Putting Together the Vestibular System Puzzle

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Learning Outcomes

- Participants will be able to list possible tests in a comprehensive neurodiagnostic vestibular-balance battery.
- Participants will be able to identify best-practice protocols for assessing patients in the vestibular clinic.
- Participants will be able to discuss current trends in objective vestibular measures.
- Participants will be able to discuss patterns of dysfunction in common vestibular disorders.

Keeping your Balance

External Stimuli

- Visual
  - Tells brain about the world outside and conveys information about motion
- Somatosensory
  - Muscle receptors provide tactile information about surfaces (feet , legs, joints) and conveys info on head position relative to the others (neck)

Internal Stimuli

- Vestibular
  - Tells the brain where the head is in space, its direction of movement, and acceleration

Central Nervous System

- Integrates internal and external stimuli and produces motor control responses to keep you stable

Vestibular System Impairment

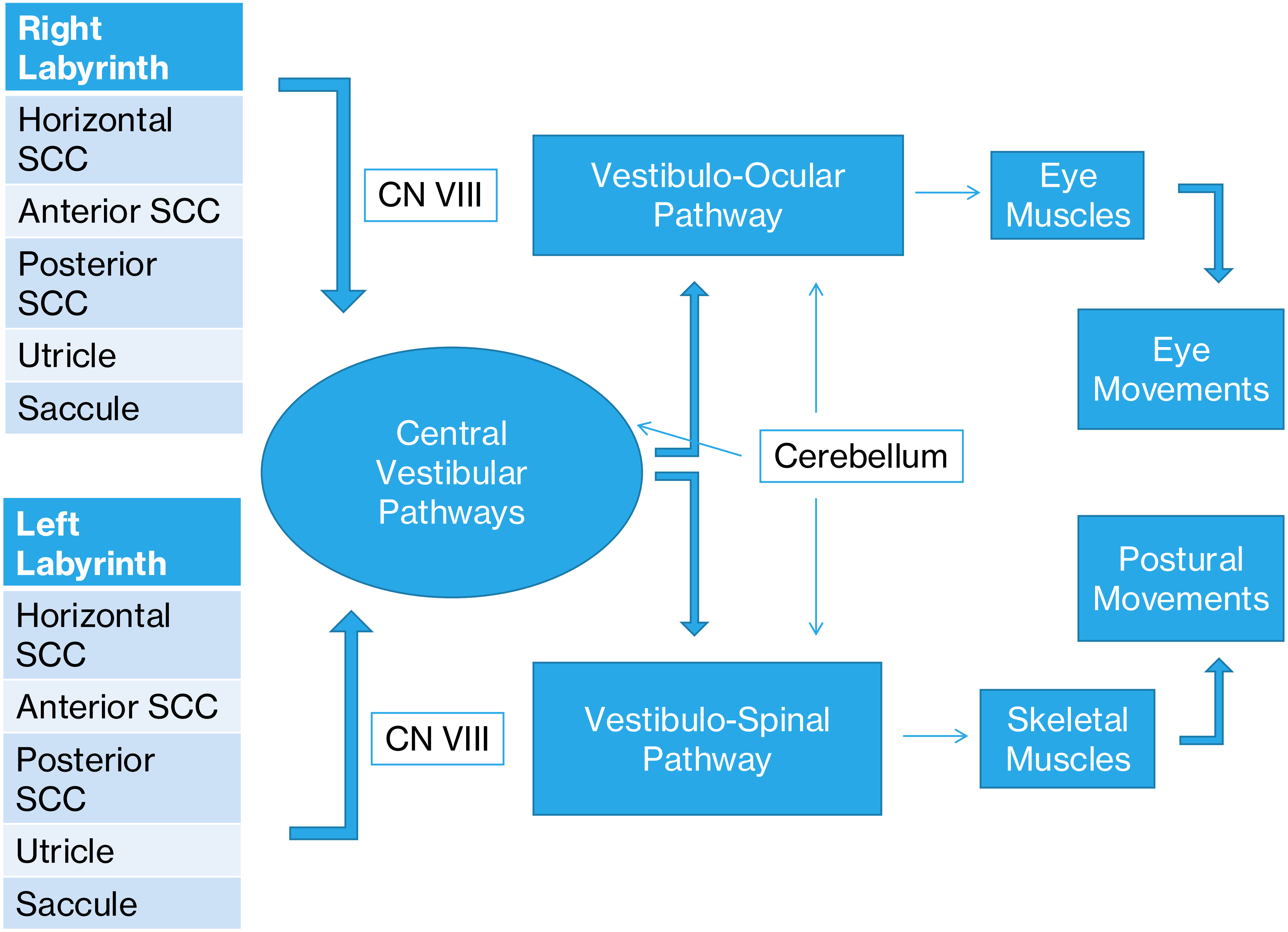
The vestibular system contains 10 receptors (5 per side)

If each receptor can develop a lesion independently, there are more than 1000 combinations of ways the vestibular receptors can become dysfunctional

Does not take into consideration how each individual compensates for, or the functional impact of, the lesion for each patient

Localization of Vestibular System Impairment

- Main goals during a comprehensive vestibular evaluation:
  - Determine if an impairment exists
  - If one exists, whether the impairment affects the peripheral or central vestibular system
  - If it is a peripheral impairment, which of the end organs are impaired
  - If the peripheral impairment is unilateral or bilateral
  - The degree of impairment
  - Whether static and/or dynamic compensation has occurred in the wake of the injury


Right Labyrinth
Horizontal SCC
Anterior SCC
Posterior SCC
Utricle
Saccule
CN VIII
Vestibulo-Ocular Pathway
Eye Muscles
Eye Movements
Central Vestibular Pathways
Cerebellum
Left Labyrinth
Horizontal SCC
Anterior SCC
Posterior SCC
Utricle
Saccule
CN VIII
Vestibulo-Spinal Pathway
Skeletal Muscles
Postural Movements

Vestibular System Diagnostics

Evaluate Ocular Motor Pathways

Evaluate Vestibular Ocular Reflex

Evaluate Otolith Function

Evaluate Vestibular Spinal Reflex

Evaluate functional integration of somatosensory, vision and vestibular inputs

- How are the eyes moving when the head is not in motion?

Ocular Motor Pathways

- Central Subtests
  - Gaze holding, Smooth Pursuit, Saccade Testing, Optokinetic
- Presence or absence of nystagmus could guide the peripheral versus central site of lesion discussion

- Convergence Screening

Vestibular Ocular Reflex (VOR)

- Calorics
- Rotary Chair
- Video Head Impulse Test (vHIT)

- Connection between the inner ear balance system and the extraocular eye muscles are integral in keeping clear vision while we move our head
- Vestibular driven
- If it’s not working, blurred vision with head movement

Vestibular Spinal Reflex (VSR)

- Vestibular system has a few pathways that run down the spinal column, both ipsilaterally and bilaterally
- Protect against falls by making quick adjustments around joints and activating muscle groups
- Vestibular Evoked Myogenic Potential Testing (VEMPs) can help detect abnormal function in our two inner ear organs responsible for gravity control: Otolith Organs
  - Saccule and Utricle

Vestibular Tests & the Anatomy Assessed

Structure(s)	Assessment Tool
Utricle • Innervated by the superior vestibular nerve	Ocular VEMP
Saccule • Innervated by the inferior vestibular nerve	Cervical VEMP
Anterior semicircular canal • Innervated by the superior vestibular nerve	Video Head Impulse Test (high acceleration, natural head movement VOR)
Posterior semicircular canal • Innervated by the inferior vestibular nerve	Video Head Impulse Test (high acceleration, natural head movement VOR)
Horizontal semicircular canal • Innervated by the superior vestibular nerve	Caloric testing (very low-frequency VOR function) Rotary Chair (low-mid frequency VOR function) Video Head Impulse Test (natural head movement and high-frequency VOR)
Central Vestibular Pathways	Oculomotor assessment – gaze holding, saccades, pursuit tracking, optokinetic nystagmus, and spontaneous nystagmus

Typical Vestibular Test Battery

Case History

Oculomotor Testing (Central Subtests)

- Spontaneous nystagmus
- Gaze – vertical and horizontal
- Saccades
- Smooth Pursuit
- Optokinetic Nystagmus

Positioning Testing

Positional Testing

Calorics / assessment of VOR function

Supplemental Tests

- Behavioral audiometry, Fistula screen, ECoG, ABR, cVEMPs, oVEMPs, Rotational testing, Posturography

Full Test Battery

- Auditory Brainstem Response (ABR)
- Electrocochleography (ECoG)
- Videonystagmography (VNG) – oculomotor and positional/ing
- Calorics with/without visual suppression assessment
- Rotary Chair – SHA, step, VOR suppression
- Ocular vestibular myogenic potential (oVEMP)
- Cervical vestibular myogenic potential (cVEMP)
- Postural Stability (Computerized Dynamic Posturography, Gans Sensory Organization Test, etc.)
- Neurocognitive screening
- Video Head Impulse Test (vHIT) of horizontal, and both vertical canals
- Subjective Visual Vertical (SVV)

Ocular-Motility Testing

- Looks at the functional classes of eye-movements
- Can be used to indicate central nervous system involvement and may be able to suggest differential lesions within the CNS
- However, all these tests require patient participation and can be affected by fatigue, medications, and drowsiness

- Gaze
- Saccades
- Smooth Pursuit
- Optokinetics
- Spontaneous nystagmus

Ocular-Motility Testing

Saccades

Target is detected on the edge of the visual field, the ocular-motor system quickly moves the eye to place the image of interest on the fovea

Smooth Pursuit

Allows us to stabilize moving targets on the fovea when the head is not moving

Optokinetics

Allows us to stabilize an entire moving visual field on the retina when the head is not moving

Gaze

Holding a motionless target on the fovea of the retina

Positioning Testing

Benign Paroxysmal Positional Vertigo - BPPV

- Intense, but brief, vertigo and nystagmus provoke by changes in the position of the head
- Loose calcium carbonate debris (otoconia)
- 85-90% posterior canal, 8-10% lateral canal, 1-2% anterior canal
- Triggers – position changes
  - Turning in bed, looking up, bending forward, etc.
- Use different maneuvers to not only see if vertigo is provoked but really to analyze the patterns of any nystagmus to diagnose the correct canal in order to treat

