Journal of Neurotrauma
39:1133–1145 (September 2022)

DOI: 10.1089/neu.2022.0103

Journal of Neurotrauma

Open camera or QR reader and scan code to access this article and other resources online.

REVIEW

Military Traumatic Brain Injury: The History, Impact, and Future

Megan A. Lindberg,[1,2,*] Elisabeth M. Moy Martin,[1] and Donald W. Marion[1,3]

Abstract
This review examines how lessons learned from United States military conflicts, beginning with the United States Civil War through the engagements in Iraq and Afghanistan, have shaped current traumatic brain injury (TBI) care in the United States military, influenced congressional mandates and directives, and led to best practices in caring for the warfighter. Prior to the most recent war, emphasis was placed on improving the surgical and medical care of service members (SM) with severe and especially penetrating brain injuries. However, during the Iraq and Afghanistan conflicts, also known as the Global War on Terrorism (GWOT), blast injury from improvised explosive devices most often caused mild TBI (mTBI), an injury that was not always recognized and was labelled the "signature wound" of the GWOT. This has led to extensive research on objective diagnostic technologies for mTBI, the association of mTBI with post-traumatic stress disorder (PTSD), and the long term consequences of mTBI. Here we summarize the key findings and most important advances from those efforts, and discuss the way forward regarding future military conflicts.

Keywords: Department of Defense; history; service members; traumatic brain injury

Introduction

Soon after the terrorist attacks on September 11, 2001, the United States and its allies began military operations in Afghanistan and Iraq, which collectively became known as the Global War on Terrorism (GWOT) 2001–2021. Since October 2001, > 1,600,000 United States military service members (SM) have deployed to Iraq and Afghanistan. It is estimated that between 5% and 35% of them sustained a concussion, also called mild traumatic brain injury (mTBI), during their deployment. It is important to note that the United States military and Veterans Affairs (VA) consider mTBI and concussion to be the same, as directed by the Department of Defense Instruction (DoDI) 6490.11.[1] Up to 80% of the concussions experienced in theater were secondary to blast exposures.[2] Although cerebral edema and prolonged cerebral vasospasm are observed with a variety of TBI mechanisms, these features may be more prominent with blast TBI (bTBI).[3] Some studies suggest that diffuse axonal injury (DAI) seen following explosive blast exposure is different than DAI from focal impact injury.[4]

Important lessons have been learned by physicians in the theaters of war, particularly regarding the response to mass casualties, blast and fragmentation injuries, and resuscitation of casualties in austere environments. The evolution of a streamlined trauma system in the war zone, the introduction of an in-theater institutional review board process, and dedicated personnel to collect combat casualty data have resulted in improved data capture and real-time, in-theater research opportunities. This review is intended to put into context the lessons learned from GWOT regarding the evaluation and acute care of SMs

[1]Traumatic Brain Injury Center of Excellence, Silver Spring, Maryland, USA.
[2]Credence Management Solutions, LLC, Vienna, Virginia, USA.
[3]General Dynamics Information Technology, Fairfax, Virginia, USA.

*Address correspondence to: *Megan A. Lindberg, BS, Traumatic Brain Injury Center of Excellence, 1335 Easy West Highway, Silver Spring, MD 20910, USA E-mail:* megan.a.lindberg.ctr@mail.mil

with TBI, and how those lessons have evolved since the United States Civil War—the earliest conflict with clear documentation of battlefield TBI care.

United States Civil War 1861–1865

The United States Civil War was the first United States conflict to extensively document war injuries. A comprehensive six-volume medical book titled *Medical and Surgical History of the War of the Rebellion, 1861-1865* detailed wartime medical activities and healthcare conditions encountered by Civil War physicians and surgeons.[5] The book highlights case studies of various injuries sustained from the Civil War, including brain injuries.

