MILD TRAUMATIC BRAIN INJURY AND CONCUSSION IN INFANTS, CHILDREN, AND ADOLESCENTS

An Evidence-Based Clinical Guide

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FOREWORD

Mild Traumatic Brain Injury and Concussion in Infants, Children, and Adolescents: An Evidence-Based Clinical Guide provides important information and insights for speech-language pathologists (SLPs) about the field of acquired brain injury (ABI) across the pediatric lifespan. Over the past decades, the field of traumatic brain injury (TBI) and ABI has undergone a specific transformation driven by research and the needs of individuals who experience these injuries.

In 1985, Dr. Mark Ylvisaker and I wrote the first book on TBI in children, titled *Head Injury Rehabilitation: Children and Adolescents*, which provided developmental evidence on how to help children recover from TBI, as research on the effects of TBI in children was nonexistent. Dr. Paul T. Fogle provides a book that offers evidence-based information on the background, diagnosis, treatment, and outcomes of brain injuries in children and adolescents. The book focuses on cognitive-communication issues and rehabilitation, which aligns with the work SLPs do with patients. TBIs and ABIs are unexpected events whose effects can change the lives of not only the child but also the family. These can include effects on cognition, memory, attention, cognitive-communication, behavior, and executive functions that can limit a child's participation in family and community activities and at school.

Over the past 10 to 20 years, pediatric TBI has become a major area of interest and a specialty among some speech-language pathologists and other medical and rehabilitation specialists, particularly those who work with concussion. SLPs who work in most any setting need to become very knowledgeable about pediatric TBI. Although the injuries are acute, functional deficits from mild TBI may cause chronic burdens on the children, their families, and health-care systems. TBI can change the core of a person's being—their thinking, memory, personality, and behavior (Chan et al., 2024).

Children who experience TBI are likely to have special healthcare needs and activity limitations that can affect their learning, participation, and social skills over their development into adulthood. Currently, children have the highest rate of brain injuries in the United States, with up to 90% being mild TBI, which supports the need for evaluation and treatment. However, care for children with mild TBI in healthcare and educational systems is not well coordinated or integrated, resulting in inadequate service delivery and increased risk for poor outcomes. Potential solutions include identifying at-risk children following mild TBI, evaluating their need for rehabilitation and transitional services, and improving utilization of educational services that support children across the lifespan (Haarbauer-Krupa et al., 2017).

The main themes of this book include and cover the pediatric age span, including infants, school-age children, and adolescents,

including late adolescents: background and foundational information on mild TBI and concussion in children; differences in injury severity and signs and symptoms of mild TBI and concussion; understanding the effects of mild TBI and concussion; evidence-based evaluation of mild TBI and concussion; recovery and outcomes following mild TBI and concussion; evidence-based evaluation and assessment of mild TBI and concussion; and evidence-based treatment of mild TBI and concussion. In every chapter, Dr. Fogle presents an up-to-date literature review and describes current developments in diagnosis and treatment, including research on the effects of mild TBI and outcomes in children. He also discusses the importance of a child's family and living environment.

After an ABI, the most prevalent communication impairments are cognitive-communication disorders, with incidence rates ranging from 75% to 100% (O'Brien et al., 2022). Acquired cognitive-communication disorders in children and adolescents have not received enough attention in courses on language and learning disorders at either the undergraduate or graduate levels (Ciccia et al., 2021). SLPs and audiologists working in community hospitals, children's hospitals, university hospitals, Veterans Administration (VA) hospitals, outpatient clinics, rehabilitation centers, trauma centers, university training clinics, schools, and private practices are seeing young people with mild TBI perhaps more than ever before. In most cases, the child had a normally functioning brain before the injury.

Dr. Fogle has a strong academic and real-life background in TBI across all ages, not just as an SLP, but also from 3 years as an ambulance EMT in Southern California and as an Army Combat Medic in Vietnam in 1969. He has seen and worked with children and adolescents from the moment of injury through discharge from rehabilitation. He has been an SLP for over 55 years in clinical, academic, and research areas. He was a university professor for 35 years, teaching courses in anatomy and physiology, neurology, neuropathologies in adults and children, motor speech disorders, dysphagia and swallowing disorders, cerebral palsy, gerontology, voice disorders, cleft lip and palate, and counseling skills for SLPs. He has a strong background and practical experience in speech-language pathology, and his book will make a significant contribution to the field.