Positional Testing

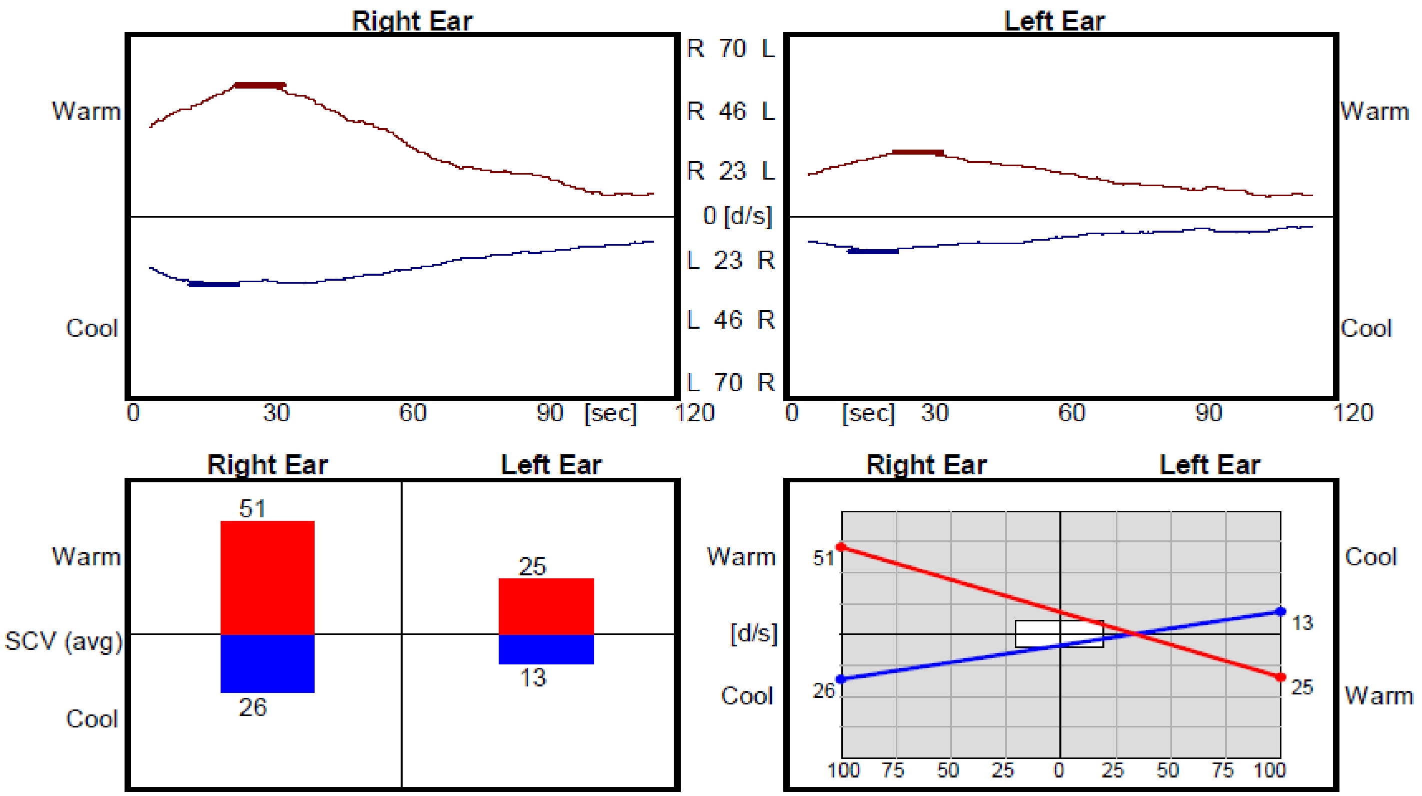
- Examines the presence of nystagmus after the induction of various head and/or body positions
  - Change the position of the head relative to the gravitational force
- Supine head right & supine head left
  - Body right and body left

VOR and Calorics

VOR and Calorics

- Vestibular Ocular Reflex
  - Most important vestibular reflex
  - How we maintain eye position during movement
  - Eye movement that are inappropriate cause sensations of dizziness/vertigo
- By stimulating the vestibular system and measuring eye movement responses, we can determine the function of the VOR
- We then compare the response between the ears to determine the symmetry of function
  - Unilateral weakness
  - Bilateral weakness

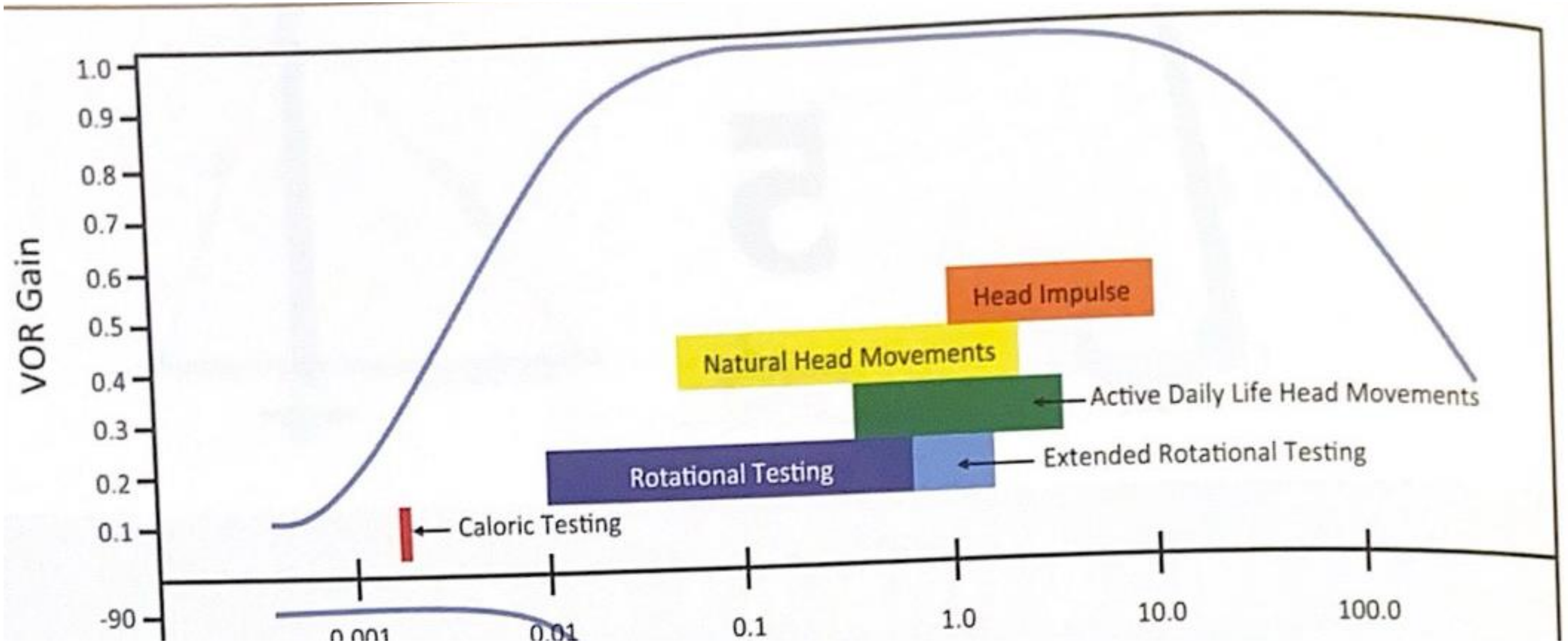
Calorics – Unilateral vs Bilateral Weakness



RVR (UW): Left Ear Response 34% weaker
DP: Right beating response 11% stronger
Total Eye Speed: 115 [deg/sec]
Spontaneous Nystagmus: None
Fixation Index (best): 0.04

VOR Frequency and Gain

Adapted from Barin (2009) & Zalewski (2018)



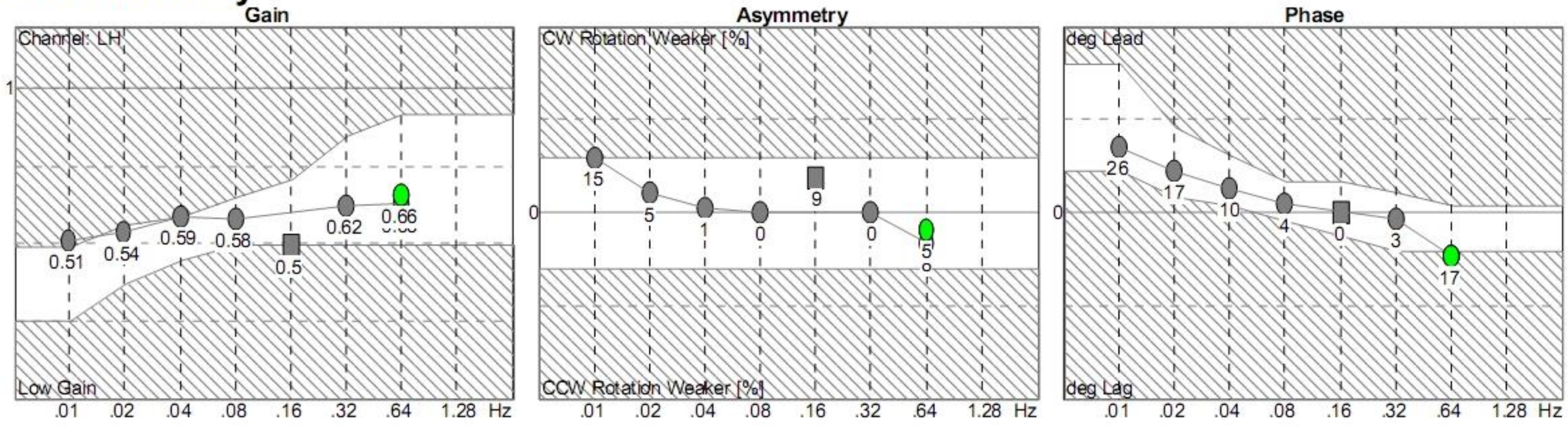
Rotational Chair Testing

- A device which activates the VOR by spinning you in a chair at various acceleration rates
- When to use it…
  - When VNG results suggests a unilateral compensated disorder despite a unilateral weakness on calorics and ongoing complaints
  - When caloric results are < 10 deg/sec (a bilateral weakness) rotational testing is used to define the extent of a bilateral weakness
  - When the results of both ears on calorics cannot be compared reliably (surgical ear on one side)

