Vestibular Assessment and Rehabilitation in the Operational Environment

Subjects: Otorhinolaryngology

Contributor: Carrie W. Hoppes, Karen H. Lambert, Susan L. Whitney, Isaac D. Erbele, Carlos R. Esquivel, Tony T. Yuan

The vestibular system, comprised of the semicircular canals, otolith organs, and eighth cranial nerves in the peripheral system, and the brainstem, brain, and cerebellum in the central system, is essential for gaze and postural stability. It allows service members to keep their eyes fixed on a target while their head is moving, and additionally contributes to the maintenance of balance. Evaluation of the vestibular system requires a systematic assessment of the visual, vestibular, and balance systems; technology can aid in this assessment. While technology can assist physical and occupational therapists in performing vestibular assessment and rehabilitation, not all such technologies are conducive to delivery of healthcare in an operational environment. In this context, the environment is characterized by the presence of extreme conditions and constrained resource availability.

Keywords: vestibular ; assessment ; rehabilitation

1. Introduction

The vestibular system, comprised of the semicircular canals, otolith organs, and eighth cranial nerves in the peripheral system, and the brainstem, brain, and cerebellum in the central system, is essential for gaze and postural stability. It allows service members to keep their eyes fixed on a target while their head is moving, and additionally contributes to the maintenance of balance. The vestibular system is especially important for balance under conditions where vision is obscured (e.g., smoke, darkness, use of night vision goggles) or the support surface is challenging or moving (e.g., walking over rocks and debris, standing in the turret of a military vehicle). This system can be damaged by threats on the battlefield, from blast waves [1] to directed energy technologies [2][3].

Akin et al. [4] reported that 5–57% of individuals with dizziness post-concussion are diagnosed with benign paroxysmal positional vertigo (BPPV). Weakness on caloric testing (a marker of horizontal semicircular and/or superior vestibular nerve dysfunction) occurred in 3–51% of individuals with dizziness post-concussion [4]. Ocular motor abnormalities (a marker of central nervous system dysfunction) occurred in ≤8% of individuals with dizziness post-concussion [4], though one study included in the review reported a frequency of 45% [5]. Dizziness and imbalance can occur as a result of blast exposure [6][7]. In individuals with dizziness and imbalance following blast exposure, the frequency of BPPV was 3–20% and the frequency of weakness on caloric testing was 0–40% [4]. The frequency of ocular motor abnormalities was 3–4% [4], though one study included in the review reported a frequency of 45% [8]. Dizziness and unsteadiness have also been reported by individuals exposed to a sound/pressure phenomenon in Havana, Cuba in 2016–2017 [2], colloquially referred to as “Havana Syndrome”. Regardless of the cause, physical and occupational therapists are well suited to evaluate and treat individuals with damage to the vestibular system who have body structure and function impairments, activity limitations, and/or participation restrictions [9].

Evaluation of the vestibular system requires a systematic assessment of the visual, vestibular, and balance systems. Technology can aid in the assessment of nystagmus (resulting from an imbalance of vestibular nuclei firing or abnormal stimulation of one or more semicircular canals). Video Frenzel goggles prevent visual fixation (which can mask nystagmus originating from the peripheral system) to allow the clinician to better visualize and quantify eye movements. Force plates, inertial measurement units (IMUs), and motion capture equipment can be used to measure kinematics of balance and gait. Similarly, vestibular rehabilitation can be delivered via smartphone- or tablet-based devices. Virtual reality systems and head-mounted devices can also be used to deliver or augment traditional vestibular rehabilitation [10]. Early vestibular rehabilitation may result in better outcomes [11].

While technology can assist physical and occupational therapists in performing vestibular assessment and rehabilitation, not all such technologies are conducive to delivery of healthcare in an operational environment. In this context, the environment is characterized by the presence of extreme conditions and constrained resource availability. Electrical power and internet may be unreliable or absent, the climate may be variable (with extremes in temperature), and clinical settings may lack level floors for the use of force plates. Dirt, dust, and moisture can have negative effects on electronic devices. Medical care may be constrained by limited time, large numbers of casualties, and security concerns. Medical assets may need to be rapidly maneuverable to remain close to service members engaged in combat, precluding use of large, heavy, and non-portable equipment. Access to specialty providers may be limited or non-existent.

