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Vestibular System Dysfunction and Clinical Interventions in Attention-Deficit/Hyperactivity Disorder (ADHD)

Zhiqing Ma *

Guangzhou Red Cross Hospital of Jinan University, Guangzhou, Guangdong, 510220, China
* **Corresponding author Email:** MASAYA2399@outlook.com

Abstract: This paper comprehensively summarizes existing objective research evidence on vestibular dysfunction in Attention Deficit Hyperactivity Disorder (ADHD), and systematically analyzes its clinical manifestations, impacts on cognitive impairment and clinical assessment approaches. Numerous clinical observations indicate that such patients commonly suffer from poor physical balance and disordered sensory information integration, accompanied by evident developmental lag of the visual-vestibular system compared with healthy peers. The decreased central inhibitory efficiency of vestibulo-ocular reflex serves as a crucial objective marker for cerebellar-vestibular damage. Vestibular deficits further impair patients' executive functions. It not only aggravates inherent behavioral abnormalities of ADHD, but also greatly elevates the risk of comorbidities including learning disabilities and dyslexia. Objective detection techniques such as cervical vestibular evoked myogenic potential, functional head impulse test and eye tracking can precisely reflect vestibular function. Acting as reliable physiological assessment indicators, these methods effectively overcome the drawbacks of conventional subjective behavioral diagnosis. Cerebellovestibular dysfunction and abnormal sensory integration are distinctive objective physiological characteristics of certain ADHD subtypes. Long-term follow-up studies are still required to clarify the independent pathological correlation between vestibular impairment and comorbid disorders. Rigorous randomized controlled trials should also be conducted to establish standardized non-pharmacological intervention and treatment protocols.

Keywords: Attention-Deficit/Hyperactivity Disorder (ADHD); Vestibular Dysfunction; Postural Control; Vestibulo-Ocular Reflex (VOR); Sensory Integration.

1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a common clinical neurodevelopmental disorder characterized by core clinical manifestations of inattention, hyperactivity, and impulsivity. Traditional studies have mostly explained its pathogenesis from the perspective of behavioral and cognitive deficits, while increasing evidence in recent years indicates that abnormal sensory processing and regulation play an important role in the pathophysiology of ADHD[1]. Multiple studies have confirmed that the degree of sensory modulation abnormalities in children with ADHD is significantly higher than that in normally developing peers of the same age, and such functional impairments are highly positively correlated with psychopathological indicators[2].More critically, alterations in basic sensory integration function can ultimately induce the characteristic behavioral manifestations of ADHD by mediating executive function impairment[3].

The vestibular system serves as the core component of the human sensory integration network. Its primary physiological function is to perceive head movements relative to gravity in real time, so as to maintain posture regulation, physical balance and spatial orientation capability. Beyond basic balance adjustment, the vestibular neural network establishes extensive and intricate neural connections with visuomotor control, particularly the interaction between visual and vestibular systems, as well as high-level cognitive brain functions[4]. Accurate and timely processing of vestibular information is an essential prerequisite for spatial perception, motor planning and attention allocation[5].Accordingly, dysfunction of vestibular pathways disrupts the integration of somatosensory and visual inputs, and further triggers a range of structural and functional adverse impacts on motor coordination and cognitive performance[2].Growing studies have verified remarkable overlaps at the neurobiological level between vestibular signal processing pathways and neurodevelopmental defects of Attention Deficit Hyperactivity Disorder (ADHD). Nevertheless, the inherent correlation between them has not been systematically clarified. Against this research backdrop, this review summarizes published domestic and overseas evidence concerning vestibular dysfunction among ADHD patients. It mainly illustrates objective clinical manifestations of vestibular damage including postural instability and abnormal vestibulo-ocular reflex (VOR), as well as their secondary adverse effects on patients' cognitive function and academic performance[5]. Meanwhile, this paper sorts out the application status of conventional objective clinical assessment methods such as cervical vestibular evoked myogenic potential (cVEMP) and functional head impulse test (fHIT), and comprehensively evaluates the clinical efficacy of diverse interventions including vestibular physical stimulation and medication therapy.[6].

2. Manifestations and Characteristics of Vestibular System Dysfunction in ADHD Patients

2.1. Deficits in Posture and Upright Balance Control

Existing literature consistently shows that children with ADHD generally exhibit decreased body stability and abnormal sensory integration function, objectively manifested as functional deficits in the three major systems of vision, somatosensation, and vestibular. Multiple case-control studies have confirmed that balance dysfunction is significantly correlated with the severity of clinical symptoms, abnormal behavioral manifestations, and cognitive impairment in patients[7]. Among them, children with combined-type ADHD (ADHD-C) show significantly reduced upright balance ability under all test conditions [8].

Human upright balance maintenance depends on the dynamic integration of visual, somatosensory, and vestibular afferent signals by the central nervous system. When input signals from a sensory pathway are disturbed, children with ADHD-C exhibit abnormal compensatory regulation patterns. Studies have shown that compared with the somatosensory and vestibular systems, the visual system occupies an abnormally dominant position in the balance control of children with ADHD-C, which is the core factor leading to their balance function deficits[9].

