.org/10.1007/s10077-014-2054-4>
- Deriu, F., Tolu, E., & Rothwell, J. C. (2005). A Sound-Evoked Vestibulomasseteric Reflex in Healthy Humans. *Journal of Neurophysiology*, 93(4), 2024-2034. <https://doi.org/10.1152/jn.01006.2004>
- Du, X., Tang, C., Ren, L., Liu, X., Wang, Y., Wang, Q., & Wu, Z. (2025). Assessing otolith dysfunction in Meniere's disease: Insights from multi-frequency vestibular evoked myogenic potential testing. *International Journal of Audiology*, 64(10), 1035-1044. <https://doi.org/10.1080/14992027.2025.2467160>
- Fife, T. D., Colebatch, J. G., Kerber, K. A., Brandt, K., Strupp, M., Lee, H., Walker, M. F., Ashman, E., Fletcher, J., & Callaghan, B. (2017). Practice guidelines: Cervical and ocular vestibular evoked myogenic potential testing: Report of the Guidelines Development, Dissemination, and Implementation Subcommittee of the American Academy of Audiology. *Neurology*, 89(22), 2288-2296.
- Fitzpatrick, R. C., & Day, B. L. (2004). Probing the human vestibular system with galvanic stimulation. *Journal of Applied Physiology* (Bethesda, Md. 1985), 96(6), 2301-2316. <https://doi.org/10.1152/jap.00008.2004>



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References

- Forbes, P. A., Kwan, A., Mitchell, D. E., Blouin, J.-S., & Cutten, K. E. (2023). The Neural Basis for Biased Behavioral Responses Evoked by Galvanic Vestibular Stimulation in Primates. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 43(11), 1905-1919. <https://doi.org/10.1523/JNEUROSCI.0987-22.2023>
- Fujimoto, C., Yamamoto, Y., Kamagishi, T., Kinoshita, M., Egami, N., Uemura, Y., Togo, F., Yamasoba, T., & Iwasaki, S. (2016). Noisy galvanic vestibular stimulation induces a sustained improvement in body balance in elderly adults. *Scientific Reports*, 6, 37575. <https://doi.org/10.1038/srep37575>
- Genesberger, K. D., Kaufmann, A. K., Dietrich, H., Branner, F., Banchi, R., Chagnaud, B. P., & Straka, H. (2016). Galvanic vestibular stimulation: Cellular substrates and response patterns of neurons in the vestibulo-ocular network. *Journal of Neuroscience*, 36(35), 9097-9110.
- Giacomini, E., Deriu, F., Tolu, E., Cuccuruzzo, B., Yates, B. J., & Billig, I. (2006). Transneuronal tracing of vestibulo-trigeminal pathways innervating the masseter muscle in the rat. *Experimental Brain Research*, 171(3), 330-339. <https://doi.org/10.1007/s00221-005-0275-8>
- Goldberg, J. M., Smith, C. E., & Fernández, C. (1984). Relation between discharge regularity and responses to externally applied galvanic currents in vestibular nerve afferents of the squirrel monkey. *Journal of Neurophysiology*, 51(6), 1236-1256.
- Harnel, R., Gaskill, P., Prosser, S., Whelan, D., Irving, R., & Reynolds, R. F. (2025). Optimising electrical vestibular stimulation (EVS) for assessing vestibular function. *Clinical Neurophysiology Practice*, 10, 359-377. <https://doi.org/10.1016/j.cnp.2025.08.006>
- Iwasaki, S., Yamamoto, Y., Togo, F., Kinoshita, M., Yoshifuji, Y., Fujimoto, C., & Yamasoba, T. (2014). Noisy vestibular stimulation improves body balance in bilateral vestibulopathy. *Neurology*, 82(11), 860-875. <https://doi.org/10.1212/WNL.0000000000000215>
- Jerin, C., Berman, A., Krause, E., Ert-Wagner, B., & Galkov, R. (2014). Ocular vestibular evoked myogenic potential frequency tuning in certain meniere's disease. *Hearing Research*, 310, 54-59. <https://doi.org/10.1016/j.heares.2014.02.001>
- Jha, R. H., Piker, E. G., & Romero, D. (2022). Effects of Age and Middle Ear on the Frequency Tuning of the cVEMP and oVEMP. *Journal of the American Academy of Audiology*, 33(5), 259-269. <https://doi.org/10.1055/a2042-1747910>
- Kim, J. (2013). Head movements suggest canal and otolith projections are activated during galvanic vestibular stimulation. *Neuroscience*, 243, 108-116. <https://doi.org/10.1016/j.neuroscience.2013.08.058>
- Kim, J., & Curthoys, I. S. (2004). Responses of primary vestibular neurons to galvanic vestibular stimulation (GVS) in the anaesthetized guinea pig. *Brain Research Bulletin*, 65(1-3), 54-59. <https://doi.org/10.1016/j.brainresbull.2004.07.008>
- Kwan, A., Forbes, P. A., Mitchell, D. E., Blouin, J.-S., & Cutten, K. E. (2019). Neural substrates, dynamics and thresholds of galvanic vestibular stimulation in the behaving primate. *Nature Communications*, 10(1), 1904. <https://doi.org/10.1038/s41467-019-09738-1>