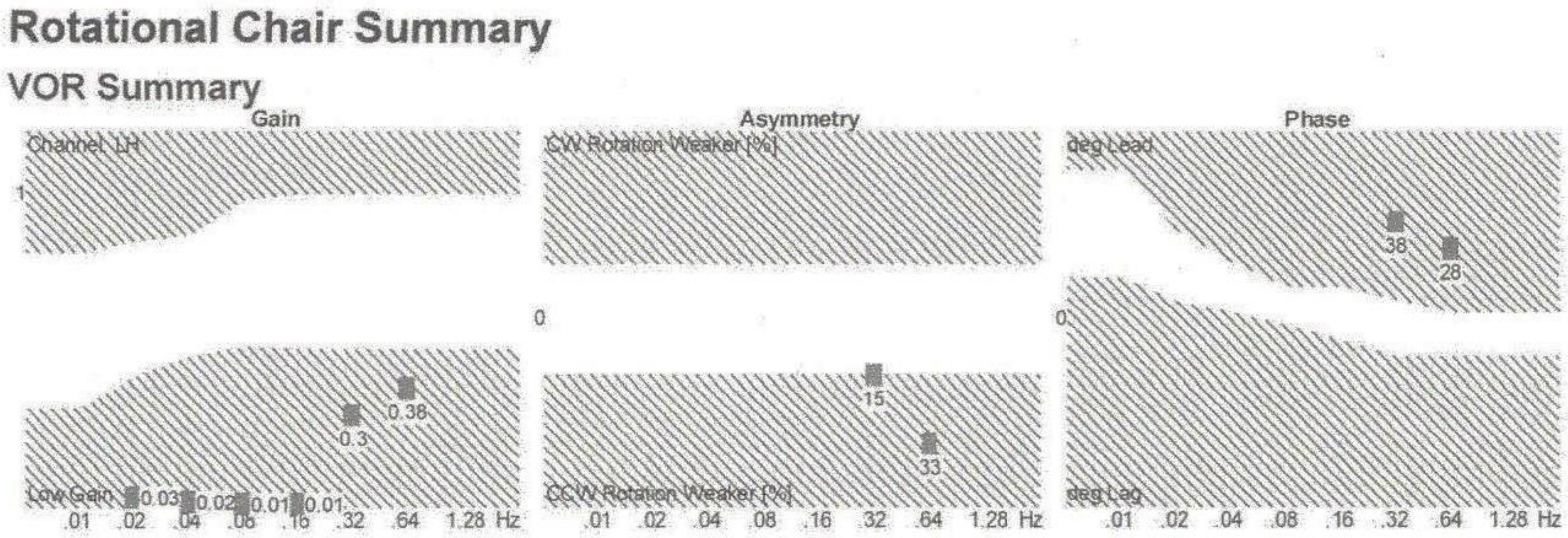
Examples

Rotational Chair Summary

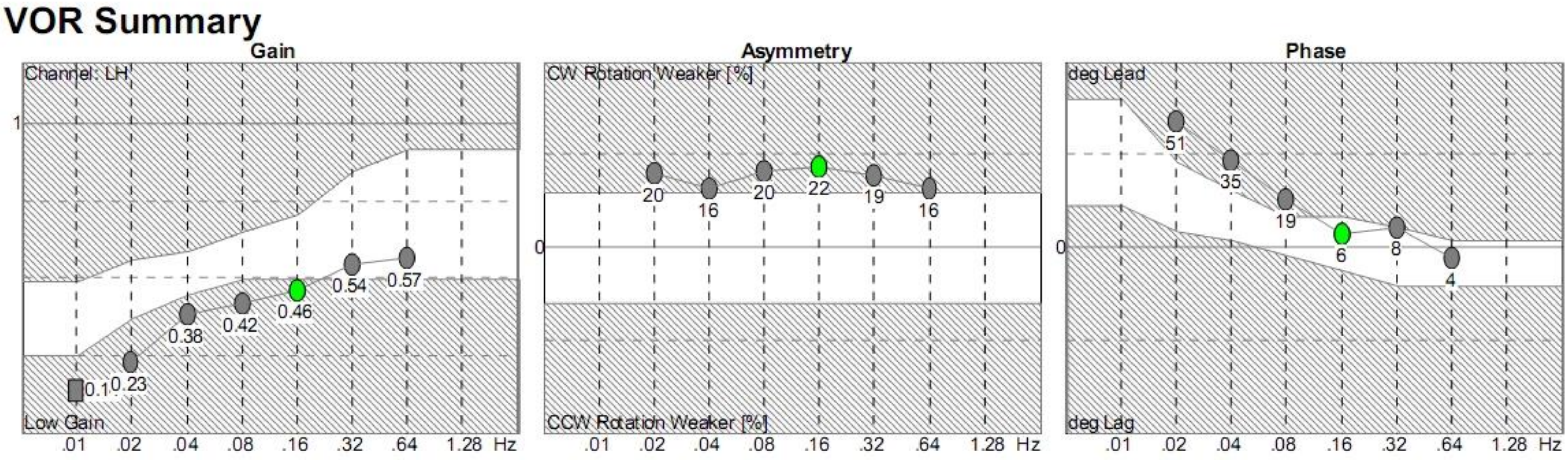
VOR Summary



Examples


Rotational Chair Summary
VOR Summary
Gain
Channel: LH
1
0.38
0.3
Low Gain
0.03
0.02
0.01
0.01
.01 .02 .04 .08 .16 .32 .64 1.28 Hz
Asymmetry
CW Rotation Weaker [%]
0
15
33
CCW Rotation Weaker [%]
.01 .02 .04 .08 .16 .32 .64 1.28 Hz
Phase
deg Lead
38
28
0
deg Lag
.01 .02 .04 .08 .16 .32 .64 1.28 Hz

Examples



VOR Summary
Gain
Channel: LH
1
0.1
0.23
0.38
0.42
0.46
0.54
0.57
Low Gain
.01 .02 .04 .08 .16 .32 .64 1.28 Hz
Asymmetry
CW Rotation Weaker [%]
0
20
16
20
22
19
16
CCW Rotation Weaker [%]
.01 .02 .04 .08 .16 .32 .64 1.28 Hz
Phase
deg Lead
0
51
35
19
6
8
4
deg Lag
.01 .02 .04 .08 .16 .32 .64 1.28 Hz

Types of Rotational Chair Assessments

- Sinusoidal Harmonic Acceleration (SHA)
- Velocity Step
- Visually Enhanced VOR
- VOR Suppression

Rotary Chair – Velocity Step

- The patient is accelerated rapidly to a constant velocity and after several seconds of rotation at that velocity, the chair is brought to a sudden stop
- Used to quantify the decay rate of nystagmus following an abrupt angular acceleration or deceleration
- Can rapidly measure gain and time constant of VOR for both CW and CCW rotations

Rotary Chair - VVOR

- The patient is rotated with stationary images projected on the booth wall
- Evaluates the interaction of the vestibular and optokinetic pathways
- For patients with poor peripheral vestibular function (low gain in the dark), VVOR should produce a significant increase in the gain and bring the phase lead down to near normal
- Patients with CNS vestibular and/or ocular motor dysfunction would likely not be able to generate the nystagmus necessary and their gain and phase would remain abnormal

Rotary Chair – VOR Suppression (VFX)

- Examines SPV produced by rotation when the patient is fixing their gaze on a laser target
- Patient is oscillated with a fixed visual target
  - Instructed to fix gaze on target
- Under these conditions the VOR (i.e. nystagmus) should be suppressed
- The attenuation of nystagmus provides insight into the integrity of the connections between the midline cerebellum and the vestibular nuclei

Vestibular Evoked Myogenic Potentials (VEMPs)

Cervical VEMPs

- Sonomotor response which looks at the vestibulocollic reflex
- Helps determine function of the **saccule** and the **inferior vestibular nerve**

Ocular VEMPs

- Sonomotor response which looks at the vestibulo-ocular reflex
- Helps determine function of the **utricle** and the **superior vestibular nerve**

