SYSTEMATIC / NARRATIVE REVIEW ARTICLE

Quantitative vestibular function tests in posterior circulation stroke patients: A review

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ABSTRACT

While specific bedside examinations are known to be sensitive in identifying stroke among acute vestibular syndrome patients, complementary quantitative vestibular function testing can be helpful to quantify vestibular loss due to stroke. In contrast to peripheral vestibular dysfunction, diagnosis of central vestibular dysfunction can be challenging for unskilful clinicians. This article presents a comprehensive overview of quantitative vestibular function test findings such as the video head impulse test (vHIT), cervical vestibular evoked myogenic potentials (cVEMPs), ocular vestibular evoked myogenic potentials (oVEMPs), videonystagmography (VNG) and caloric test among stroke patients. Vestibulo-ocular reflex (VOR) gain is usually found normal among posterior inferior cerebellar artery (PICA) stroke patients but varies among anterior inferior cerebellar artery (AICA) stroke patients. Abnormal contralesional posterior semicircular canal VOR gain can be observed due to lesions in the medial longitudinal fasciculus (MLF). AICA and PICA stroke can impair cVEMPs, oVEMPs, and VNG (i.e., smooth pursuit and saccade functions). Strokes, particularly those involving the vestibular nucleus, including both upper, lower brainstem and cerebellum, can result in various abnormalities of smooth pursuit, saccade or calorics testing. The combined evaluations of VNG, vHIT, and VEMPs can be accurately used to complement and quantify bedside vestibular evaluation in diagnosing central vestibular dysfunction. In addition, as most studies were conducted amongst acute vestibular syndrome (AVS) patients, future studies that investigate the prevalence of vestibular dysfunction in recovering stroke patients are required.

KEYWORDS:
Vestibular function tests, vestibular evoked myogenic potentials, vestibulo-ocular reflex, caloric tests, stroke

INTRODUCTION

An imbalance in the vestibular system tonic discharges following disturbances to the vestibular organs can be defined as vestibular dysfunction. Common vestibular symptoms are vertigo, dizziness, oscillopsia, and postural symptoms like unsteadiness involving peripheral vestibular organs, the vestibular ocular reflex (VOR) or both.[1,2] However, vestibular dysfunction can also be caused by a stroke. It was reported that 25% of posterior circulation stroke (PCS) patients had vertigo.[3] Among acute vertigo patients, 11%[4] to 59.5%[5] of vertigo incidences were associated with stroke. A study also found that 12.5% of emergency department visits related to vestibular symptoms were due to cerebrovascular accidents.[6] A national database survey in Taiwan reported that 3.1% of the Taiwanese adult population had vertigo, and 0.5% was having a stroke.[7]

PCS accounts for approximately 10% to 20% of annual stroke incidences.[8-10] Based on the Global Burden of Disease Study 2016 report, stroke was among the most common cause of death globally, with 80 million stroke survivors having permanent disabilities.[11]

Acute vestibular syndrome (AVS), characterised by a single episode, sudden onset of vestibular signs and symptoms can occur due to disorders and diseases as vestibular neuritis or stroke.[2] In contrast, the chronic vestibular syndrome usually occurs due to persistent symptoms and signs of vestibular disorders, such as bilateral vestibular loss or cerebellar degeneration.[2] Clinical bedside vestibular examinations have been used extensively to diagnose vestibular and oculomotor dysfunction associated with stroke. The clinical Head-Impulse-Nystagmus Test of Skew (HINTS) was introduced as the test for the angular horizontal VOR, nystagmus and skew deviation (to determine the otolithic function) to differentiate central vestibular disorders (which may be due to stroke) from a peripheral vestibulopathy.[12] Central vestibular lesions caused by a stroke can be identified by a normal head impulse test (HIT) VOR finding, presence of bilateral gaze-evoked or direction-changing nystagmus, and a positive skew deviation. Earlier studies reported these sensitivities and specificities for the HINTS battery: 94.1% sensitivity,[3] 96.5% sensitivity and 84.4% specificity,[5] 100% sensitivity and 96% specificity in diagnosing stroke in AVS patients, which is higher than the magnetic resonance imaging (MRI) within 48 hours of symptom onset.[12] Compared to HINTS, the early diffusion-weighted magnetic resonance imaging (DW-MRI) had lower sensitivity, 100% vs. 72%, and comparable specificity, 96% vs. 100%.[12]