The book's important contributions include providing in-depth, up-to-date, evidence-based information on the effects of TBI in infants, children, and adolescents, as well as on the assessment and treatment of TBI and concussion. This textbook can be used at both the undergraduate and graduate levels in courses on language disorders in children and neurological disorders to teach future SLPs how to understand, evaluate, and provide treatment for pediatric mild TBI and concussion.

Over the past 45 years, I have worked clinically with individuals living with mild TBI and concussion and have done extensive research in the field. I highly recommend using this book for students and practicing clinicians to help them understand the complexities of pediatric mild TBI and concussion, and how to provide assessments, treatment, and accommodations for this underserved population. Dr. Fogle's book, the first book written for SLPs on pediatric mild TBI and concussion, has my strongest recommendation.

—Juliet Haarbauer-Krupa, PhD,
FACRM, CCC-SLP

PREFACE

This book is, as far as I know, the first book written on the subject of infants, children, and adolescents with mild traumatic brain injury (concussion) by a speech-language pathologist. Although some physicians have written books on this topic, their work has tended to emphasize the medical perspective (diagnosis and discharge instructions) rather than the rehabilitation perspective (assessment, treatment, and monitoring).

The first book written by speech-language pathologists on theory, assessment, and treatment of children and adolescents with TBI was Dr. Mark Ylvisaker and Dr. Juliet Haarbauer-Krupa's 1985 text, *Head Injury Rehabilitation: Children and Adolescents*. Dr. Ylvisaker followed his first edition with a second edition in 1998. Both editions had numerous well-known researchers, authors, and clinicians as chapter contributors. However, there was no chapter or index entry for either mild traumatic brain injury or concussion, although there was excellent information on many related topics. This required the reader to glean out information that may be specifically relevant to mild TBI and concussion.

SLPs Dr. Roberta DePompei and Dr. Jean L. Blosser published their first edition of *Pediatric Traumatic Brain Injury: Proactive Intervention* in 1994, followed by a second edition in 2002, and a third edition in 2019. As with Dr. Ylvisaker's texts, there was no chapter devoted to mild TBI and concussion, although there are scattered references in the index that include the terms mild TBI or concussion.

These books became the foundational information for our profession (and other professions, I am certain) for knowledge about the underserved population of children and adolescents with TBIs. However, these books did not have a focus on mild TBI and concussion, which account for 70% to 90% of all TBIs (Arbabi et al., 2020), and there was relatively little information about infants and preschool children with TBIs or concussions.

During a 1971 internship at Rancho Los Amigos National Rehabilitation Center in Downey, California, I trained under Dr. Chris Hagen, the developer of the Rancho Los Amigos Levels of Cognitive Functioning Scale (Rancho Scale). I also trained once a week for 3 years under Dr. Abraham Lu, a neuropathologist, doing human brain autopsies.

My first job after my MA was working for the Los Angeles County Office of Education in what was then called an aphasia classroom. I had the first combined junior and senior high school classroom for children and adolescents with TBIs. In those days, the terms "cognition" and "cognitive" were barely in our professional vocabulary. My aphasia classroom was mostly comprised of students with TBIs. For example, Janelle (all names are changed) was 13 years old when she heard an unusual noise in her garage one evening and

went to investigate. There, she was assaulted by a burglar who hit her over the head with a baseball bat. Mike was also 13 when he hit his head on a tree while sledding in the snow. Azzie was a 16-year-old adolescent and an excellent basketball player. While he was walking home one evening after a game, someone drove by and shot him in the head. Before being transferred into my classroom, every student had been placed in special education classes for children with developmental delays. My classroom was the first to focus on language and cognition (as we understood it in the early 1970s). Over the past 55+ years, I have continued working with children, adolescents, and adults of all ages with TBIs and other neurological disorders.

I was a university professor for 35 years, supervising in the department clinic and teaching graduate courses in neurology and neuropathology, motor speech disorders, swallowing disorders, and counseling skills for SLPs, among other courses. I have also maintained a private practice since 1980, working with children and adults of all ages with a variety of disorders and severities. I have always considered myself more of a therapist than a theorist, and that has been reflected in my teaching and writing.