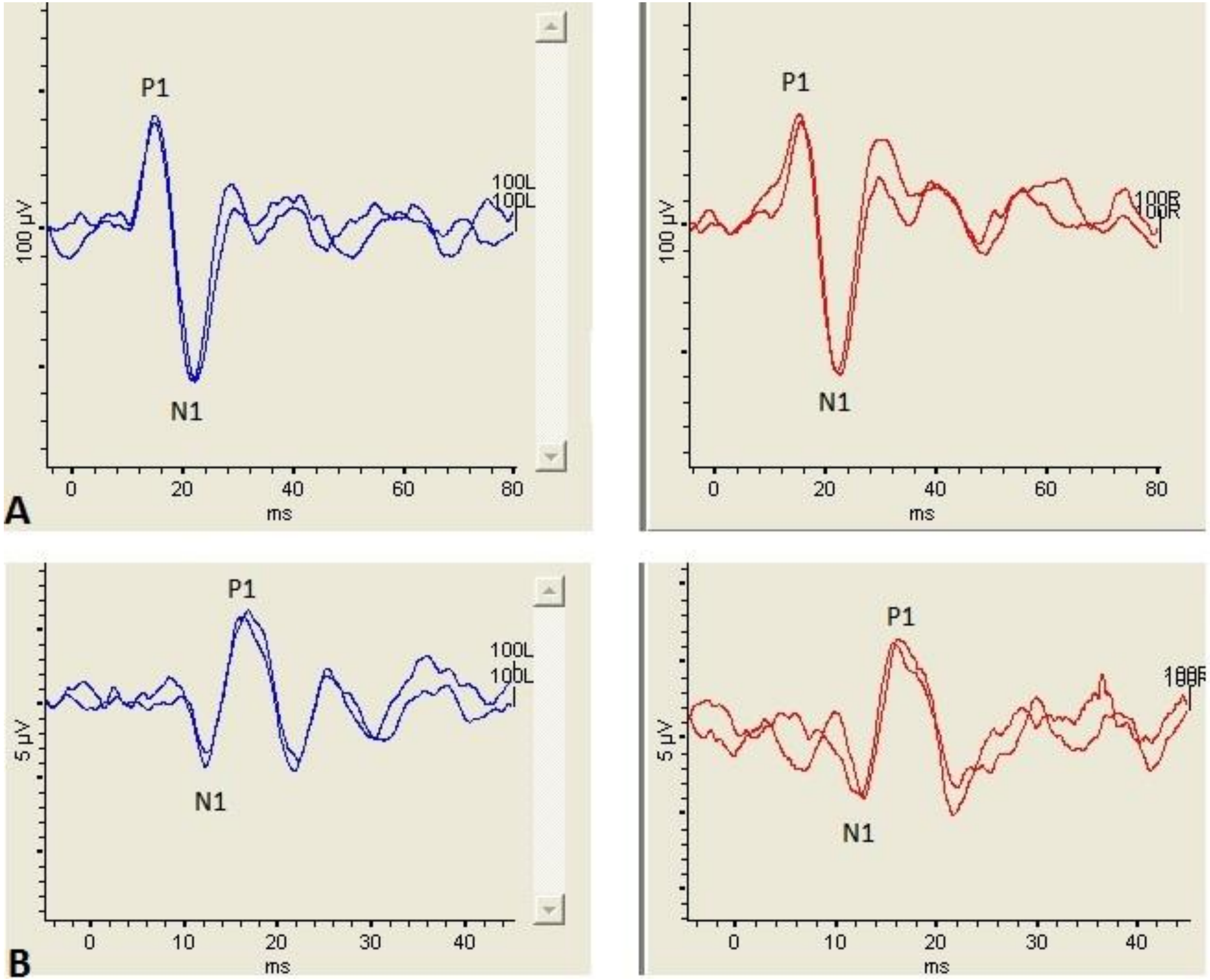
cVEMP & oVEMP

Anatomic Origins - cVEMP

- VEMP is a Sonomotor “Reflex”
- Consists of:
    - A receptor (end organ) = saccule
    - An afferent pathway = scarpa’s ganglion -> inferior vestibular nerve
    - Central connections = brainstem vestibular nuclei
    - An efferent pathway = descending medial vestibulospinal tract (MVST) ->CN XI
    - End muscles = sternocleidomastoid (SCM) muscle motorneurons

Reflex Pathway - oVEMP

- A receptor (end organ) = utricle
- An afferent pathway = superior vestibular nerve
- Central connections = vestibular nucleus
- An efferent pathway = Medial Longitudinal Fasciculus (MLF) -> Motor nucleus of the contralateral CN III
- End muscles = Contralateral inferior oblique muscle



P1
N1
100L
100L
100 µV
ms
P1
N1
100R
100R
100 µV
ms
A
P1
N1
100L
100L
5 µV
ms
P1
N1
5 µV
ms
B

Subjective Visual Vertical (SVV)

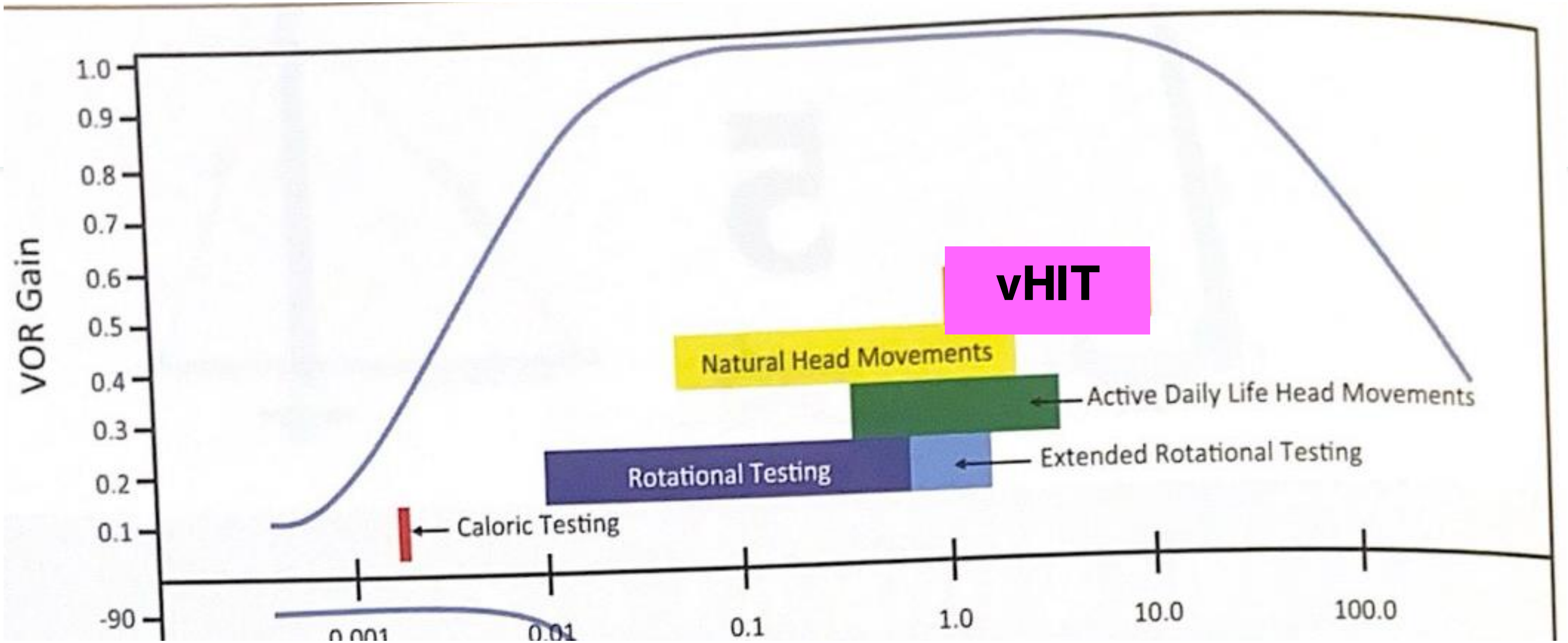
- The otoliths act as gravito-inertial force sensors and contribute to the perception of spatial orientation
- SVV is a psychophysical measure of angle between perceptual vertical and true gravitational vertical
- Can be measured with the patient in the static position, during rotation around the vertical axis (on-axis), and during rotation around the vertical axis with the patient off-set from the center (off-axis)

Subjective Visual Vertical (SVV) - Static

- Normal individuals align a visual linear marker within 2 deg of true vertical
  - Impairment of the utricle will cause the patient to tilt the static SVV towards the affected side
  - Once vestibular compensation occurs, static SVV returns to normal (±2 deg)

SVV – On-Axis and Off-Axis

- On-Axis
  - Rotating patients around the vertical axis at a constant velocity stimulates the otolith organs – specifically a centrifugal force (linear acceleration) that activates the utricles
- Off-Axis
  - Can also be measured during rotation around the vertical axis with patient off-set from center causing a unilateral certifugation



Adapted from Barin (2009) & Zalewski (2018)

Ewald’s Law & VOR

- Stimulation of the SCC causes nystagmus in the place of that canal
- Axis of nystagmus should match the anatomic axis of the canal that created it

- The VOR is 180 degree out of phase eye movement in the plane of the head movement
  - We typically discuss the horizontal VOR as that’s the only one we could previously test
  - However this theory holds true for the vertical canals too even though less attention was previously paid to them

vHIT Overview

Healthy System

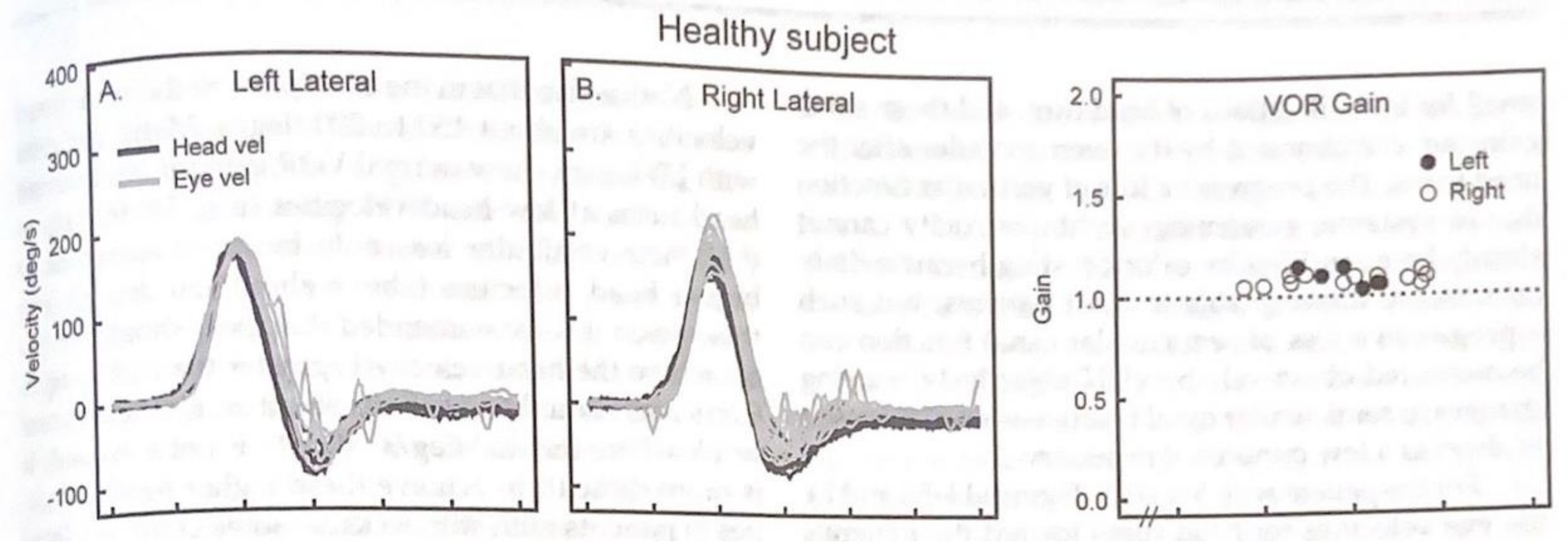
- Both eyes move to compensate for the abrupt, unpredictable, passive head turn
- Very quickly (within 10ms) there is a smooth compensatory eye movement opposite in direction and almost equal in velocity to the head velocity
- Eyes remain fixed on the target