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The HINTS algorithm was created and validated to triage vertigo patients in the acute setting, such as the emergency room. The HINTS is a highly sensitive bedside test that is quick and cost-effective to diagnose acute central vertigo (e.g., PCS), which has a high risk of mortality and morbidity. Quantitative vestibular testing such as caloric irrigation, vestibular evoked myogenic potentials (VEMPs), and videonystagmography (VNG) have also been used to complement clinical bedside testing measuring vestibular and oculomotor dysfunction. Quantitative vestibular function testing is usually used in laboratory or office settings, except for the video head impulse test (vHIT), which has also been used recently in the emergency room.[13] Quantitative vestibular testing can monitor the effects of rehabilitation and the course of recovery of chronic vestibular dysfunction over time.[14] However, quantitative testing, such as vHIT[15] and VEMPs[16] have been known to identify peripheral vestibular lesions. Recently, abnormal vHIT[13] and VEMPs[17] have also been reported among patients with central lesions such as stroke. Vestibular dysfunction can occur depending on the lesion involved in the posterior circulation (Fig. 1). This review aims to document recent clinical presentations and characteristics of quantitative vestibular test batteries among stroke patients.

METHODS

The present narrative review is based on searches from Pubmed, SCOPUS and Ovid databases with the following keywords; "(head impulse test or scleral search coil or video head impulse test or video-oculography or vestibular evoked myogenic potentials or electronystagmography or videonystagmography or caloric test) AND (stroke)". Google Scholar was also used to search for additional literature and other quantitative methods. Fifty-four, 134 and 553 articles were retrieved from Pubmed, SCOPUS, and Ovid web search engines. After excluding duplications, only 20 original articles involving quantitative vestibular testing studies were reviewed. This review includes only recent articles published from 2010 up to 2020.

RESULTS

Video Head Impulse Test (vHIT)

The vHIT concept is based on the VOR function among normal healthy individuals, which depict that the VOR moves the eyes with the same speed and contralateral direction to that of head movement, for the eyes to keep the object of interest in the fovea. The vHIT measures VOR, which originates from the semicircular canals (SCCs), i.e., part of the peripheral vestibular organs in the inner ear. Signals were then sent to the brainstem following head acceleration and deceleration. In peripheral vestibular lesions, the VOR gain is reduced, causing catch-up saccades, enabling the eyes to focus on the targeted image. From the SCCs, the VOR pathway projects to the vestibular nucleus and contralateral abducens nucleus.[18] The neurons then project to the oculomotor nucleus to activate eye muscles via the medial longitudinal fasciculus.[18]

In the early years before the availability of vHIT, the scleral search coils technique was used to measure the VOR gain. However, the coils require special equipment and are only available for research outside the standard clinical practice. A recent study reported that the VOR gain for the horizontal SCC is usually normal among PCS patients.1[9] The study indicated that quantitative HIT could distinguish between peripheral or central vestibular dysfunction among AVS patients in the emergency department. However, studies using vHIT and dual-search coils showed that, based on blood circulation territories, acute stroke patients had distinct VOR gain findings (Table I). The VOR gain for horizontal SCCs among anterior inferior cerebellar artery (AICA) stroke patients were bilaterally reduced[13,20-22] or varied[20-22] compared to normal individuals. The reduction or variation in the VOR gain findings was attributed to the level of involvement following ischemic insults in the labyrinth, vestibular nucleus or flocculus.[20] For example, floccular infarction could cause a more severe ipsilesional gain reduction.[20] However, due to the risk of misclassifying AICA stroke in diagnosing central vestibular dysfunction, HIT VOR gain should not be used in isolation but only when accompanied by other tests and clinical oculomotor examination.[21]

The VOR gain for the horizontal SCCs was within normal symmetrical ranges among PICA stroke patients.[21,22] But, in the dual-search coils study, 17 PICA and three superior cerebellar arteries (SCA) stroke patients with AVS had a 25% symmetrical mean gain reduction for the horizontal SCCs when compared with the control subjects.[20] Although there was only a slight reduction in the gain values, this finding indicates some cerebellar influence in the high-acceleration VOR.[20] Another study also found that, when a stroke involved PICA and SCA territories, the VOR vHIT gains for the horizontal SCCs revealed normal values.[13] Overall, among AVS patients, abnormal VOR gains for the horizontal SCCs typically indicate vestibular neuritis, while normal gains usually predict the likelihood of stroke.[13,20-22] The vHIT VOR gain for the horizontal SCCs has a sensitivity of 88%[21] to 94%[20] or accuracy of 100%[13,22] when identifying PCS among AVS patients. In another study among stroke patients with lesions in the lateral medulla, only three of fourteen patients had mild to moderate gain deficits for the horizontal or posterior SCCs.[23] The patients with abnormal VOR gain had lesions in the rostral medulla. However, most patients with lesions involving the caudal or middle medulla had normal VOR gain values. Overall, the study indicated that the VOR gain is usually normal for the horizontal SCCs in the lateral medullary infarct patients.[21,23]