2. Prevention

The prevention of vestibular injuries might be an overlooked topic, given the limited literature and available technologies, but could serve as a critical unmet need for military medicine. Although there is no conclusive evidence that helmets can prevent vestibular injury, it would stand to reason that they may afford some protection to the skull (the vestibular system is located in the petrous portion of the temporal bone of the skull) and brain. A systematic review on the effects of noise exposure on the vestibular system reported an association between noise over-exposure and vestibular dysfunction [12]. There is no conclusive evidence that hearing protection can prevent vestibular injury, but given the proximity of the cochlea and labyrinth, perhaps it may afford some protection. Hearing protection should be worn during all live-fire events to include combat [13]. However, wear of hearing protection while on patrol can be as low as 4% [14]. Jones and Pearson reported a decline in wear of hearing protection in at least one ear from 39% to 12% following a health promotion activity [15]. Reasons for non-use can include decreased situational awareness (interference with detecting and localizing auditory warnings), impaired communication (exchanging information and hearing verbal orders), and poor fit (devices were incompatible with other gear and/or difficult to fit) [16]. In addition to military personal protective equipment, there are several promising therapeutic approaches that might also afford some prevention of vestibular injury. Jiang et al. [17] conducted a review on protection of vestibular hair cells. Promising strategies for preventing loss or damage of vestibular hair cells include pharmacotherapy (such as induction of heat shock proteins, antioxidant treatments, use of antiapoptotic agents, use of insulin-like growth factor-1, use of other protective agents or molecules, or a combination of different drugs) or gene therapy [17].

3. Monitoring Exposure

Vartanian et al. [18] leveraged blast gauges (BlackBox Biometrics, LLC, Rochester, NY, USA) to record changes in overpressure and acceleration during breacher training exercises. Advanced technological devices have the potential to yield valuable data regarding blast exposures, while simultaneously serving as an early warning system to prompt medical providers to conduct injury screening when specific pre-defined thresholds are reached. For instance, when the green status light-emitting diodes change to yellow or red, this can be a visual indicator to the service member, unit personnel and leaders, and medical personnel that the service member should be removed from duty and screened for vestibular impairments post-blast. Blast exposure data could be correlated with qualitative and quantitative measurements of vestibular system function. Such devices may be leveraged for monitoring exposure to repetitive, low-level blasts as well. External sensors data from the Blast Gauge® System do not necessarily align with physiological symptoms or clinical outcomes. While Suttles [19] commented on the measurement of head impact severity using telemetry, these devices have low specificity in predicting concussion [20]. However, as technology continues to advance and direct relationships are drawn between exposure parameters and physiological responses, perhaps blast gauges and helmet-based sensors can mature to have greater clinical utility in the future.

4. Vestibular-Ocular Motor Evaluation

A thorough examination of the vestibular system should include the evaluation of eye movements (such as in response to positional testing) with fixation removed. Halmagyi et al. have deemed them “essential for any clinician dealing with dizzy patients” [21]. While the literature search did not find any articles leveraging video Frenzel goggles (video nystagmography [VNG]) in the operational environment, there are numerous companies that have developed goggles that could be used in an austere setting. Low-technology, low-cost options that can be carried in a uniform pocket or medical kit are also available [22][23][24].

Similarly, the video Head Impulse Test (vHIT) is becoming the standard of care for identifying an acute unilateral vestibulopathy [25]. Several companies have developed vHIT goggles, which enable the visualization of overt and covert saccades, as well as calculation of vestibular-ocular reflex (VOR) gain. Some vHIT goggles may also offer the Suppression Head Impulse (SHIMP) test [26], which may eliminate covert saccades for more precise measurement of VOR gain [27]. Parker et al. [28] developed a custom app that used an iPhone Xs (Apple, Inc., Cupertino, CA, USA) to perform the vHIT. While using a smartphone is novel, the collected data had to be manually postprocessed and analyzed.

Depending on operational security restrictions, smartphone-based assessment of the VOR may be possible in the operational environment, but automated data analysis and easy-to-interpret visualization of results would be critical. Kuroda et al. [29] developed a prototype iPhone-vHIT system that is inexpensive and portable, and may hold promise for testing in austere settings.

Both VNG and vHIT technologies are valuable in the operational environment to improve assessment, especially to determine the origin (whether the condition is peripheral or central) and urgency of the underlying condition. In an operational environment, the basic assessment can consist of a Head Impulse Nystagmus Test of Skew (HINTS) exam [30], which can include horizontal canal vHIT, and positional (Dix-Hallpike and Roll) tests for BPPV. The VNG and vHIT devices would need to be ruggedized to withstand extremes in temperature, as well as dirt, dust, and moisture. Battery back-up would be beneficial in an austere setting where electrical power may be unreliable or absent. Other technologies like caloric, ocular vestibular-evoked myogenic potential (VEMP), and rotary chair testing are not practical in austere environments.