This book was written for professors who teach undergraduate and graduate courses on language disorders in children, as well as professors who teach neurological disorders in children and adults. It was written equally for therapists who work in all settings—acute and subacute hospitals, rehabilitation centers and clinics, schools, and private practices with infants and preschool children—and for therapists working with all kinds of clients, from students in elementary school, high school, and college (late adolescents) to those who are no longer in educational systems.

If you, as an SLP in schools, or even in hospitals, rehabilitation centers, clinics, or private practices, do not feel well prepared in the area of pediatric mild TBI and concussion, take heart; you are not alone. Most training programs do not teach students to any level of competence and confidence about this important and common level of TBI.

This book is divided into two units, with Unit I focusing on foundational information on TBI in infants, children, and adolescents. Chapter 1 gives an overview of TBI in children. Some readers may be surprised to learn that pediatric TBI is a high-incidence and high-prevalence medical, rehabilitation, educational, and family issue in the United States (and probably many other countries), with the vast majority of the affected children and adolescents having mild TBIs. The incidence is particularly high with those of lower socioeconomic status, those (particularly young girls) who have experienced domestic violence, nonbinary and transgender youths, youths in the criminal justice system, young Indigenous people in the United States and other countries, refugees and asylum seekers, and trafficked children and adolescents. There are numerous mechanisms (causes) of pediatric TBI, and there are numerous federal and state acts and laws regarding students with TBIs.

Chapter 2 discusses the signs and symptoms of pediatric TBI. The chapter begins with a review of cognition and common cognitive-communication symptoms in infants, children, and adolescents. Often, when there is a TBI, there are receptive and expressive language disorders, some related to cognitive impairments and others not necessarily related. There are also learning disabilities, sensory impairments, effects on school readiness, educational achievement, and employability. Victimization and bullying are common when a child has had a TBI, and a disproportionate number of incarcerated juveniles have had TBIs.

Unit II focuses entirely on mild TBI and concussion, and you will find interesting case studies in each of the chapters. Chapter 3 discusses the scope of the problem of concus-

sions in infants through late adolescents. A few of the many definitions of concussions are presented, along with information on the incidence of pediatric concussions and the pathophysiology of concussion. Subconcussions needed to be discussed before sports-related concussions. There is a discussion of the severity of concussions because not all concussions are equal. Extensive information is provided on the signs and symptoms of concussions in infants, toddlers, and preschool children. This is followed by postconcussive cognitive-communication impairments in children through late adolescence. Clinical subtypes of mild TBI are discussed, as well as persistent postconcussion symptoms and other concussion-related symptoms.

Chapter 4 adds depth of information about mild TBI for each of the several age groups: (a) infants, toddlers, and preschool children; (b) elementary school children; and (c) middle school children, high school adolescents, and late adolescents. Legislation addressing concussion in school-age children is presented. The role of SLPs with children and adolescents with concussions is discussed.

Chapter 5 presents information on recovery and outcomes from mild TBI for each age group discussed in Chapter 4. Persistent symptoms after concussion are discussed, as well as second impact syndrome and chronic traumatic encephalopathy. There is also a discussion of how concussions are misrepresented and erroneously portrayed in the media, including "seeing stars."

Chapter 6 presents evidence-based evaluation and assessment of mild TBI in children and adolescents. It begins with discussions of evaluation and treatment patterns of concussion among physicians in emergency departments, primary care, and urgent care clinics for preschool children through adolescents. This is followed by SLPs' evidence-based screening for mild TBI in preschool through high school students, including an alphabetical list of published screening tools and brief assessments discussed in the literature. (Note: The eBook includes an extensive annotated list of over 280 screening and assessment tools that are discussed in the literature on pediatric TBI.) Evidence-based assessments of elementary age through late adolescence are discussed, including interviewing techniques and test selection. There are discussions of the numerous areas that SLPs assess, including cognition, attention, memory, processing speed, social cognition and social communication, theory of mind, discourse, executive functions, gist reasoning, and adaptive functioning. Each assessment area includes an alphabetical list of numerous tests in the mild TBI and concussion literature for clinicians to choose from.