The study using dual-search coils HIT also provided further saccade analysis for the horizontal SCCs.[20] Overall, the saccades for the horizontal SCCs in both AICA and PCA and SCA groups were small, with 97% of the patients in both groups had <61% saccade asymmetry.[20] Due to larger ipsilesional saccade amplitude after contralesional trials, there was also negative saccade asymmetry among 70% of PICA and SCA stroke subjects in the study.[20] The saccade asymmetry in PICA and SCA stroke was attributed to the hypometria of the infarcted dorsal vermis in the cerebellum, caused by refoveated eyes after saccade undershooting.[20] The fact that PCS patients had small saccades with amplitude asymmetry, more pronounced in PICA and SCA than AICA stroke, may warrant further investigation on saccade potential in diagnosing central vestibular dysfunction.[20] In a recent study that utilised vHIT in the assessment of PCS patients, it was reported that there was no significant difference in the saccades prevalence for the horizontal SCCs

Table I: Quantitative head impulse test findings in posterior circulation stroke (PCS) studies

Authors	Duration From Stroke Onset	Measurement Techniques	Subjects	Gain Findings	Saccade Amplitude Findings
Guler et al. (13)	Acute	vHIT	9 brainstem infarct (PICA-SCA stroke) patients	Horizontal SCC (mean±SD)= Ipsilesional 0.79±0.25; Contralesional 0.80±0.23	
			7 cerebellar infarct (PICA-AICA stroke) patients	Horizontal SCC (mean±SD)= Ipsilesional 1.02±0.13; Contralesional 0.97±0.16	
Calic et al., (19)	Mean 7 days	vHIT	22 PCS patients	Horizontal SCC (mean±SD)= 0.85±0.3	Horizontal SCC (mean±SD)= Amplitude 2.2±1.7°;
Chen et al., (20)	< 7 days	Dual-search coil	17 PICA and 3 SCA	Horizontal SCC (mean±SD)= Ipsilesional 0.75±0.09; Contralesional 0.74±0.08	Horizontal SCC (mean±SD)= Ipsilesional 2.1±0.4°; Contralesional 3.0±0.8°
			13 AICA	Horizontal SCC (mean±SD)= Ipsilesional 0.38±0.13; Contralesional 0.57±0.12	Horizontal SCC (mean±SD)= Ipsilesional 4.7±1.4°; Contralesional 3.3±0.7°
Mantokoudis et al. (21)	< 7 days	Video-oculography	7 PICA	Horizontal SCC mean (SE)= Ipsilesional 0.94 (0.04); Contralesional 0.93 (0.04)	
			3 AICA	Horizontal SCC mean (SE)= Ipsilesional 0.84 (0.10); Contralesional 0.74 (0.10)	
Newman-Toker et al. (22)	< 7 days	Video-oculography	3 AICA	Horizontal SCC: 2 patients with VOR gain 0.6-0.8, 1 patient with VOR gain <0.6	
Lee et al. (23)	Acute up to 16 days	vHIT	17 lateral medulla	3 patients had mild to moderately reduced VOR gain (1 patient with reduced ipsilesional horizontal and posterior SCC, 1 patient with ipsilesional horizontal, ipsilesional posterior SCC and contralesional posterior SCC, 1 patient with contralesional posterior SCC).	Covert saccades: Latency 84 -111 ms, Peak velocity 42-104°/s. Overt saccades: Latency 314-368 ms, Peak velocity 90 to 130°/s.
Choi et al. (24)	1-3 weeks	Magnetic search coil	10 patients with unilateral INO	90% had reduced VOR gain for the contralesional posterior SCC and 50% had reduced VOR gain for the ipsilesional horizontal SCC	
Lee et al. (25)	1-131 days	vHIT	16 unilateral INO	Horizontal SCC (mean±SD)= Ipsilesional 0.77±0.27; Contralesional 0.90±0.24 Anterior SCC (mean±SD)= Ipsilesional 0.75±0.17; Contralesional 0.76±0.19 Posterior SCC (mean±SD)= Ipsilesional 0.73±0.18; Contralesional 0.55±0.11	
			5 bilateral INO	Horizontal SCC (mean±SD)= 0.82±0.32 Anterior SCC (mean±SD): 0.58±0.19 Posterior SCC (mean±SD)= 0.43±0.11	