While cervical VEMP, auditory brainstem response (ABR), and electrocochleography (ECoG) are not technologies for vestibular-ocular motor evaluation, they are often employed in hospital and research settings as part of an assessment battery. However, they are not practical in austere environments. Quantitative electroencephalogram (EEG), especially now that it can be portable, may have promise in aiding diagnosis of central vestibular disorders (e.g., concussion). Brown et al. [31] conducted a review of emerging techniques in sport-related concussion; they noted that use “depends on well-trained personnel to ensure quality data acquisition, and hands-on review to ensure that artifacts are identified and removed”. As EEG technology and algorithms continue to advance, perhaps it will have greater clinical utility in the future.

5. Assessment, Treatment and Monitoring Rehabilitation Progress

Gera et al. [32] and Martini et al. [33] leveraged IMUs (Opal; APDM Wearable Technologies, Inc., Portland, OR, USA) to instrument the modified Clinical Test of Sensory Integration and Balance. Inertial measurement units may reveal subtle qualities of movement that are imperceptible in the absence of such instrumentation, thereby enhancing the assessment and monitoring of rehabilitation progress. Several companies offer ruggedized IMUs that could be used for precision measurements in an operational environment. Ruggedized IMUs are designed to withstand harsh environments and extreme conditions, such as high shock and vibration, extremes in temperature, and exposure to dirt, dust, and moisture.

Patterson et al. [34] conducted a pilot study using the SWAY Balance Mobile Application (SWAY Medical, Tulsa, OK, USA) on an Apple iPod Touch (Apple Computer Inc., Cupertino, CA, USA). Dewan et al. [35] later explored use of the SWAY Balance™ Mobile Application (version 2.1.1, SWAY Medical, Tulsa, OK, USA) on a smartphone held with both hands against the chest to provide objective measurement of thoracic sway during a series of balance tasks. EQ Balance (Highmark Interactive Inc., Oakville, ON, Canada) also uses a smartphone held with both hands against the chest to provide objective measurement of performance during a series of balance tasks and offers remote monitoring of patient performance. These types of assessment and monitoring systems leverage the accelerometers, gyroscopes, and/or magnetometers contained in smartphones and tablets. Depending on operational security restrictions, smartphone-based assessment of postural sway may be possible in the operational environment. Their use for telemedicine may allow for remote assessment and delivery of balance rehabilitation. This may be especially helpful in an operational environment where access to specialty providers (e.g., physical therapists) may be limited or non-existent.

The Barany Society Classification OverSight Committee has not established specific diagnostic criteria for cervical dizziness [36]. Despite this, it is commonplace to evaluate cervical range of motion and joint position sense during the assessment of individuals with cervical dizziness. Bagaianu et al. [37] leveraged the Zebris CMS 20 (Zebris Medizinetechnik GmbH, Isny, Germany), configured using a helmet and a thoracic belt that were each fitted with three ultrasound microphones to determine three-dimensional head-on-body motion, to evaluate joint position sense. This device relies on the timing of the intervals between the emission and the reception of ultrasound pulses to measure distances to the microphones [37]. It can accurately and reliably measure cervical spine range of motion [38]. However, it is not known how the battlefield environment with its high intensity and/or impulse noise or other ambient noise might influence device usability. With regard to measurement of range of motion and joint position sense, a device such as the NeckCare™ System (NeckCare, Minneapolis, MN, USA) could allow for assessment of range of motion and joint position sense in an operational environment. Advanced technological devices, like the ones noted, can enhance the precision of clinical measurements for assessment and monitoring of rehabilitation progress, which could be critical in providing data for return-to-duty decisions.

Whitney et al. [39] developed VestAid (BlueHalo, Rockville, MD, USA), a tablet device that utilizes eye and facial recognition software to record head velocities and eye-gaze accuracy while patients perform gaze stability exercises. Their small case series demonstrates that advanced technological devices can enhance the precision of clinical measurements for assessment and monitoring of rehabilitation progress. A device such as the Bertec Vision Advantage (Bertec Corporation, Columbus, OH, USA) could allow for an assessment of the VOR using the Dynamic Visual Acuity and Gaze Stabilization Test paradigms in an operational environment.