Chapter 7 begins with an overview of evidence-based treatment of mild TBI by SLPs. The Centers for Disease Control and Prevention (CDC) Guidelines on the Diagnosis and Management of Mild Traumatic Brain Injury, as they relate to preschool through elementary school, are discussed. This is followed by the CDC's guidelines for middle- and high-school-age children and adolescents. The American Speech-Language-Hearing Association (ASHA) 2017 Clinical Practice Guideline: Cognitive Rehabilitation for the Management of Cognitive Dysfunction Associated with Acquired Brain Injury is reviewed with application to adolescents. Sheila MacDonald has permitted me to include her 2017 Model of Cognitive-Communication Competence to Guide Evidence-Based Communication Interventions in its entirety in this book. Other published guidelines and treatment approaches that apply to mild TBI from well-known authors include the *Personalized Dynamic Approach for the Management of Prolonged Concussion Symptoms* (J. Wright & Sohlberg, 2021), *Target Principles of Cognitive Rehabilitation in a Functional Context* (Sohlberg & Turkstra, 2011), *Proactive Intervention*

for Pediatric Brain Injury (DePompei & Blosser, 2019), *Cognitive Symptom Management Rehabilitation Program* (CogSMART; Twamley et al., 2014), *Guidelines for Cognitive Rehabilitation Following Traumatic Brain Injury: Methods, Overview, and Principles* (Bayley et al., 2023), and *The Rehabilitation Treatment Specification System* (Hart et al., 2019; Sohlberg et al., 2023). There are also discussions of restorative and compensatory approaches, holistic approaches, errorless learning, metacognitive strategy instruction, executive function treatment, and interventions for impaired social cognition. The chapter ends with MacDonald's Life Integration Approach.

Chapter 8 discusses potential therapeutic approaches and considerations for preschool children with concussions—focusing first on parents, then on children—which provide some direction for clinicians when counseling. For parents, there are several examples of hospitals' emergency department postdischarge instructions to help them manage their child during the early days of recovery. This is followed by examples of evidence-based treatment approaches for elementary and middle school students who have sustained a concussion. The final part of the chapter presents the application of evidence-based treatment for concussion in high school through late adolescence.

This book should be considered a tool in the clinician's repertoire of resources for mild TBI and concussion. The book is scholarly, with more than 2,000 references and countless citations in each chapter. There are specific texts referenced in the chapters that are highly recommended for clinicians to obtain, including Sohlberg, Hamilton, and Turkstra's 2023 *Transforming Cognitive Rehabilitation: Effective Instructional Methods*, and DePompei and Blosser's 2019 *Pediatric Traumatic Brain Injury: Proactive Intervention*.

Because most SLPs were not provided with substantial information or training on pediatric mild TBI and concussion in graduate school, they need to educate themselves on this important topic. They also need to make themselves available to be on return-to-school (return-to-learn) teams.

Over the past ten decades (more than 100 years) of our profession, we have added areas of needed expertise, including language, cognition, and swallowing. The newest area of focus is on pediatric mild TBI and concussion. There is much to learn about this important topic to better serve children, adolescents, and their families.

- Requires more days of rest before returning to normal activities.

- **Grade III (Severe)**
  - Any loss of consciousness.
  - Can be further categorized as:
    - **IIIa:** Loss of consciousness measured in seconds.
    - **IIIb:** Loss of consciousness measured in minutes.
  - Amnesia can last 24 hours or longer.
  - Other symptoms can include severe headache, vision issues, prolonged vomiting, and loss of coordination.
  - Carries the highest risk for long-term symptoms or permanent brain damage.

World Health Organization

The WHO Centre Task Force on Mild Traumatic Brain Injury (Carroll et al., 2004) defined mild TBI as acute damage to the brain resulting from an external force, with the operational criteria for clinical identification including:

1. One or more of the following: confusion or disorientation, LOC for 30 min or less, posttraumatic amnesia for less than 24 hours, and other transient neurological abnormalities such as focal signs, seizure, and intracranial lesion not requiring surgery.
2. Glasgow Coma Scale score of 13 to 15 after 30 min postinjury or later on presentation for health care.
3. Manifestations of mild TBI must not be due to drugs, alcohol, or medications; caused by other injuries or treatment for other injuries (e.g., systemic injuries, facial injuries, or intubation); caused by other problems (e.g., psychological trauma, language barrier, or coexisting medical conditions), or caused by penetrating craniocerebral injury (p. 115).