AICA: anterior inferior cerebellar artery; PICA: posterior inferior cerebellar artery; SCA: superior cerebellar artery; INO: internuclear ophthalmoplegia; SCCs: semicircular canals; SD: Standard Deviation; SE: Standard Error

between the standard healthy control and PCS.[19] However, in the study, the saccade metrics such as saccade amplitudes and velocities were smaller, with saccadic latency longer in the PCS than in the standard controls. The fact that the PCS patients had small saccade with amplitude asymmetry, more in PICA and SCA than AICA stroke, may warrant further investigation of the application of saccade potential in diagnosing central vestibular dysfunction.[20]

While HIT gain measured on lateral SCCs can sensitively differentiate peripheral from central vestibular dysfunction, the HIT can also be used to investigate angular VOR deficiency for the vertical SCCs. The medial longitudinal fasciculus (MLF) transmits the VOR signals from the vertical SCCs to the ocular motor nuclei.[24,25] In a study on unilateral internuclear ophthalmoplegia (INO) stroke patients, reduced VOR gains were found in contralesional posterior SCCs more

Table II: cVEMPs and oVEMPs abnormalities in posterior circulation stroke (PCS) studies

Authors (year)	Test Duration From Stroke Onset	Blood Supply Territories	Lesion Locations	cVEMPs	oVEMPs
Heide et al. (17)	The first week after symptom onset		Brainstem	12/29 (41%) patients had unilateral abnormal AC clicks cVEMPs	
Calic et al. (19)	Mean 7 days	PCS		38% had asymmetrical cVEMPs	9% had asymmetrical oVEMPs
Ahn et al. (27)		AICA	Brainstem, cerebellum or both	8/16 (50%) patients had abnormal clicks cVEMPs on the lesion side (absent or decreased amplitude)	
Weng and Young (28)		PICA, AICA	Brainstem, cerebellum or both	PICA group: (8/22) 36% were abnormal AICA group: 3/4 (75%) ear were abnormal	PICA group: 8/14 (57%) ears were abnormal AICA group: 1/2 (50%) ears were abnormal
Choi et al. (29)	10 -13 days	PICA, PICA & SCA, SCA, AICA	Unilateral cerebellum	11/27 (41%) patients had abnormal AC TB cVEMPs	9/27 (33%) patients had abnormal head tap oVEMPs
Kim et al. (30)	1-14 days		Lateral medulla	9/21 (43%) patients had abnormal AC TB cVEMPs (7 unilateral and 2 bilateral)	
Kim et al. (31)	1-11 days		Lateral medulla	13/45 (29%) patients had abnormal AC tone burst (9 increase IAD with 6 ipsilesional and 3 contralesional reduced amplitude; 4 increased p13 latency with 1 ipsilesional, 2 contralesional, 1 bilateral)	12/45 (27%) patients had abnormal had tap oVEMPs (absent in 3, 5 increased IAD with 4 ipsilesionally and 1 contralesionally reduced amplitude, 4 increased N1 latency)
Kim et al. (32)	2 days -3 years		Medial medulla	7/14 (50%) patients had ipsilesional abnormal AC TB cVEMPs	
Kim et al. (33)	1 week		Medial longitudinal fasciculus	3/12 (25%) patients had abnormal AC TB cVEMPs (2 reduced amplitude, 1 absent on lesion side)	8/12 (67%) patients had abnormal head tap oVEMPs (7 on lesion side, 1 bilateral)

cVEMPs: cervical vestibular evoked myogenic potentials; oVEMPs: ocular vestibular evoked myogenic potentials; AC: air conduction; TB: tone burst; IAD: interaural amplitude difference ratio; AICA: anterior inferior cerebellar artery; PICA: posterior inferior cerebellar artery; SCA: superior cerebellar artery

than the anterior SCCs. INO occurred due to damage in the MLF, resulting in impaired adduction of an ipsilesional horizontal eye and dissociated nystagmus from the contralesional abducting intact eye. These findings suggest that the MLF mediates the excitatory VOR from posterior SCCs to the ocular motor nuclei. As the VOR gain for the anterior SCCs is slightly affected than the posterior SCCs, it was postulated that the anterior SCCs input is also mediated outside the MLF. The VOR signal from the anterior SCCs can also be transmitted by the ventral tegmental tract and brachium conjunctivum and the MLF.[24,25]

Vestibular Evoked Myogenic Potentials (VEMPs)