There are significant differences in postural control ability among patients with different ADHD subtypes. Compared with normal controls, male children with ADHD as a whole have impaired visual and vestibular information processing functions, which in turn leads to decreased static postural control ability. Notably, male children with predominantly inattentive ADHD (ADHD-I) exhibit the most severe deficits in static postural control and vestibular function when processing conflicting sensory information[10].such physiological abnormalities are considered important pathological mechanisms leading to their characteristic clinical manifestations and cognitive impairment [11].

Vestibular and sensorimotor function deficits are not limited to the childhood developmental stage. Studies on adult ADHD have shown that adult patients also have motor function impairment centered on postural instability, mainly manifested as long-term persistent decline in sensorimotor behavioral stability[12].This lifelong abnormality in postural and sensorimotor control is highly pathologically consistent with the core clinical features of impulsivity and hyperactivity in ADHD[13].

2.2. Abnormalities in Visual-Vestibular Interaction and the Oculomotor System

In normally developing male children aged 7-14 years, the saccadic, antisaccadic, and visual-vestibular interaction systems are in a continuous maturation process. Comparative studies have found that the developmental trajectories of the oculomotor system and visual-vestibular interaction system in male children with ADHD of the same age are significantly delayed compared with normal children [14]. This developmental delay has obvious age specificity, with the most significant functional difference between the two groups at the age of 11-12 years[15].

The vestibular system maintains visual stability during head movement primarily through the vestibulo-ocular reflex. Rotational test results show that children with combined-type ADHD have significantly higher VOR gain than normal children, along with significantly reduced visual fixation suppression ability[16]. Since VOR gain is mediated by the inferior olivary nucleus and regulated by cerebellar circuits, high VOR gain combined with failed fixation suppression indicates central regulatory and inhibitory deficits in vestibular function in patients[17].This abnormality is usually associated with structural or functional damage to the cerebellar midline region, providing direct objective physiological evidence for vestibular system dysfunction in children with combined-type ADHD[18].

2.3. Sensory Processing and Modulation Dysfunctions

Physiological and Behavioral Characteristics of Sensory Modulation Dysfunction (SMD)

Multiple objective physiological tests and parent-reported assessment results have confirmed that the degree of sensory regulation dysfunction in children with ADHD is significantly higher than that in normally developing children, manifested as significantly increased variability in physiological responses to sensory stimuli. In the ADHD patient population, the severity of sensory modulation dysfunction is highly positively correlated with psychopathological scores on the Child Behavior Checklist (CBCL)[19].

By analyzing the score distribution characteristics of the Sensory Integration and Praxis Tests, the strengths and weaknesses of patients' sensory processing abilities can be identified[20]Studies have found that patients with ADHD perform relatively normally in non-motor visual perception and tactile localization, but have significant deficits in vestibular information processing and most motor ability domains[21]. Among all subtests of the SIPT, the "Spatial Visualization" subtest has the highest discriminative efficiency between patients with ADHD and the normal population[22].

3. Secondary Impacts of Vestibular Dysfunction on Cognitive, Behavioral, and Academic Performance

Sensory system deficits and core ADHD symptoms do not have a simple parallel relationship but form an intrinsic causal connection through higher-order cognitive processes[6]. Studies have shown that abnormal changes in basic sensory integration function are essentially linked to executive function impairment. In this pathological pathway, executive function plays a key mediating variable role: basic sensory integration disorders first lead to executive function impairment, which in turn induces the characteristic overt behavioral manifestations of ADHD. This mechanism provides an important neurobiological perspective for explaining how basic sensory function abnormalities cascade to cause complex behavioral symptoms[3].

Vestibular deficits significantly affect patients' academic abilities, and are particularly closely related to the occurrence and development of learning disabilities and reading disorders[21].Among school-age male children with learning difficulties, reading disorders, inattention, and vestibular dysfunction, vestibular system lesions directly impair the spatial perception ability necessary for reading acquisition[23]. In addition, abnormally elevated vestibulo-ocular reflex (VOR) gain and decreased central inhibitory ability (such as failed fixation suppression) are highly correlated with academic difficulties both theoretically and practically[3].These specific vestibular impairments directly trigger dyslexia, general poor learning ability, as well as concomitant symptoms such as dizziness and motion sickness in children with ADHD[6].

The visual perception of ADHD patients is markedly modulated by concurrent sensory processing abnormalities[14].Among children diagnosed with ADHD, those complicated with sensory processing disorder (SPD) exhibit notably weaker visual perception compared with unaffected counterparts. The deterioration of visual perception is closely associated with overall sensory processing function, and interacts particularly with physiological responses triggered by vestibular and proprioceptive inputs. Such interplay between vestibular dysfunction and visual perception indicates that the impact of abnormal sensory processing shall be fully taken into account when evaluating academic performance and visuospatial deficits in children with ADHD[21].