Incidence of Pediatric Mild Traumatic Brain Injury and Concussion

The true incidence and prevalence of mild TBI are likely to be vastly underestimated, particularly in low-resource countries, owing to underreporting and lack of formal care. Reporting of mild TBI is further complicated by incomplete data, regional variations in injury definitions and documentation, and limited access to health care. Pediatric mild TBI is a significant global health burden and demands a multifaceted, child-centered response (Agrawal et al., 2026).

Ingram et al. (2025) conducted a systematic review and meta-analysis of the incidence of sports-related concussions in children and adolescents across different sport types, ages, and years, and in numerous countries. The investigators concluded that collision sports such as rugby, American football, and ice hockey put youth athletes at a much higher risk of concussion than sports with lower levels of contact, and concussion incidence is markedly higher during competition than in practice. There are high rates of concussions in contact sports, with player-to-player contact most common, but head-to-ground contact is also significant. Rugby and ice hockey have the highest rates of concussions, but American football has highest number of concussions overall because of the number of children and adolescents who play the sport. Approximately 45% of the concussions in

children 5 to 7 years old were sports-related, compared with about 65% in children 8 to 12 years old.

In the United States, 70% to 90% of the 1.7 million annual TBIs are classified as concussions (Arbabi et al., 2020). Arbogast et al. (2016) reported that in a large urban healthcare network, over 80% of children seeking care for a concussion had their initial visit at a pediatrician's office rather than at a hospital. Hospital-based administrative data sets do not include visits made to pediatricians' offices. It is estimated that 62 million individuals sustain mild TBIs annually worldwide and perhaps as many as 6 to 8 million individuals in the United States per year, most of whom are never formally medically diagnosed (Dewan et al., 2018). Concussions among youth account for about 85% of the nearly 700,000 emergency department visits annually in the United States (C. A. Taylor et al., 2017). Even if only a small proportion of children and adolescents with mild TBI suffer adverse outcomes, this is a major public health problem (Choe et al., 2016).

Two populations that are considered high risk for mild TBI and concussion are athletes who play in high-impact sports and the military personnel, specifically those in combat. (*Note:* In 2024, approximately 15% of military personnel were under 21 years of age, with the Army having the largest number of individuals under 21 [Statista, 2026].) Similarities between the high-risk mild TBI and the general mild TBI populations are becoming increasingly apparent. For example, concerns about repetitive mild TBIs are not limited to athletes in high-impact sports such as football and boxing but also to individuals in the general population who have sustained repetitive concussions for a variety of reasons (Isaki, 2021).

J. N. Sturm et al. (2026) surveyed nearly 2,000 children and adolescents, 13 to 17 years old, from the general German population with a history of concussion. More than half (about 60%) of children and up to about 65% of adolescents were classified as impaired despite not having experienced a TBI. The researchers concluded that their data suggest that concussion symptoms are not exclusively TBI-specific.

Although most research on children with mild TBI is on adolescents and the sequelae of sports-related injuries, more than one third of concussions in this age group are caused by other factors (e.g., being struck by an object, being assaulted, or being in a motor vehicle accident). However, only about 20% of concussions sustained by children 0 to 4 years old are sports-related, compared with greater proportions for older children (about 65% for ages 5–11, about 75% for ages 12–14, and about 75% for ages 15–17; Haarbauer-Krupa, Arbogast, et al., 2018).

An extensive study of nearly 9,000 children between 5 and 18 years old was conducted in Australia and New Zealand. The children and adolescents presented at emergency departments with GCS scores of 13 to 15 less than 24 hours postinjury, with no abnormalities on CT scans if performed, and one or more signs or symptoms of concussion. Sports-related concussions accounted for about 45% of all concussions, meaning that over half of the concussions were caused by MVCs, falls, altercations, and other mechanisms. With the increasing age of the children, there was an increase in the sports-related concussion rate; that is, about 20% for 5- to 8-year-olds, about 50% for 9- to 12-year-olds, and about 65% for 13- to 18-year-olds. The most common acute symptoms of postinjury were headache (about 65%), disorientation (about 35%), amnesia and memory problems (about 30%), and vomiting (about 30%). Loss of consciousness increased with increasing age, with about 10%, about 20%,

and about 35%, respectively. Symptom profiles were broadly similar between males and females (Bable et al., 2021).