Cervical VEMPs (cVEMPs) represent the vestibulo-collic reflex projections from the saccule in the inner ear to the vestibular nucleus in the brainstem that transmits through the inferior vestibular nerve.[16] The saccular projections later descend to the ipsilateral sternocleidomastoid (SCM) muscles through the medial vestibulospinal tract.[16] The cVEMPs consist of P13-N23 peak-to-peak waveforms attributed solely to the ipsilateral sacculo-colic reflex and N12-P20 waveforms from the contralateral SCM muscle, originating from the utricle.[26] cVEMPs can be abnormal among PCS patients (Table II). In a recent study among PCS patients, cVEMPs were found abnormal in 59% of patients.[19] Among 16 AICA stroke patients, cVEMPs stimulated using clicks stimuli were reported to be abnormal (six absent and two reduced amplitude) on the lesion side.[27] Those with abnormal cVEMPs also had canal paresis on caloric irrigation test and were found to have sensorineural hearing loss due to ischemia in the root of the entry zone to the eighth nerve of the inner ear.[27] cVEMPs were also reported to be delayed or absent in 36% of PICA and 75% of AICA groups, due to lesion in the lower brainstem.[28] Apart from the brainstem, lesions located in the cerebellum may also exhibit abnormal air-conducted cVEMPs responses. Eleven of 27 patients (41%) had increased interaural amplitude difference (IAD) ratio, absent or delayed responses with no cVEMPs directionality to the lesion side.29 The authors concluded that the asymmetrical cVEMPs responses might be related to the otolith lateralisation effect in the unilateral cerebellar lesions.[29] The absence of cVEMPs directionality may indicate that there are crossed or bilateral otolithic vestibular modulating pathways occurring within the cerebellum.[29] However, no lesion subtraction analysis was performed in the study to investigate the specific cerebellar structure involved in generating cVEMPs.[29]

Damage to the vestibular fascicles, vestibular nuclei, or its descending fibres in the brainstem can disrupt cVEMPs responses.[30] In one study among 21 lateral medullary infarct

Table III: Caloric irrigations and oculomotor tests findings in posterior circulation stroke (PCS) studies

Authors (year)	Test Durations From Stroke Onset	Test Durations territories	Lesion Locations	Oculomotor Testing using Electronystagmography (ENG) /Videonsytagmography (VNG)	Caloric irrigations
Ling et al. (35)	Acute	PCS		9/30 (23.7%) abnormalities in gaze testing, 12/30 (31.6% abnormalities in saccade testing, 57.9% abnormalities in smooth pursuit testing, 50% abnormalities in optokinetic testing	
Weng and Young (28)		AICA, PICA	Brainstem, cerebellum or both	Among the PICA group: 9/11 (82%) had abnormal pursuit, (8/11) 73% had abnormal saccade, (9/11) 82% had abnormal optokinetic nystagmus	Among PICA group patients: 14/22 (64%) ears had abnormal caloric, 8/14 (57%) had abnormal visual suppression test
				Among AICA group: (2/3) 67% abnormal pursuit, (2/3) 67% abnormal saccade, (3/3) 100% abnormal optokinetic nystagmus	Among AICA group patients: 3/6 (50%) ear had an abnormal caloric test, 2/4 (50%) had abnormal visual suppression test
Kim et al. (36)	1-7 days	19 PICA, 3 AICA, 1 pontine artery	18 cerebellar, 4 medulla, 1 pons	11/23 (48%) patients had direction-changing nystagmus, 6/23 (27%) periodic alternating nystagmus	7/23(30%) patients had fixation failure, 15/23 (65%) patients had spontaneous nystagmus without canal paresis
Kim and Kim (37)	1-18 days		Middle cerebellar peduncle	15/23 (65%) patients had horizontal gaze-evoked nystagmus (GEN), 14/19 (73%) abnormal smooth pursuit	14/18 (78%) patients with infarctions had canal paresis
Su and Young (38)	Acute		Posterior Fossa	19/22 (86%) patients had abnormal optokinetic nystagmus test, 21/22 (95%) abnormal eye tracking test	19/22 (86%) patients had abnormalities (1 hyperfunction; 8 canal paresis; 10 caloric areflexia), 22/22 (100%) patients had abnormal visual suppression test

AICA: anterior inferior cerebellar artery; PICA: posterior inferior cerebellar artery; SCA: superior cerebellar artery