Impaired System

- As their head is turned to the affected side, their eyes do not receive adequate neural drive from the SCCs on the affected side to compensate for the head turn
- Their eyes do not stay on the target but move with the head then must saccade back to the target at the end of the head movement
  - Overt Saccade

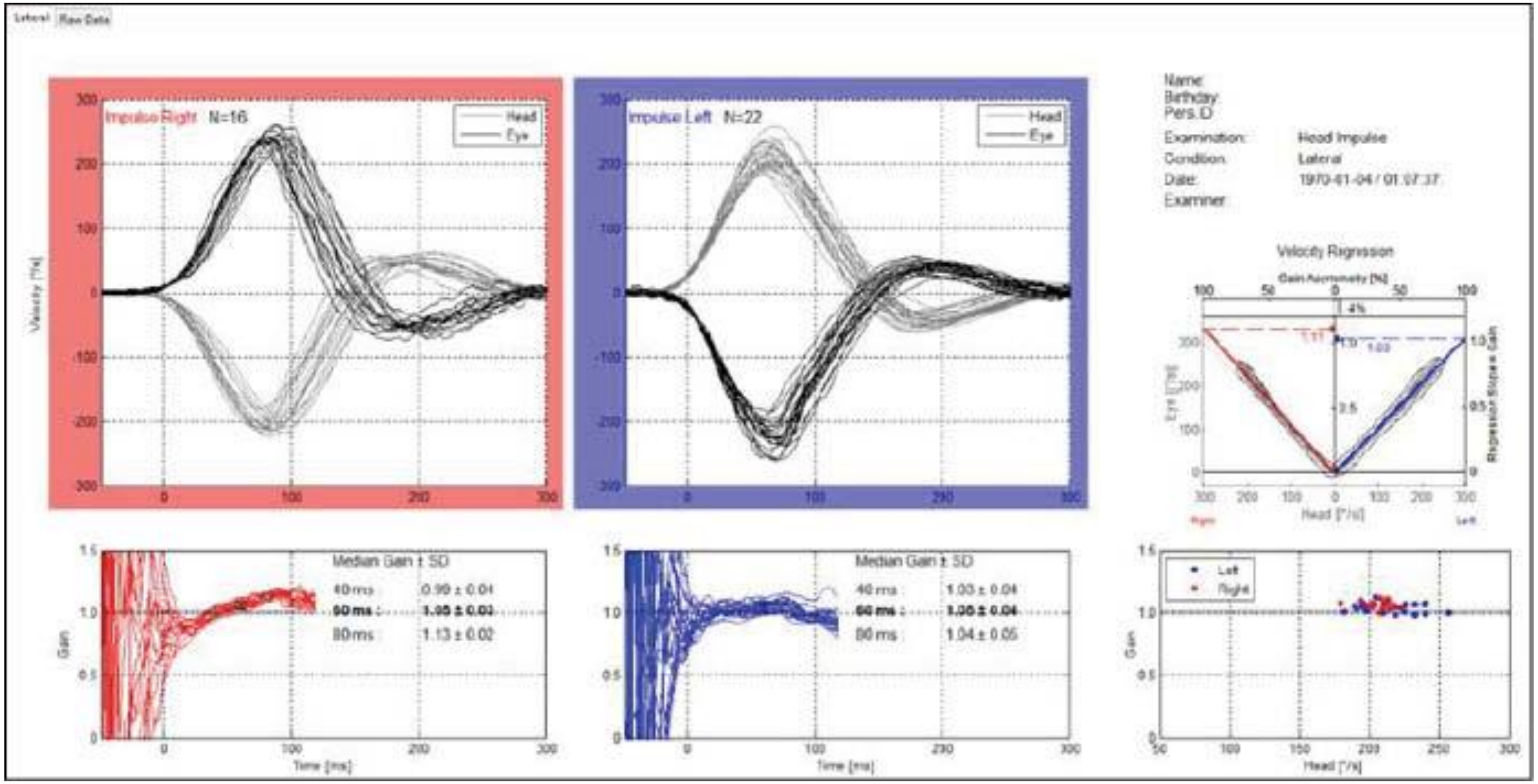
What are we Measuring?

- Eye velocity compared to head velocity
- VOR Gain
- Presence of any covert or overt saccades

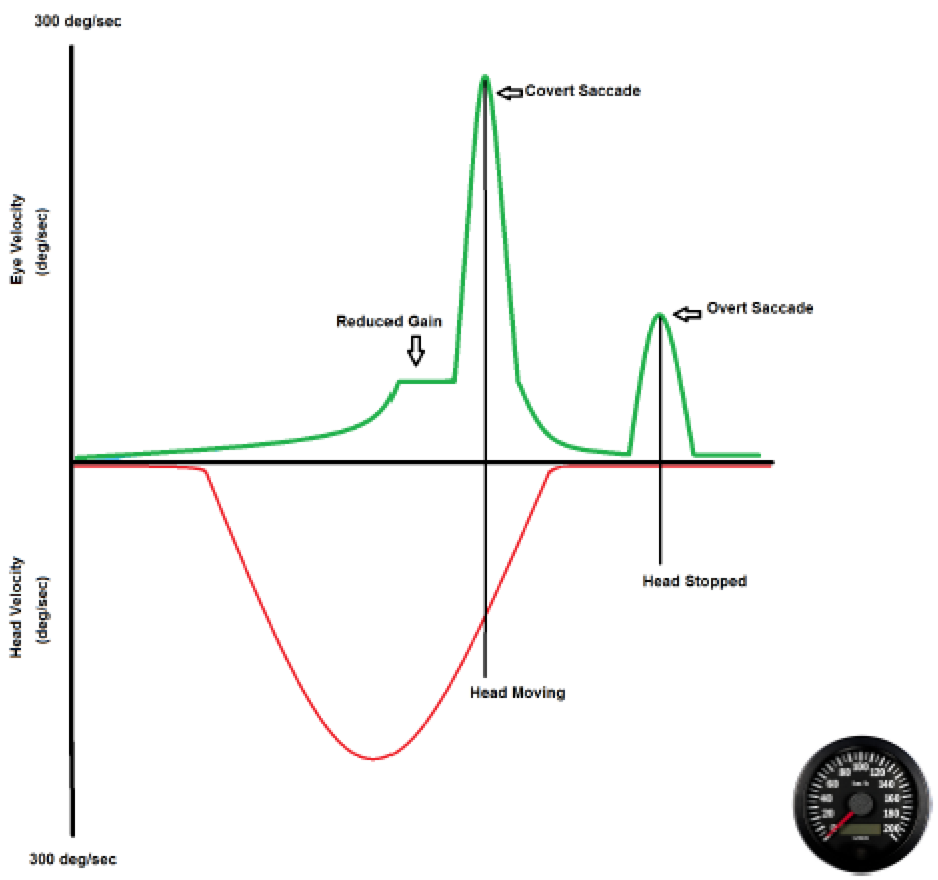


Jacobson (2021)