The Civil War was a 4-year conflict between the United States and 11 Southern states, and was the largest and most destructive conflict before World War I (WWI). Mortality rates were staggering. Among the 2,400,000 soldiers involved, ~752,000–851,000 deaths occurred.[6] Technological advances such as the Minie ball and shrapnel-filled explosive shells changed the distribution and severity of injuries from those previously seen.[7] The low-velocity, soft lead bullets promoted sepsis, as they carried large pieces of clothing into the wound and were prone to lodge deep within tissues.[8] Ninety-four percent of all injuries were caused by gunshot wounds. Gunshot wounds to the head were common, with fatalities <70%, and survival was poor as a result of infection.[9] Cranial wounds were classified as incised and puncture wounds, blunt injuries, and gunshot wounds. There were few treatment options during this time and infection rates were high, as antibiotics did not become widely available until WWI. Treatment primarily involved the superficial debridement of gunshot wounds, and the key principles were finding the bullet, controlling the bleeding, and preventing further brain injury.[10] For intracranial injuries, the goal was to safely remove all splintered bone fragments and bullet remnants that were easily accessible to the surgeon without causing more neurological injury. Fragments and foreign objects were commonly left behind if they were too deep to access. For extracranial injuries, it was important to remove all bone fragments along with the bullet to prevent infection and allow for proper healing. Physicians had limited experience with battlefield trauma, and there were long delays between the time of injury and surgery.[10] Surgical procedures were often performed outdoors, without gloves or disinfectant. William Keen, who some consider to be the first brain surgeon in the United States, gave the following description of conditions during surgery: ''Our hands were, as a rule, as clean as those of a gentleman but were never disinfected. The patient's skin was similarly clean or cleansed but not disinfected. Our instruments, from germ-gathering velvet lined cases, were laid out on a table and not disinfected.''[11]

There were several accomplishments that came from the Civil War, including the treatment of open wounds.[12] It became standard practice to leave superficial wounds open to heal by granulation, which is still done today. Pocket manuals were introduced to educate physicians on medical problems encountered in war.[13] Many of these provided detailed approaches to brain surgery. One of the more prominent pocket manuals was written by Samuel David Gross. He was known as a forefather in surgery, and his two-volume work, *A System of Surgery, Pathological, Diagnostic, Therapeutic and Operative (1861)* became a standard reference book during the second half of the nineteenth century. In addition, the establishment of an ambulance corps created a coordinated system of casualty evacuation from the point of injury back through the division rear. This organized system of battlefield evacuation led to the establishment of division field hospitals as part of the evacuation chain.[14]

Spanish-American War 1898

The Spanish–American War lasted <8 months (April 21, 1898–December 10, 1898). Although it was a brief conflict and yielded few casualties, it led to important advances that impacted military medicine.[15] Lessons learned from outbreaks of typhoid fever were how epidemic diseases spread, and an increased awareness of bacteria leading to better sanitation techniques.[15] In 1867, shortly after the Civil War ended, British surgeon Joseph Lister introduced antisepsis to surgery. This discovery significantly reduced the incidence of post-operative infections.[16] In contrast to during the Civil War, surgeons began to carefully wash their hands prior to surgery, sterilize their surgical instruments, and otherwise adhere to antiseptic techniques.[8]

Radiographs were also introduced during the Spanish–American War, which helped localize bullets and other foreign bodies, and reduced the risk of neurological injury from digital probing of penetrating cerebral wounds.[8,12] However, radiographs did not become incorporated into field hospitals at the front lines until WWI.

***Correction added** on July 21, 2022 after first online publication of June 3, 2022: The year 1897 was inadvertently indicated as the year of the Spanish-American War. The correct year is 1898. This has been corrected.

WWI 1914–1918

Trench warfare was common during WWI and resulted in the head and upper body being a frequent target for snipers.[17] Compared with in earlier wars, the muzzle velocity of rifles was moderately faster, and the bullets were smaller and much less deformable, allowing easy penetration of the skull without producing shock waves and cavitation in the brain.[18] Helmets were used, but gave insufficient protection to the back of the head, and many soldiers sustained and survived occipital bullet wounds. Those wounds to the occipital lobes of the brain were often fairly discrete lesions and prompted studies of the visual pathways by a number of investigators.[19] Gordon Holmes, a British neurologist, created a retinotopic map of the visual cortex from studying >400 cases of occipital injuries, and his work laid the foundation for understanding visual processing.[19]