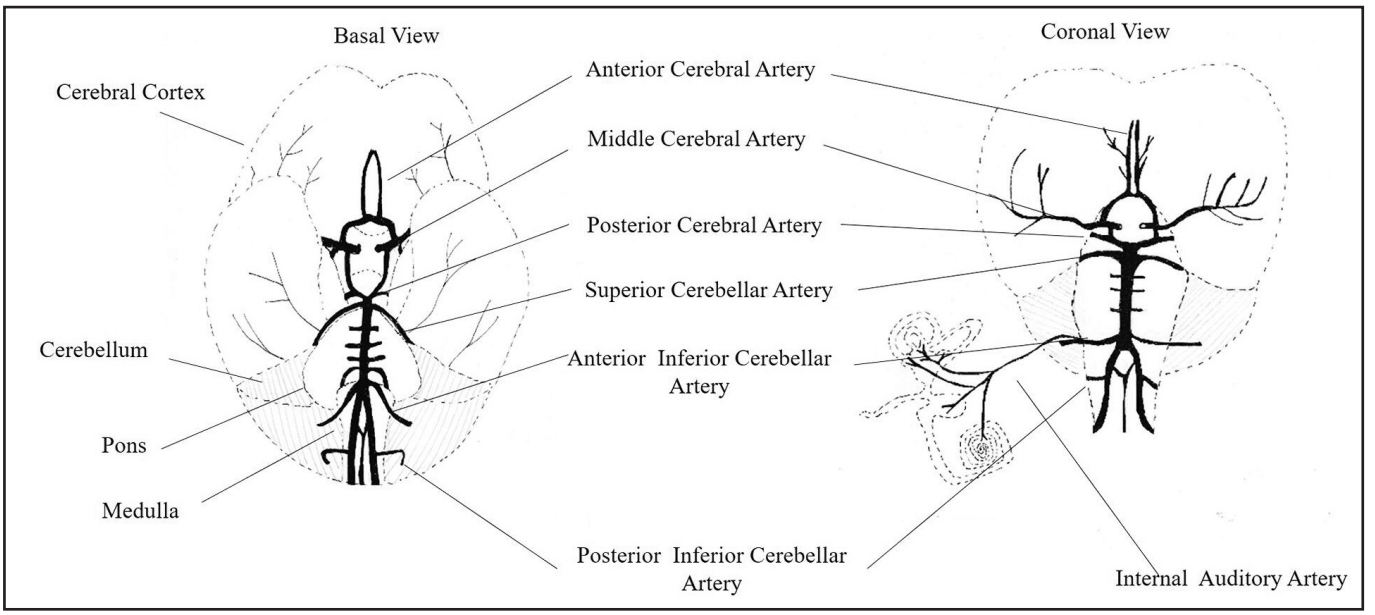

Fig. 1: Circle of Willis and blood supply to the inner ear. The posterior cerebral artery (PCA), anterior inferior cerebellar artery (AICA), posterior inferior cerebellar artery (PICA) and superior cerebellar artery (SCA) form the posterior circulation of the brain. The anterior cerebral artery (ACA) and middle cerebral artery from the anterior circulation of the brain. The internal auditory artery (ACA), a segment of AICA, also supplies the inner ear.

patients, nine subjects (43%) had abnormal air conduction (AC) tone burst cVEMPs (seven unilateral and two bilateral).[30] In this study, six ears had reduced amplitude, six ears had delayed latencies, and two ears had reduced and delayed latencies. Two patients exhibited abnormal cVEMPs responses on the contralesional side. These findings suggest that the commissural fibres had a role in modulating the contralateral sacculocollic input pathway in the brainstem.30 Any isolated or combined damage to the commissural fibres can result in abnormal contralesional or bilateral cVEMPs responses.[30] While decreased or absent cVEMPs both indicate the presence of ischemia, delayed latency can be a sign of demyelination following incomplete infarct.[30] Another study also reported that 29% of the patients with lateral medullary infarction also had abnormal cVEMPs with increasing IAD ratio or longer p13 latency.[31] The abnormalities were due to lesions in the caudal and rostral medulla, where the vestibular nuclei are located.[31] Most patients in the study also had abnormal ocular tilt reaction and subjective visual vertical on the ipsilesional side, but fewer of these patients reported abnormal cVEMPs and oVEMPs. These suggest the dissimilarities of otolithic substrates processing located in the dorsolateral medulla.[31]

In a study of 29 patients with brainstem lesions, 12 had unilateral abnormal cVEMPs (eight absent, four reduced amplitude) while seven had bilateral absent cVEMPs responses to AC clicks stimuli. This study shows that lesions in the lateral medulla and lateral lower pons where the spinal accessory nerve and vestibular nuclei are located, respectively, can impair the generation of cVEMPs. It was also determined that the pyramidal tract lesions, located in the upper pons, disrupt the cVEMPs output, suggesting that the abnormal cVEMPs can also be affected by lesions up to the mesencephalon, above the vestibular nuclei level.[17]