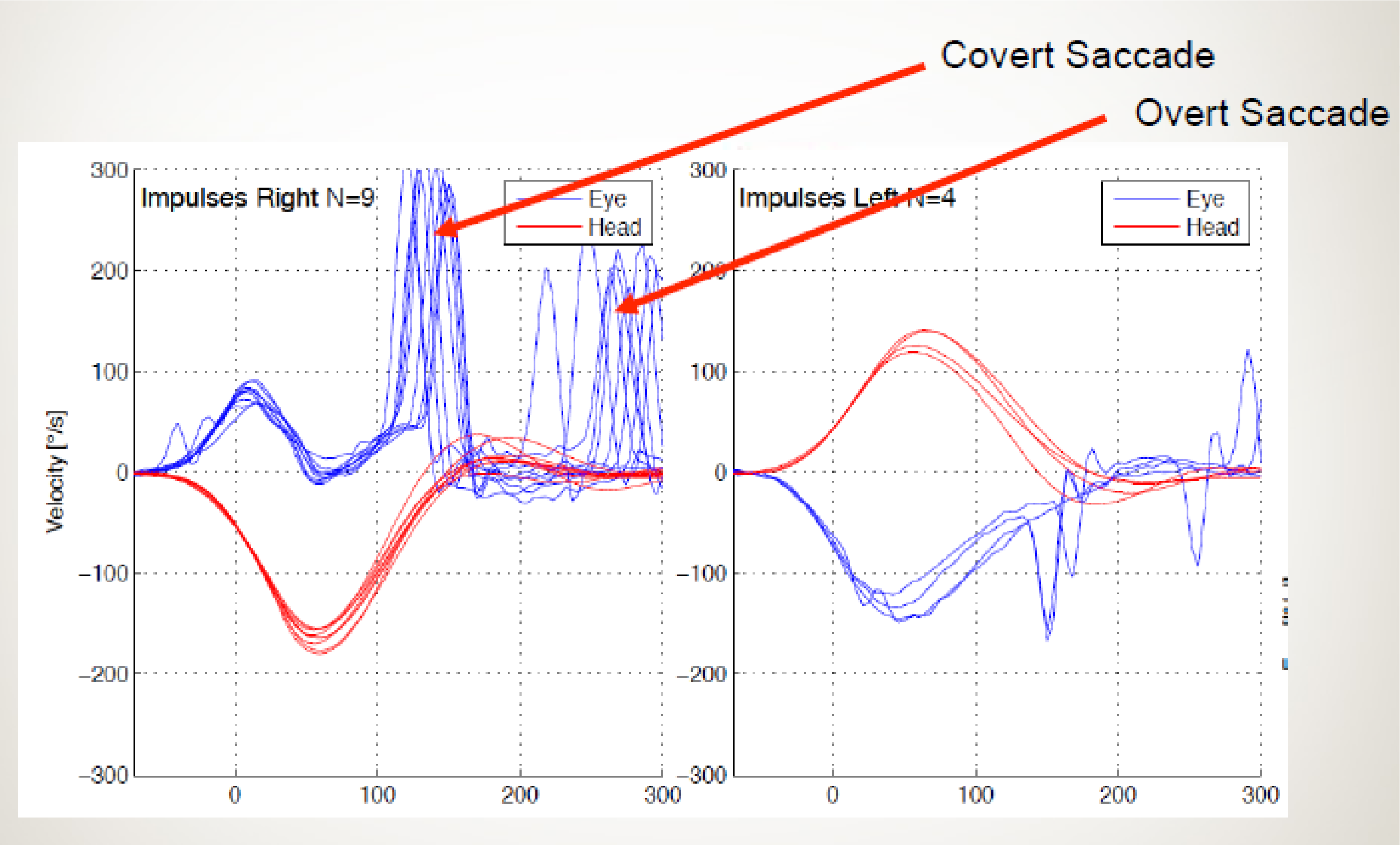
Normal vHIT Response



Abnormal vHIT Response

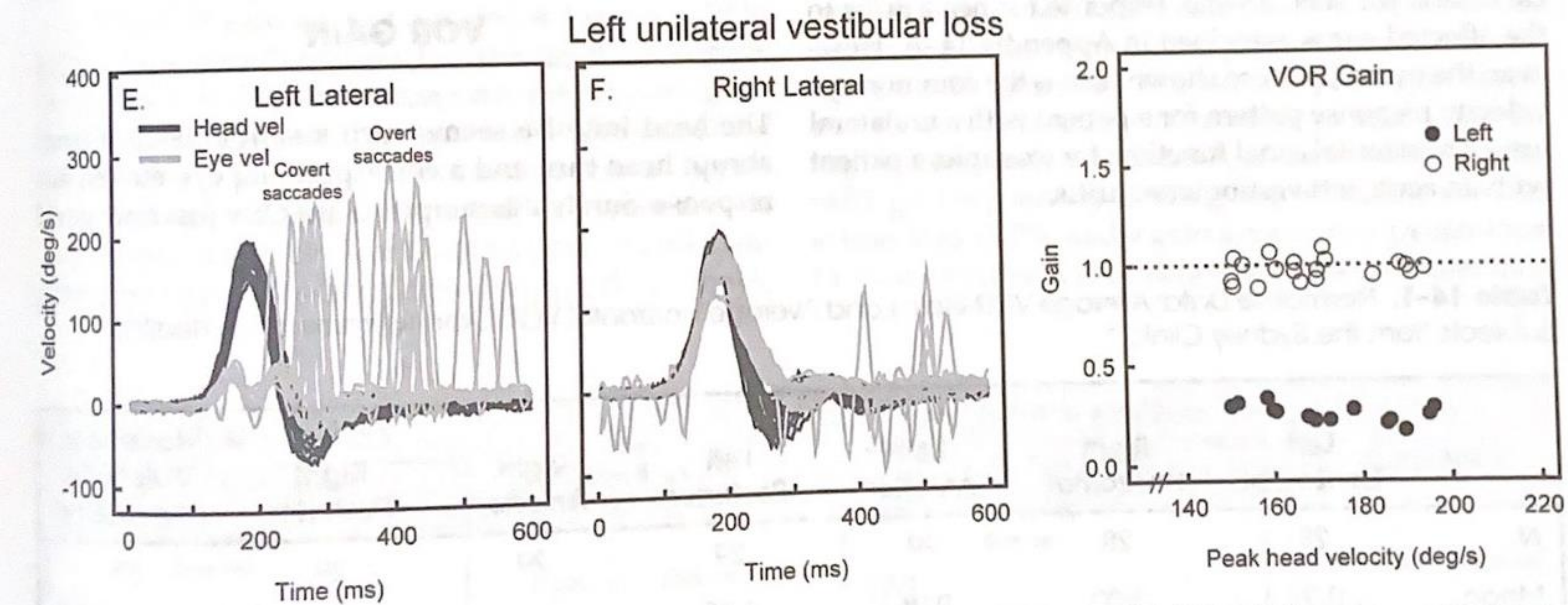


Abnormal vHIT Response

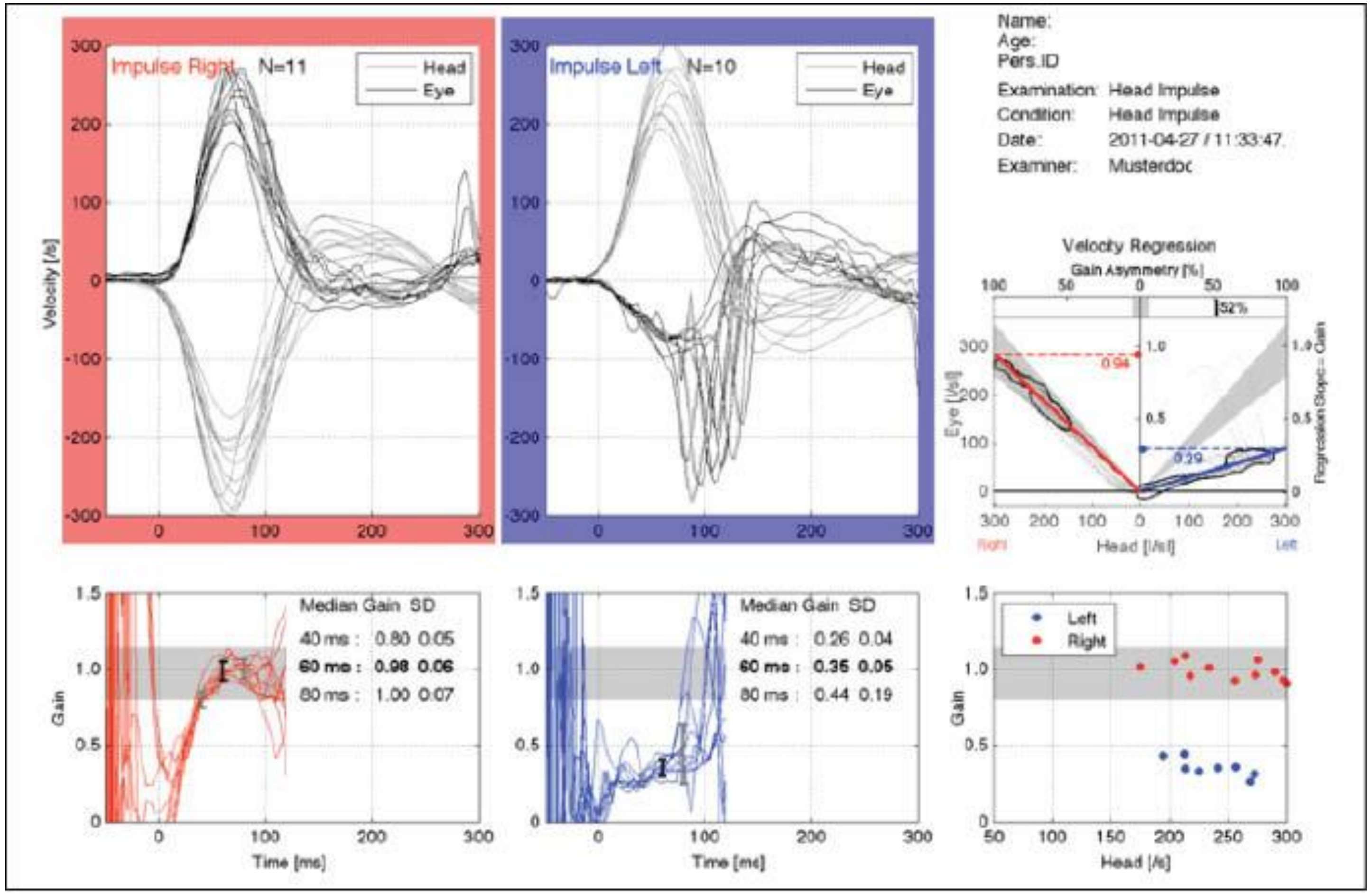


Abnormal vHIT Response

Jacobson (2021)