From 2001 to 2005, U.S. children 8 to 19 years old had an estimated 500,000 emergency department visits for concussions. Approximately half of all emergency department visits for concussions were sports-related (Rausa et al., 2024). Omalu (2018, p. 30) stated that every blow to the head has the potential to cause brain damage—a subconcussion, concussion, or worse. The absence of symptoms does not mean brain damage has not occurred.

A U.S. Consumer Product Safety Commission investigation through its National Electronic Injury System reported about 455,000 sports-related head injuries were treated at U.S. hospital emergency departments in 2018. The actual incidence of head injuries may potentially be much higher. The following sports and recreational activities represent the top 10 sports-related head injury categories among children aged 14 and younger:



- Skateboards: ≈3,000
- Powered recreational vehicles (e.g., bicycles, scooters): ≈6,000
- Trampolines: ≈8,000
- Swimming: ≈9,000
- Baseball and softball: ≈12,000
- Soccer: ≈13,000
- Basketball: ≈20,000
- Cycling: ≈20,000
- Football: ≈30,000
- Playground equipment: ≈35,000

The 2024 ASHA Schools Survey (ASHA, 2024) reported that the median caseload size for elementary school SLPs was 51 students per week, and 50 students per week for secondary schools. Approximately 14% of SLPs regularly serve students with acquired brain injury, with about 2 (1.8) as the mean number of students regularly served. About 50% of clinicians also reported that they serve students with cognitive-communication disorders (commonly related to concussions), with about 10.5 as the mean number of students regularly served.



The "invisible" nature of mild TBI, notably the lack of any external physical evidence of head or brain damage, was an important factor in the earlier impression of its inconsequentiality. However, with the combination of recreation, sport, and military personnel concussions in children, adolescents, and late adolescents being at the forefront of many people's awareness, there is increasing research into this neurological impairment and its numerous effects (Hallock et al., 2023). Concussion is now a relatively frequent topic of conversation in homes, schools, and on television. It has become a significant focus of sports programs in communities and schools at all levels. As of 2017, all 50 states and the District of Columbia had enacted laws (Potteiger et al., 2018) and the National Collegiate Athletic Association had adopted rules to protect athletes (Mullally, 2017). However, concussions in all children need to be taken just as seriously as those in student athletes (Halstead et al., 2018).

Arbogast et al. (2016) reported that research on concussions has been limited primarily to those who are high school age or older, participate in organized sports, and are treated in emergency departments. There was a significant increase in overall emergency department visits for TBI among children 0 to 17 years old from 2006 to 2013. Approximately 85% of emergency department visits for children with TBI are for mild TBIs, about 15% are for moderate TBI, and 2% are for moderate to severe TBI (CDC, n.d.-c). The increase in emergency department visits for pediatric mild TBI may be, in part, the result

of increased knowledge and awareness among parents, coaches, athletic trainers, and others about concussions (Corwin et al., 2017). (Note: The *Archives of Physical Medicine and Rehabilitation* published "Concussion Recognition: A Guide for Parents and Coaches" [Connolly et al., 2026]).

Pathophysiology of Concussion

A concussion causes a shock wave (pressure wave) in the brain. When the head is struck or experiences sudden deceleration, the brain can move within the skull and collide with its inner walls. This impact can create a shock wave that propagates through the brain tissue. The shock wave's effects are not limited to the point of impact. The shock wave can be reflected and refracted by the skull and brain structures, causing damage in various areas. The more severe the impact, the greater the shock wave, which affects more brain regions. (Much like a bullet: The greater the speed of the bullet, the greater the shock wave it creates.) Even minor concussions can result in widespread neuronal death where negative pressure waves coincide, pulling apart and damaging cellular structures, thereby increasing the complexity of cellular pathophysiology (Al Mahmud et al., 2022; Espindola et al., 2017).