Infarcts occurring in the descending pathway can also impair cVEMPs. Seven of fourteen patients (50%) with medial medullary infarct had abnormal AC tone bursts cVEMPs responses (either absent, delayed or reduced amplitude) on the lesion side.[32] This study reported that damage in the medial medulla, which contains the MLF, could disrupt the vestibulospinal tract pathway that runs in the MLF to descend and contract sternocleidomastoid muscles in the neck.[32] This finding is supported by another cVEMPs study on 12 patients with isolated INO. Twenty-five per cent of the patients had abnormal cVEMPs responses (two decreased amplitude, one absent) on the side of the lesion, suggesting that the MLF played a role in mediating ipsilesional cVEMPs descending pathway.[33]

In contrast to cVEMPs, the oVEMPs reflect the function of a crossed utricular pathway that projects from the utricle in the inner ear to the vestibular nuclei via the superior vestibular nerve.[16] It later activates both the inferior oblique and inferior rectus muscles of the eyes.[16] The oVEMPs consist of the N10-P15 complex of the contralateral side.[26] Unlike cVEMPs, only a few studies have reported oVEMPs findings among stroke patients.

Abnormal oVEMPs were reported in 5% of PCS patients.[19] Among the PCS patients, abnormal oVEMPs have been found among PICA/AICA patients due to lesions in the upper brainstem.[28] oVEMPs in response to head tap were reportedly abnormal among 12 of the 45 patients with infarcts in the lateral medulla.[31] In the study, two patients with abnormal responses also had lesions in the rostral medulla, where the vestibular nucleus is located.[31] oVEMPs in response to head tap were also reported to be abnormal (four absent and three reduced amplitude on the lesion side; one absent bilaterally) among 12 patients with INO.[33] These findings indicate that the MLF mediates the ascending crossed otolith-ocular reflex signal.[33] More than 30% of unilateral cerebellar infarct subjects also had abnormal head tap oVEMPs responses (either delayed, reduced amplitude or absent), suggesting a cerebellar role, such as the nodulus and uvula, in mediating oVEMPS pathway. However, results did not show any directionality of abnormal response to the lesion side involved.[29] As PICA supplies the nodulus, uvula, inferior cerebellar hemisphere and medulla,[28] injuries to the surrounding areas can also cause abnormal VEMPs.

Electronystagmography (ENG) / Videonystagmography (VNG) Oculomotor Testing

Abnormalities of the saccades, smooth pursuit, gaze and optokinetic system can be reliably identified using bedside examination or measured quantitatively using video-oculography (VOG) or nystagmography. Saccades and gaze are modulated in the brainstem and cerebellum and project to the extraocular muscles of the eyes.[34] The smooth pursuit has a long pathway and is generated in many locations in the brain, from the brainstem and cerebellum towards frontal eye fields.[34] A study reported that eye movement abnormalities occurred in 78.9% of PCS patients.[35] Among the PCS patients, 23.7% had abnormal gaze testing, 31.6% had abnormal saccade testing and 57.9% had abnormal smooth pursuit testing. Fifty per cent of patients in the study also had optokinetic nystagmus. Another study found abnormalities of smooth pursuit, saccade and optokinetic nystagmus in both PICA and AICA stroke patients, indicating the presence of central vestibular dysfunction when tested using electronystagmography (ENG).[28] In a study among 19 PICA, three AICA and one pontine artery stroke patient tested using videonystagmography (VNG), 48% had direction-changing nystagmus, and 27% had periodic alternating nystagmus.[36] As most patients in the study did not have neurological signs and showed normal imaging during AVS onset, the study suggested that for examinations of delayed neurological signs, VNG can assist in diagnosing vertebrobasilar stroke among AVS patients.[36] In another study of patients with unilateral middle cerebellar peduncle infarction tested using video-oculography (VOG), 78% had horizontal gaze-evoked nystagmus, while 73% had abnormal smooth pursuit function.[37] An injury to the vestibular nucleus, flocculus and pontocerebellar fibres near the middle cerebellar peduncle (MCP) can disrupt the neural integrator responsible for holding gaze.[37] The pursuit function can be impaired as the MCP also carries fibres from the flocculus, uvula and dorsal vermis to the frontal eye field.[37] A study found that overall, 86% had abnormal optokinetic nystagmus among the patients with posterior fossa stroke, while 95% had abnormal eye-tracking tests.[38]