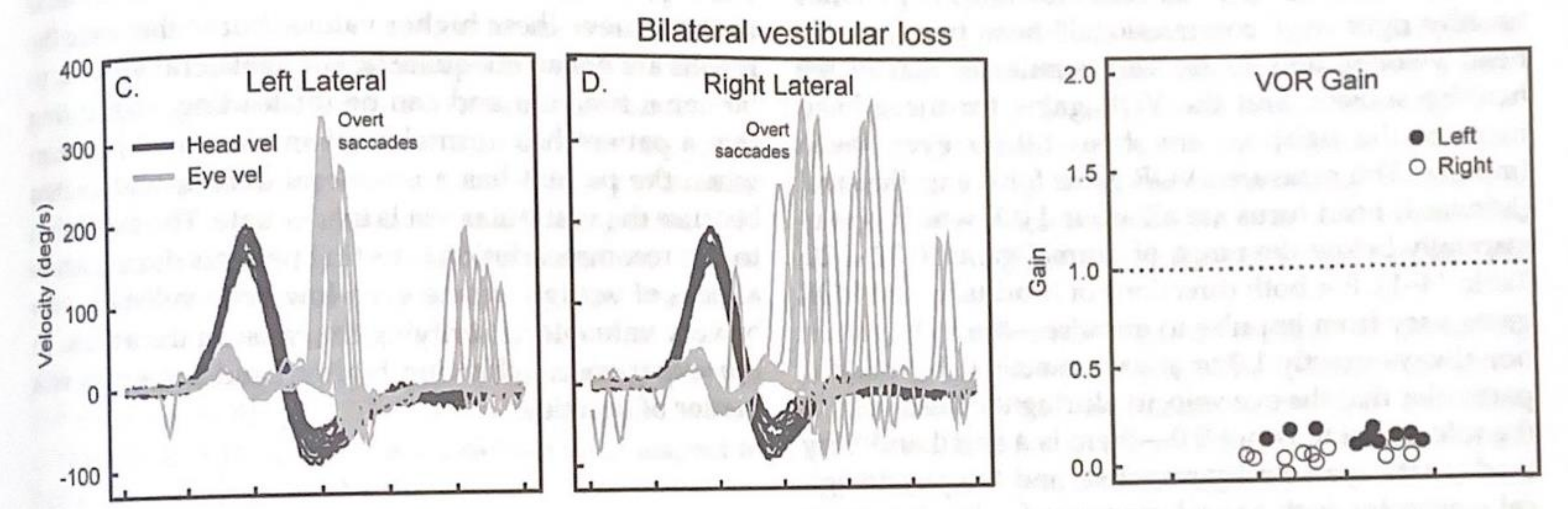


Abnormal vHIT Response



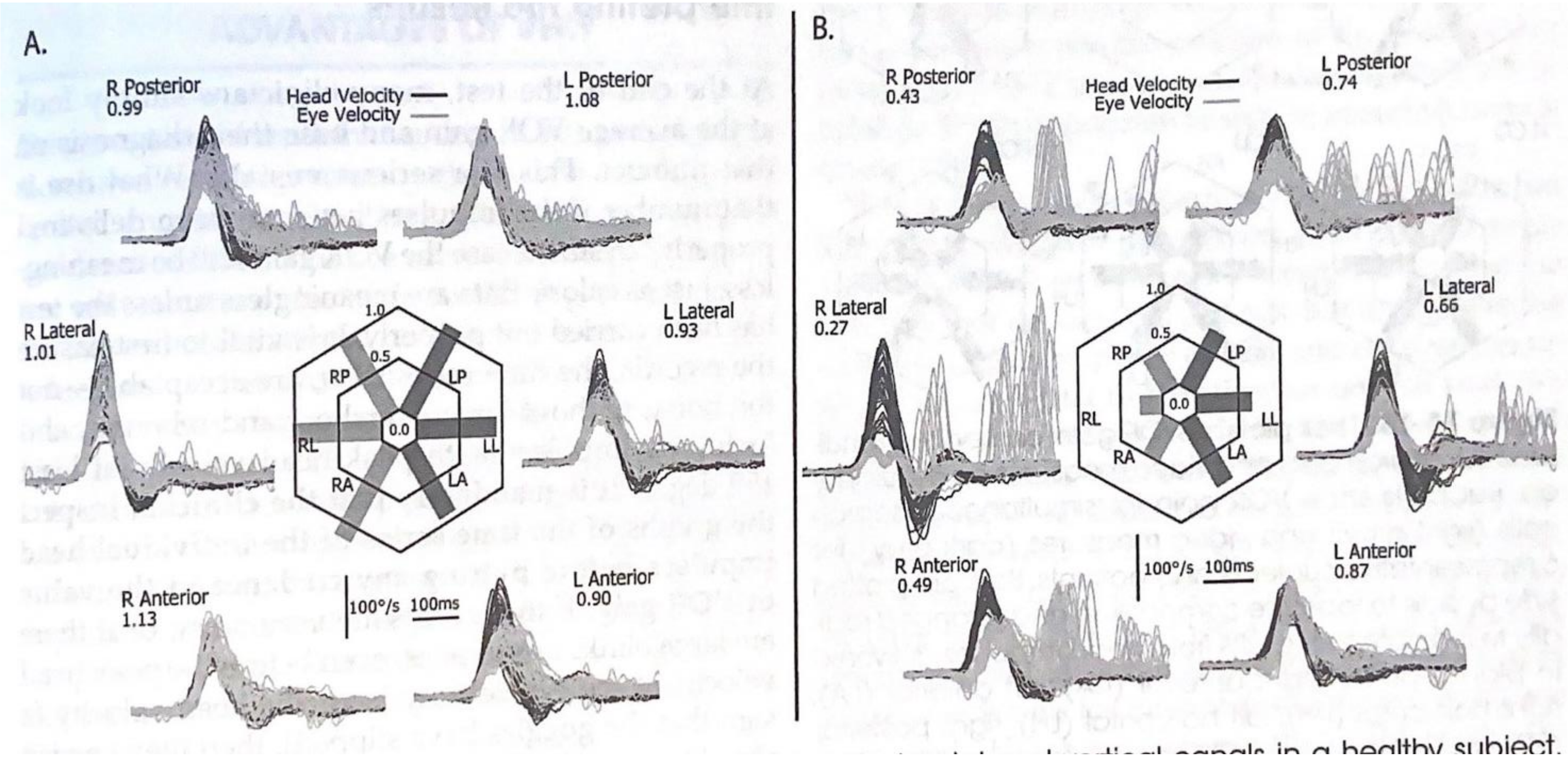
Abnormal vHIT Response

Jacobson (2021)



All the Canals

Jacobson (2021)



All the Canals

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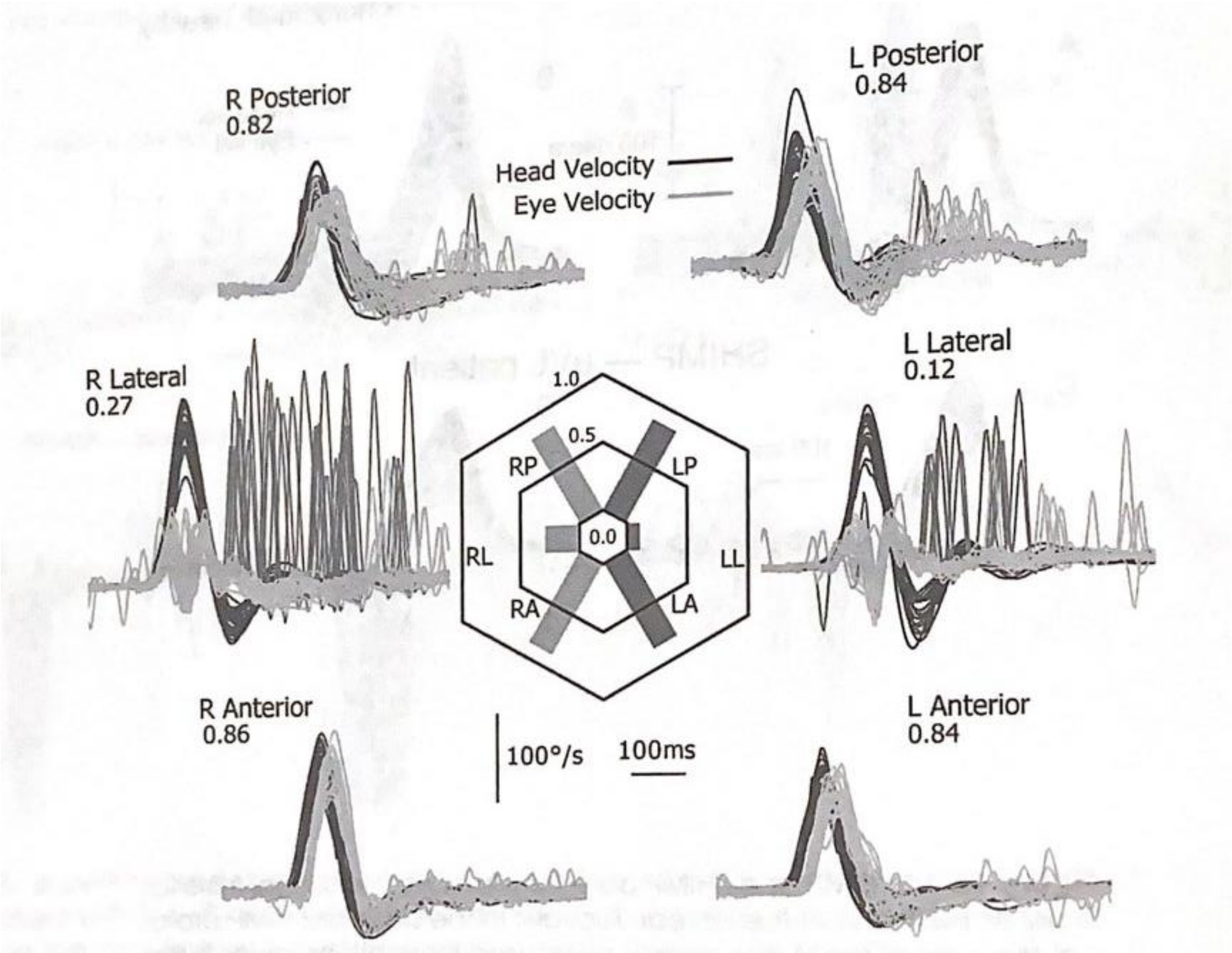

Possible Site of Lesion

- Horizontal SCC – calorics & rotary chair
- Saccule – cVEMP
- Utricle – oVEMP
- Superior vestibular nerve – calorics, rotary chair, oVEMP
- Inferior vestibular nerve – cVEMP
- VOR pathway – calorics, rotary chair, oVEMP
- Vestibulocollic pathway – cVEMP
- Cerebellar vermis and central connections to the vestibular nuclei – VOR suppression (fixation during calorics & rotary chair)

Possible Site of Lesion

- If we add calorics/rotary chair/vHIT + cVEMP + oVEMP there should be patterns of abnormality that emerge
- There should be overlap in the pathways for the caloric/rotary chair/vHIT and oVEMP tests
- If impairment affects the superior vestibular nerve only, cVEMPs should be unaffected
- If impairment affects the inferior vestibular nerve only, there should only be abnormalities in the cVEMP alone

Patterns of Test Results & the Possible Impaired Structures

- A = Abnormal, N = normal, contra = contralateral, ipsi = ipsilateral, p = posterior,
- a = anterior, h = horizonal

Impairment	Caloric	Horiz vHIT	Vert vHIT	cVEMP	oVEMP
Normal	N	N	N	N	N
hSCC	**A ipsi**	**A ipsi**	N	N	N
aSCC	N	N	**A contra downward impulse**	N	N
pSCC	N	N	**A ipsi upward impulse**	N	N
Utricle	N	N	N	N	**A ipsi ear stimulated**
Saccule	N	N	N	**A ipsi ear stimulated**	N
Sup. Vestib N	**A ipsi**	**A ipsi**	**A contra downward impulse**	N	**A ipsi ear stimulated**
Inf. Vestib N	N	N	**A ipsi downward impulse**	**A ipsi ear stimulated**	N
Total Unilat	**A ipsi**	**A ipsi**	**A ipsi**	**A ipsi ear stimulated**	**A ipsi ear stimulated**