The pathophysiology of concussion is involved and complex and can occur in just an instant. Pathophysiology involves excessive neurotransmitter release, metabolic changes, neuroinflammation, alterations in cerebral blood flow, and axonal disruption. The initial biomechanical impact of a concussion results in abnormal cellular function, which initiates a cascade of events that may lead to permanent microstructural changes (Howell & Southard, 2021; Steenerson & Starling, 2017). In TBI, changes occur at the ion level of atoms in cell bodies, axons, dendrites, and synapses. (An ion is an atom with a net electric charge due to the loss or gain of one or more electrons.) Immediately after biomechanical injury to the brain, there is an abrupt, indiscriminate release of neurotransmitters and unchecked ionic changes (Giza & Hovda, 2014).

When a concussion occurs, the brain rapidly repairs ionic imbalances caused by neurochemical miscommunication. The healing process requires increased glucose availability and adequate blood flow. A healthy brain closely regulates cerebral blood flow with a set of vasoconstrictive substances, but mild TBI compromises the process.

Cost of Mild Traumatic Brain Injury in the United States

In a study of mild TBI in the United States that used insurance claims data to assess health care utilization and costs, the average follow-up care per patient for mild TBI in 2016 dollars was about $13,500 (about $18,100 in 2025 dollars; Pavlov et al., 2019). Estimates of the economic burden of mild TBI, as reported by the CDC in 2006, were $16.7 billion (about $26.7 billion in 2025 dollars; Rutland-Brown et al., 2006). However, indirect costs of mild TBI cannot be calculated (e.g., loss of a parent's wages from missing work to care for a child or adolescent, nonprescription medications for pain or other symptoms, loss of a student's full-time equivalent [FTE] funding from the state or county, loss of a student's part-time or full-time wages, and so on).

Dysregulation of the baseline cerebral blood flow and the increased demand for glucose widen the energy gap, which could contribute to fatigue symptoms following a concussion. Numerous neurometabolic effects cascade following TBI (Howell & Southard, 2021; Iverson et al., 2015). Mild TBI also alters autonomic nervous system function; consequently, blood pressure, heart rate, and other autonomic-regulated processes may be affected by concussion (Pertab et al., 2018).

Biomarkers of Mild Traumatic Brain Injury

There is growing evidence that mild TBI triggers complex biological changes, including abnormalities in neurons, inflammation, cerebrospinal fluid, metabolism, blood (plasma), vasculature, microvasculature, and axons. Regardless of whether the brain undergoes acceleration or deceleration (a sudden speeding up or slowing down) of the head, the result is a collision of the brain against the inside of the skull.

Fluid-based biomarkers have drawn increased attention as objective measures for diagnosing and managing pediatric mild TBI (Hossain et al., 2022; Mannix et al., 2020). Blood biomarkers have revealed relationships to subconcussions and concussions, as well as their effects on brain functioning, including cognition (Palacios et al., 2020; Zuidema et al., 2023). Blood proteins may serve as a helpful guide in determining whether athletes can return to play after sustaining a concussion (Pattinson et al., 2020).

Woodpecker Brains

For decades, scientists and engineers wondered why woodpeckers do not have brain injuries (concussions). Mike O'Connor (2007) authored the book ***Why Don't Woodpeckers Get Headaches?***, based on a question a sixth grader asked him. As a woodpecker's beak drills into wood, it creates a force in the range of 1,000 gs, 10 times higher than the 80 to 100 gs that football players may experience that can cause a concussion. Woodpeckers may forcefully peck about 10,000 times a day and up to 20 times a second, with a single impact of a peck lasting only milliseconds, with the nonimpact time lasting longer than the impact time.

Woodpeckers' skulls are spongier than those of humans, which means impacts are absorbed more effectively. Woodpeckers also have hyoid bones that differ significantly from those in humans. The hyoid bone of a woodpecker extends from the back of the mouth all the way around the skull and ends between the eyes (somewhat heart-shaped), which provides extra protection for the skull in an impact. Their neck muscles are also extremely strong, helping diffuse the blows. The bird's brain is positioned differently in the skull than a human's, which helps more evenly distribute the forces of an impact.

Using scaling laws, a woodpecker's brain is eight times smaller than a human's brain. The brain has very little cerebrospinal fluid and is more tightly packed in the skull, which reduces the brain's motion within the skull on impact and the effects of shock waves transmitted through the brain. However, the main reason woodpeckers do not get concussions is simple physics: They are very lightweight, and the force applied to their brains is much less than that of a heavier human head (about 10 pounds) hitting a tree.