Caloric Irrigation Testing

The caloric irrigation test was used to identify the peripheral

vestibular lesion in the horizontal SCCs and central pathway in the brainstem.[27,28,34] Caloric thermal irrigation measures the velocity storage to the low-frequency signals.[34] The visual suppression test (VST) measures fixation's ability to reduce the nystagmus slow phase velocity.[34] VST overrides the VOR pathway in the parietal-occipital cortex, brainstem and cerebellum.[34] Visual lack of suppression is also a sign of disturbance in the cerebellum due to reduced inhibition of the superior and medial vestibular nuclei by the floccular Purkinje cells.[28] Previous studies have revealed abnormalities in the caloric irrigation test and VST measurements due to central vestibular dysfunction (Table III). In a study among PICA stroke patients, 64% of ears had either canal paresis, caloric areflexia or hyperactive responses to the irrigation.[28] Among the AICA stroke patients in the study, 50% of the ears had canal paresis or caloric areflexia.[28] The study concluded that the canal paresis or caloric areflexia in these PCS patients were due to reduced VOR following brainstem infarcts. The hyperactive caloric responses might also indicate cerebellar lesions.[28] Among 19 PICA, three AICA and one pontine artery stroke patient, 30% had fixation failure due to cerebellar lesion.[36] Eighty-six per cent of posterior fossa stroke patients in their study also had abnormal caloric responses, while one patient had hyperfunction, eight patients had canal paresis, and ten patients had caloric areflexia.[38] All patients in the study also had abnormal visual suppression tests, possibly due to unilateral floccular lesion.[38] In another study among patients with MCP stroke, 78% had caloric paresis due to the impairment in the vestibular nuclear complex, which is located adjacent to the MCP.[37]

Summary and future recommendations in the use of quantitative vestibular testing

Quantitative vestibular tests, along with clinical bedside examinations, can be used to identify central vestibular dysfunction among ischemic stroke patients. The presence of normal VOR gain for lateral SCCs using quantitative HIT among AVS patients can indicate a stroke, usually in the PICA, SCA or both. However, abnormal VOR gain, mainly in the posterior SCCs, can be observed when stroke involves the MLF. AICA stroke usually results in variable gain findings. Further investigations using vHIT as the latest VOR technology to identify the role of the central vestibular pathway in modulating saccades are needed. Compared to magnetic search coils, vHIT is less invasive and easier to use to measure VOR.

Both cVEMPs and oVEMPs are abnormal when the lesions involved the upper, lower, or parts of the brainstem, particularly the vestibular nuclei. However, the results varied with various lesion locations and parameters such as latencies, amplitudes and testing stimuli. Moreover, many subjects, particularly the healthy elderly, also exhibited reduced response rate, amplitude and prolonged latencies for both cVEMPs[39,40] and oVEMPs responses.[39] Therefore, it is difficult to ascertain whether the abnormal cVEMPs and oVEMPs are attributable to ageing or stroke.

There were only a few studies performed on stroke patients using caloric irrigation and VNG. Caloric irrigation may not be tolerated well by stroke patients.[28] However, VNG is a sensitive test of oculomotor function and can be used along with HIT and VEMPs to measure central vestibular dysfunction quantitatively. On the other hand, the bedside approach is still mandatory as it is a quick, cheap, and highly sensitive method to diagnose stroke during the acute stage. In contrast to clinical bedside testing, quantitative vestibular testing may not be readily available in acute care settings and is costly, time-consuming and requires trained personnel. Quantitative VFT, such as VNG, is also prone to artefacts. Besides, appropriate control group or normative clinical data and standardised parameters for VEMPs and VNG are necessary to ensure an accurate diagnosis of central vestibular dysfunction. Therefore, quantitative measures can be used as supplementary, complementary and subordinate tests to clinical bedside testing to identify central vestibular dysfunction or topographic mapping of vestibular lesions. Also, quantitative VFT may be more applicable to chronic vestibular symptoms or when quantitative information of central vestibular dysfunction is required.

There are several limitations of this narrative review. This type of review has a less systematic method approach with potential bias in selecting and reporting findings. However, given the complexity and broad research topic, a narrative review was proposed to present the overall patterns of findings and to provide a greater depth of the research topic to the clinicians. Given the limitations, broader and systematic search databases were used and only original research articles specific to the research topics were presented. This allowed comprehensive sources with a relevant and in-depth selection of articles to the study subject.

Most studies measured vestibular function during acute stroke. A study found that vertigo and nystagmus may be reduced within one week of stroke onset.[41] However, persistent unsteadiness or dizziness among recovering stroke patients, without known causes, may occur even months following stroke onset.[42] Future studies are required to quantify vestibular dysfunction among stroke patients to understand the progression or adaptation of vestibular disorders in stroke patients.

In summary, when a stroke involves the vestibular nucleus, both the upper and lower brainstem and cerebellum can produce various abnormalities during quantitative VFT. Thus, quantitative VFT can be used to complement bedside vestibular testing in identifying vestibular dysfunction among PCS patients. Future studies to investigate the prevalence of vestibular dysfunction in post-stroke patients are required.

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