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References

- Lucier, F., van der Lubbe, M., van Stiphout, L., Janssen, M., Van Rompaey, V., Devocht, E., Perez-Formas, A., Guinand, N., & van de Berg, R. (2024). Multi-frequency VEMPs improve detection of present otolith responses in bilateral vestibulopathy. *Frontiers in Neurology*, 15, 1368448. <https://doi.org/10.3389/fneur.2024.1368448>
- MacDougall, H. G., Brizuela, A. E., & Curthoys, I. S. (2003). Linearity, symmetry and additivity of the human eye-movement response to maintained unilateral and bilateral surface galvanic (DC) vestibular stimulation. *Experimental Brain Research*, 148(2), 166-175. <https://doi.org/10.1007/s00221-002-7289-0>
- MacDougall, H. G., Brizuela, A. E., Curthoys, I. S., & Halmagyi, G. M. (2002). Three-dimensional eye-movement responses to surface galvanic vestibular stimulation in normal subjects and in patients: A comparison. *Annals of the New York Academy of Sciences*, 956, 546-550. <https://doi.org/10.1111/j.1749-6632.2002.tb02878.x>
- Mahmud, M., Hazi, Z., Prendergast, M., Ciocca, M., Saad, A. R., Pondeca, Y., Tai, Y., Scott, G., & Seemungal, B. M. (2022). The effect of galvanic vestibular stimulation on postural balance in Parkinson's disease: A systematic review and meta-analysis. *Journal of the Neurological Sciences*, 442, 120414. <https://doi.org/10.1016/j.jns.2022.120414>
- McLaren, R., Smith, P. F., Taylor, R. L., Ravindran, S., Rasheed, U., & Taylor, D. (2022). Efficacy of nGVS to improve postural stability in people with bilateral vestibulopathy: A systematic review and meta-analysis. *Frontiers in Neurosciences*, 16, 1636-1648. <https://doi.org/10.3389/fnins.2022.1010239>
- Oleson-Ellman, J., Treviño, C., Winnick, A., Zuo, D. S., Carey, J. P., & Renshaw, A. (2017). The video ocular counter-roll (VOCR): A clinical test to detect loss of otolith-ocular function. *Acta Otolaryngologica*, 137(6), 593-597. <https://doi.org/10.1080/00016389.2016.1269364>
- Patterson, J. N., Rodriguez, A. I., Gordon, K. R., Honaker, J. A., & Janak, K. L. (2021). Age Effects of Bone Conduction Vibration Vestibular-evoked Myogenic Potentials (VEMPs) Using B81 and Impulse Hammer Stimuli. *Ear and Hearing*, 42(5), 1238. <https://doi.org/10.1097/AUD.0000000000000204>
- Pires, A. B. de A., Labanca, L., Christo, P. P., Teixeira, M. C., Barroso, J. C., Diniz, M. L., & Gonçalves, D. U. (2025). Galvanic vestibular stimulation to rehabilitate postural instability in Parkinson's disease. *Arquivos de Neuro-Psiquiatria*, 83, 1-8. <https://doi.org/10.1590/s0004-0808-2024-180812>
- Romero, D. J., Jacobson, G. P., & Roberts, R. A. (2022). The effect of EMG magnitude on the masseter vestibular evoked myogenic potential (mVEMP). *Journal of Otology*, 17(3), 263-270. <https://doi.org/10.1016/j.joto.2022.06.004>
- Rosenfeld, S. M., Colebatch, J. G., Young, A. S., Govender, S., & Weigand, R. S. (2019). Vestibular evoked myogenic potentials in practice: Methods, pitfalls and clinical applications. *Clinical Neurophysiology Practice*, 4, 47-68.



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References

- Rosengren, S. M., Govender, S., & Colebatch, J. G. (2011). Ocular and cervical vestibular evoked myogenic potentials produced by air- and bone-conducted stimuli: Comparative properties and effects of age. *Clinical Neurophysiology*, 122(11), 2282–2289.
- Séverac Cauquil, A., Faldon, M., Popov, K., Day, B. L., & Bronstein, A. M. (2003). Short-latency eye movements evoked by near-threshold galvanic vestibular stimulation. *Experimental Brain Research*, 149(3), 414–418. <https://doi.org/10.1007/s00221-002-1326-z>
- Tax, C. M. W., Bom, A. P., Taylor, R. L., Todd, N., Cho, K.-K. J., Fitzpatrick, R. C., & Welgampola, M. S. (2013). The galvanic whole-body sway response in health and disease. *Clinical Neurophysiology*, 124(10), 2036–2045. <https://doi.org/10.1016/j.clinph.2012.12.041>
- Tessler, I., Wolfvitz, A., Gececi, N. A., Hazan, T., Livneh, N., Alsalebi, S., & Gimmon, Y. (2025). The Video Ocular Counter-Roll Test: Validation for Vestibular Dysfunction Diagnosis in Clinical Practice. *Otolaryngology–Head and Neck Surgery*, 172(5), 1703–1710. <https://doi.org/10.1002/ohn.1164>
- Todd, N. P. M., Cody, F. W. J., & Banks, J. R. (2000). A saccular origin of frequency tuning in myogenic vestibular evoked potentials?: Implications for human responses to loud sounds. *Hearing Research*, 141(1), 180–188. [https://doi.org/10.1016/S0378-5955\(99\)00222-1](https://doi.org/10.1016/S0378-5955(99)00222-1)
- Todd, N. P. M., Rosengren, S. M., & Colebatch, J. G. (2009). A utricular origin of frequency tuning to low-frequency vibration in the human vestibular system? *Neuroscience Letters*, 451(3), 175–180. <https://doi.org/10.1016/j.neulet.2008.12.055>
- Walther, L. E., & Westhofen, M. (2007). Presbyvertigo-aging of otoconia and vestibular sensory cells. *Journal of Vestibular Research: Equilibrium & Orientation*, 17(2–3), 89–92.