Depending on operational security restrictions, smartphone-based assessment and rehabilitation may be possible in the operational environment. Noda et al. [40] conducted a scoping review on devices and apps for taking a patient history and recording subjective symptoms, objective testing, diagnosis, and treatment of vestibular dysfunction. Such devices and apps may be used for telemedicine, allowing for remote assessment and delivery of rehabilitation. This may be especially helpful in an operational environment where access to specialty providers (e.g., audiologists, otolaryngologists, and neurologists) may be limited or non-existent. Shah et al. [41] found that eye movements recorded using a smartphone camera during the Dix-Hallpike test could be remotely assessed by neuro-otologists. Young et al. [42] used custom-made lightweight swimming goggles with monocular infrared lights attached to an audio/video recorder (Dizzy-cam video goggles) for vision-blocked assessment of vertigo attacks. Even when receiving care in-person, Kıroğlu and Dağkıran found that patients who were able to record their eye movements using a smartphone camera were diagnosed with Meniere's disease sooner than those in a control group who did not record their eye movements (two attacks with a mean of 40 days in the video group and four attacks with a mean of 102 days in the control group, $p < 0.001$) [43].

Smartphone apps have also been developed for subjective visual vertical (SVV) testing (as an assessment of utricular function). Brodsky et al. found that a cutoff of >2.13° using the Visual Vertical (Clear Health Media, Wonga Park, Australia) app on an iPhone 5 (Apple, Cupertino, CA, USA) resulted in 66.7% sensitivity, 97.0% specificity, 80.0% positive predictive value, and 94.1% negative predictive value for detecting peripheral vestibular loss in pediatric patients [44]. Ulozienė et al. described the VIRVEST wearable virtual reality-based system for assessing SVV [45]. It consisted of a head-mounted display, Myo gesture control armband (Thalmic Labs Inc., Kitchener, ON, Canada) or general purpose gamepad (Red Samurai gamepad, GameStop Corp. Inc., Brampton, ON, Canada), and smartphone or tablet [45]. Similarly, Zabaneh et al. used a head-mounted display (C-SVV® goggles) and OtoAccess™ software to assess SVV in patients with Meniere's disease [46]. Zaleski-King et al. used a head-mounted display to assess SVV and the related Rod and Disk Test [47]. Given that the maculae of the otolith organs may be more vulnerable to pressure waves than the cristae of the semicircular canals [48], SVV may provide a quick injury screening when medical care is constrained by limited time or large numbers of casualties.

Meldrum et al. [49] developed a head-worn sensor and smartphone app for the delivery of vestibular rehabilitation (and they now also offer an associated clinician portal). The sensor (VG02; www.vertigenius.com accessed on 22 January 2024) uses an inertial measurement unit to measure the angular velocity of the head during gaze stabilization exercises [49]. A Bluetooth connection between the sensor and app allows the patient to receive real-time feedback on their exercise performance [49]. The Vertigenius device can enhance the precision of clinical measurements for assessment and monitoring of rehabilitation progress.

Nehrujee et al. [50] developed the VEstibular GAming System (VEGAS), consisting of a smartphone-based 3D virtual reality headset (Convergence VR Tech Labs Pvt. Ltd.) and two games for vestibular assessment and training. Serious games may encourage participation and adherence to the prescribed rehabilitation regimen; and game-based rewards for correct execution of gaze stability exercises may increase patient motivation and bolster performance. There are several smartphone applications that can be used with Google Cardboard (https://arvr.google.com/cardboard/ accessed on 22 January 2024) that could be utilized in austere environments, including VR Tunnel Race: Speed Rush VR (DTA Mobile, Cau Giay, Hanoi, Vietnam), VR XRacer: Racing VR Games (DTA Mobile, Cau Giay, Hanoi, Vietnam), VR RollerCoasters (VR Games Ltd.), and VR Escape Game (Blacksmith DoubleCircle).

6. Conclusions

While many technologies can assist physical and occupational therapists in performing vestibular assessment and rehabilitation, not all such devices are conducive to delivery of healthcare in an operational environment. Some technology is feasible for vestibular assessment and rehabilitation in an austere setting. There is untapped potential for leveraging such technology for prevention; vestibular-ocular motor evaluation; monitoring exposure to mechanisms of injury; assessment, treatment, and monitoring of rehabilitation progress after vestibular injury.

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