Vestibular Neuritis

Superior Vestibular Nerve

Test	Structures				
	Horizonal	Superior	Utricle	Saccule	Posterior
oVEMP			Anormal ispi ear stimulated		
cVEMP				Normal	
vHIT	Reduced gain/saccades	Reduced gain/saccades			Normal
Rotary Chair	Reduced gain/phase lead/Asymmetry				
Caloric	Reduced or absent on the affected sided				

Vestibular Neuritis

Inferior Vestibular Nerve

Test	Structures				
	Horizonal	Superior	Utricle	Saccule	Posterior
oVEMP			Normal		
cVEMP				Reduced/absent	
vHIT	Normal	Normal			Reduced gain/saccades
Rotary Chair	Normal				
Caloric	Normal				

Meniere’s Disease

Test	Structures				
	Horizonal	Superior	Utricle	Saccule	Posterior
oVEMP			Variable		
cVEMP				Variable	
vHIT	Normal	Normal			Normal
Rotary Chair	Normal				
Caloric	Abnormal ipsilesional				

Superior Semicircular Canal Dehiscence Syndrome (SSCD)

Test	Structures				
	Horizonal	Superior	Utricle	Saccule	Posterior
oVEMP			Enhanced Amplitude /Asymm./Reduced Threshold		
cVEMP				Enhanced Amplitude /Asymm./Reduced Threshold	
vHIT	Normal	Normal			Normal
Rotary Chair	Normal				
Caloric	Normal				

Bilateral Vestibular Impairment

Test	Structures				
	Horizonal	Superior	Utricle	Saccule	Posterior
oVEMP			Bilaterally absent		
cVEMP				Bilaterally absent	
vHIT	Abnormally low gain	Abnormally low gain			Abnormally low gain
Rotary Chair	Abnormally low VOR gains				
Caloric	Response is absent for cool, warm, and ice water				

Future Areas of Research

- Spatial learning and memory and the growing evidence for the importance of the otoliths and vestibular sensory input
- Using vHIT and rotary chair in assessment of children with dizziness as they cannot tolerate calorics as well
    - Also use of remote cameras for rotary chair and vHIT for small children who cannot or will not wear the goggles
- Diagnostic criteria, epidemiology and pathophysiology of bilateral vestibulopathy
- Combined use of calorics, vHIT, and VEMP tuning for more specific diagnosis of Meniere's Disease

Questions?

Resources

- Akin, F. W., & Murnane, O. D. (2009). Clinical assessment of otolith function. *ASHA Leader*, *14*(2), 14–17.
- American Academy of Audiology. Scope of Practice, *Audiology Today*. 2004 15(3):44-45.
- Andreescu, C. E., De Ruiter, M. M., De Zeeuw, C. I., and De Jeu, M. T. (2005). Otolith deprivation induces optokinetic compensation. *J. Neurophysiol*. 94, 3487–3496.
- Angeli, S. I., & Goncalves, S. (2019). Cervical VEMP tuning changes by Meniere's disease stages. *Laryngoscope investigative otolaryngology*, *4*(5), 543–549.
- Barin, K. (2009). Rotational tests of vestibular function. *Seminars in Hearing*, *30*(04), 253–266.
- Barin, K. (2020). Estimating loss of canal function in the video head impulse test (vHIT). *Journal of Vestibular Research*, *29*(6), 295–307.
- Besnard, S., Lopez, C., Brandt, T., Denise, P., and Smith, P. F. (eds) (2016). “The vestibular system in cognitive and memory processes in mammals,” in *Frontiers in Integrative Neuroscience,* (Lausanne: Frontiers Media), 246.
- Čakrt, O., Slabý, K., Kučerová, K., Balatková, Z., Jeřábek, J., & Bouček, J. (2023). Subjective visual vertical and postural control in patients following cochlear implantation. *Journal of vestibular research : equilibrium & orientation*, *33*(6), 403–409.
- Cullen, K. E. (2012). The vestibular system: multimodal integration and encoding of self-motion for motor control. *Trends Neurosci*. 35, 185–196.
- Curthoys, I. S., Grant, J. W., Pastras, C. J., Fröhlich, L., & Brown, D. J. (2021). Similarities and Differences Between Vestibular and Cochlear Systems - A Review of Clinical and Physiological Evidence. *Frontiers in neuroscience*, *15*, 695179.
- Curthoys, I. S., MacDougall, H. G., Vidal, P. P., and de Waele, C. (2017). Sustained and transient vestibular systems: a physiological basis for interpreting vestibular function. *Front. Neurol*. 8:117.
- Gans, R. E. (2022). 20Q: Adding vestibular-balance neurodiagnostics to your audiology practice. *AudiologyOnline,* Article 28232.
- Gans, R. E., & Rutherford, K. (2020) Multidisciplinary approach to the management of the adult dizzy patient. *ENT & Audiology News*, *29*(2), 2-4.
- Guo, P., Zhao, J., Jia, G., Li, H., & Li, W. (2023). Dynamic change of vestibular function and the long-term prognosis of vestibular neuritis. *Journal of vestibular research : equilibrium & orientation*, *33*(6), 411–422.
- Jacobson G P, McCaslin D L, Grantham S L, Piker E G. Significant vestibular system impairment is common in a cohort of elderly patients referred for assessment of falls risk. *J Am Acad Audiol* . 2008;19(10):799 – 807.

Resources

- Jamon, M. (2014). The development of vestibular system and related functions in mammals: impact of gravity. *Front. Integr. Neurosci.* 8:11.
- Janky, K. L., & Patterson, J. (2020). The Relationship Between Rotary Chair and Video Head Impulse Testing in Children and Young Adults With Cochlear Implants. *American journal of audiology*, *29*(4), 898–906.
- Lopez, C., Falconer, C. J., Deroualle, D., and Mast, F. W. (2015). In the presence of others: self-location, balance control and vestibular processing. *Neurophysiol. Clin.* 45, 241–254.
- Maheu, M., Alvarado-Umanzor, J. M., Delcenserie, A., & Champoux, F. (2017). The Clinical Utility of Vestibular-Evoked Myogenic Potentials in the Diagnosis of Ménière's Disease. *Frontiers in neurology*, *8*, 415.
- Manzari, L., Graziano, D., & Tramontano, M. (2020). The Different Stages of Vestibular Neuritis from the Point of View of the Video Head Impulse Test. *Audiology Research*, *10*(2), 31–38.
- Maxwell, R., Jerin, C., & Gürkov, R. (2017). Utilisation of multi-frequency VEMPs improves diagnostic accuracy for Meniere's disease. *European archives of oto-rhino-laryngology : official journal of the European Federation of Oto-Rhino-Laryngological Societies (EUFOS) : affiliated with the German Society for Oto-Rhino-Laryngology - Head and Neck Surgery*, *274*(1), 85–93.
- McCaslin, D. L., Rivas, A., Jacobson, G. P., & Bennett, M. L. (2015). The dissociation of video head impulse test (vHIT) and bithermal caloric test results provide topological localization of vestibular system impairment in patients with "definite" Ménière's disease. *American journal of audiology*, *24*(1), 1–10.
- Noij, K. S., Herrmann, B. S., Guinan, J. J., Jr, & Rauch, S. D. (2019). Cervical Vestibular Evoked Myogenic Potentials in Menière's Disease: A Comparison of Response Metrics. *Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, *40*(3), e215–e224.

Resources

- Obeidat, F. S., Alghwiri, A. A., & Bell, S. L. (2024). Vestibular evoked myogenic potential (VEMP) test-retest reliability in adults. *Journal of vestibular research : equilibrium & orientation*, *34*(1), 39–48.
- Piker, E. G., Picou, E., Jacobson, G. P., & Coltisor, A. (2022). Agreement Between Caloric and Horizontal Video Head Impulse Testing in School-Aged Children Presenting With Dizziness. *American journal of audiology*, *31*(2), 299–304.
- Shepard, N. T. (2007). Dizziness and balance disorders. *ASHA Leader*, *12*(7), 6–17.
- Slattery, E. L., Sinks, B. C., & Goebel, J. A. (2011). Vestibular tests for rehabilitation: applications and interpretation. *NeuroRehabilitation*, *29*(2), 143–151.
- Smith P. F. (2019). The Growing Evidence for the Importance of the Otoliths in Spatial Memory. *Frontiers in neural circuits*, *13*, 66.
- Strupp, M., Kim, J. S., Murofushi, T., Straumann, D., Jen, J. C., Rosengren, S. M., Della Santina, C. C., & Kingma, H. (2017). Bilateral vestibulopathy: Diagnostic criteria Consensus document of the Classification Committee of the Bárány Society. *Journal of vestibular research : equilibrium & orientation*, *27*(4), 177–189.
- Wei, E. X., Oh, E. S., Harun, A., Ehrenburg, M., and Agrawal, Y. (2017). Saccular impairment in Alzheimer’s disease is associated with driving difficulty. *Dement*. *Geriatr*. *Cogn*. *Disord*. 44, 294–302.
- Wei, E. X., Oh, E. S., Harun, A., Ehrenburg, M., and Agrawal, Y. (2018). Vestibular loss predicts poorer spatial cognition in patients with Alzheimer’s disease. *J. Alzheimers*. *Dis*. 61, 995–1003.
- Wei, E. X., Oh, E. S., Harun, A., Ehrenburg, M., Xue, Q. L., Simonsick, E., et al. (2019). Increased prevalence of vestibular loss in mild cognitive impairment and Alzheimer’s disease. *Curr. Alzheimer Res*.
- Xu, X. D., Ding, C. R., Yu, J., Han, Z., Gu, J., Gao, N., et al. (2016). The hidden dysfunction of otolithic organs in patients with profound sensorineural hearing loss. *Hear. Res*. 331, 41–46.