4. Objective Clinical Assessment Methods for Vestibular Dysfunction in ADHD

Cervical vestibular evoked myogenic potential (cVEMP) serves as a vital neurophysiological indicator for vestibular function evaluation[24]. Relevant studies adopting cVEMP have verified obvious abnormalities in vestibular brainstem reflexes among children with certain ADHD subtypes. Combined application of cVEMP and rotary chair test can objectively identify vestibular damage, characterized by increased vestibulo-ocular reflex (VOR) gain and declined visual fixation capacity. Given that such examinations can detect physiological anomalies overlooked by behavioral assessment, cVEMP reflex test is highly recommended to be incorporated into routine clinical evaluation of ADHD patients.

Functional head impulse test (fHIT) is an advanced clinical detection tool. It quantitatively assesses the overall vestibular function by analyzing functional responses of vestibulo-ocular reflex (VOR). Existing researches have proven its practical value in assessing children suffering from neurodevelopmental disorders (NDDs) including ADHD [25]. Preliminary evidence suggests that there are abnormal changes in the working efficiency of the vestibular system in this population. Therefore, VOR function abnormality indicators obtained through fHIT testing can serve as surrogate markers for neurodevelopmental disorder-related impairments, and are expected to become potential objective biomarkers for early identification and disease monitoring of ADHD[26].

The combined application of fHIT with complex environmental assessment protocols can further improve its diagnostic efficiency. By evaluating the effects of optokinetic stimulation and dual-task execution on VOR function, comprehensive data on both vestibular function status and cognitive function levels in children with ADHD can be obtained simultaneously[27].This methodological improvement has important clinical practice significance: traditional ADHD diagnosis is highly dependent on subjective clinical judgment and behavioral reports, while fHIT combined with the dual-task paradigm provides a completely objective and highly reliable alternative assessment method [4].

Eye tracking technology has unique and precise clinical value in assessing the core symptom of ADHD — distractibility. This technology can continuously record and analyze eye movement trajectories when subjects are exposed to task-irrelevant distracting stimuli, thereby enabling direct quantification of the attention allocation process[10].The application of eye tracking technology in distraction paradigms can reveal the underlying pathological mechanisms of abnormal attentional processes, providing measurable objective physiological correlates for the clinical symptom of "inattention" [15].

5. Conclusion

Attention Deficit Hyperactivity Disorder (ADHD) ranks among the most prevalent neurodevelopmental disorders in children and adolescents. Its core clinical manifestations include persistent age-inappropriate inattention, hyperactivity and impulsive behaviors. For a long time, academic research mainly focused on behavioral anomalies and cognitive deficits. Nevertheless, accumulating evidence over the past decade has proven that abnormal sensory processing and modulation exert a pivotal influence on the pathophysiological progression of ADHD. Clinical statistics indicate that children with ADHD suffer from more severe sensory modulation disorders than healthy peers. The severity of such abnormalities is significantly positively correlated with psychopathological indicators including hyperactivity, impulsivity and poor concentration. Deficiencies in fundamental sensory integration impair executive functions, which further trigger typical behavioral symptoms of ADHD.

As the central hub of human sensory integration network, the vestibular system undertakes basic physiological functions such as posture maintenance, physical balance and spatial orientation. It also establishes intricate neural connections with visuomotor regulation system and advanced cognitive regions governing memory, attention and decision-making. Vestibular dysfunction disrupts the integration of multisensory inputs from vision, audition and somatosensation, thereby exerting widespread adverse effects on motor coordination and cognitive performance.

Against this research backdrop, this review summarizes domestic and overseas published studies on vestibular dysfunction in ADHD patients, and elaborates its clinical symptoms, secondary impacts on cognition and behaviors, as well as conventional objective clinical assessment methods. Existing research reveals that vestibular abnormalities in ADHD patients are reflected in three typical aspects. The first refers to deficits in posture and upright balance control. Most children with ADHD exhibit reduced physical stability in daily activities and clinical tests, manifested as frequent falls, unsteady gait and difficulty maintaining static standing posture. Children with combined-type ADHD show evident balance decline under all testing conditions regardless of visual state and movement patterns. They excessively rely on visual cues to compensate vestibular insufficiency, making the visual system play an abnormally dominant role in balance regulation. Children with predominantly inattentive-type ADHD present distinctive vestibular impairments. Their balance function deteriorates most drastically when coping with conflicting multisensory information, accompanied by severe vestibular damage. These impairments hardly alleviate naturally with aging and often persist into adulthood, showing strong correlation with the severity of core ADHD symptoms such as inattention and impulsivity.

The second aspect covers developmental abnormalities in visual-vestibular interaction and oculomotor system. Relevant studies on male pediatric patients demonstrate that oculomotor development of children aged 7 to 14 with ADHD lags far behind that of healthy counterparts, and the developmental gap reaches its peak between 11 and 12 years old.

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