Most of the deaths from brain injuries in WWI that did not occur on the battlefield were caused by infection.[20] Recognizing this, improved principles of penetrating head trauma management were established by Harvey Cushing.[21] He advocated radical debridement of the scalp and skull and aggressive irrigation of wound tracks to remove foreign bodies. He advocated a water-tight dural closure, even if that meant using a fascial graft. As a result of these practices, Cushing documented a decrease in his operative mortality from 54.5% to 28.8% for the first 133 casualties with penetrating cranial wounds that he operated on.[7]

An Italian military surgeon, Lorenzo Bonomo, promoted the use of pre-operative radiographs, writing that two radiographic images (lateral and frontal) were required to properly localize a foreign body in the cranial cavity.[17] However, he is perhaps most famous for his detailed post-mortem descriptions of penetrating injuries: ''Shots at very close-range turn cerebral substance into mush. Bullet shrapnel, bone splinters and hair are commonly found within the trajectory wound, outwardly, towards the exit wound. These severe explosive effects on the cranium can be observed when the shot is fired through modern war rifles from within a 500 meters range. Beyond that range, cerebral damage is less acute. When a shot is fired from within a 1200 meters range, the cranium presents perforations and sometimes short, sometimes long radial fractures.''[17]

Trinitrotoluene, a strong explosive, was first incorporated into artillery shells in 1902 and was widely used during WWI. During battles, soldiers endured frequent bombing from these high-energy artillery shells, with the shockwaves likely magnified by the trenches. Many of the troops exposed to these explosions developed severe headaches, balance problems, confusion, and other symptoms. Initially this cluster of symptoms was referred to as ''NYDN (Not Yet Diagnosed, Neurologic),'' and later as ''neurasthenia,'' or ''shell shock.''[22] After repeated exposures, soldiers typically presented with persistent headache, amnesia, inability to concentrate, difficulty sleeping, and mood disturbance, including periods of depression and despondency, and suicide was not uncommon.[22] Although shell shock was never formally accepted as a medical definition, cases increased during the war and many soldiers required inpatient hospital stays for evaluation. Shell shock was then described as a functional disorder, related to emotional trauma and repression of memories that compromised a patients' ability to adapt to stresses of combat. This later became the accepted etiology that led to the psychiatry specialty emerging from neurology.[22]

World War II (WWII) 1939–1945

Neurosurgeons were initially ill prepared for the acute care of casualties at the start of World War II (WWII), and those who were deployed to Europe had to bring their own instruments and equipment.[12] Before 1942, the army did not have a neurosurgical ward in the United States and had very little neurosurgical equipment.[20] At that time, there were ~200 fully trained neurosurgeons in the United States. Soon after the start of the war, a 4–7 month training program was created to train young general surgeons in neurosurgical techniques. These surgeons were placed in forward hospitals to reduce the time from injury to surgery. In May of 1942, the first army neurosurgical center was set up at Walter Reed General Hospital.[20] Roy Spurling formed the first neurosurgical service at Walter Reed, and his direction of the neurosurgical service during World War II has been described as among his most important achievements.[23]

By 1944, 19 military neurosurgical centers staffed by 88 neurosurgeons had been established.[7] Donald Matson headed a neurosurgical team with the 3rd Auxiliary Surgical Group, and his performance with this group was so outstanding that, at the age of 30, he was asked to write the monographs on head and spinal injuries caused by missiles for the surgeon general of the United States Army.[24]

Antiseptic techniques, and antibiotics such as sulfonamides and penicillin, were widely used and significantly reduced infections and mortality.[7,25] Aggressive debridement for penetrating craniocerebral injuries, as had been recommended by Cushing, was reintroduced.[26] Local anesthesia using a field block allowed for emergency cranial surgery in less than ideal conditions.[27] Penetrating injuries were common, and aggressive debridement of the surrounding skull fragments left many patients with large and unsightly skull defects. Cranioplasty using tantalum, a malleable metal that was biologically inert to acid and oxidative stresses, was introduced, and facilitated a single-stage cosmetic repair of those cranial defects.[28] Tantalum became the preferred cranioplasty material for >1000 procedures performed during WWII.[29,30] In addition to the cosmetic benefit of restoring the normal contour of the skull, the insertion of the plate would often relieve post-traumatic headaches, although not the risk of seizures.[25]

Other innovations that came from WWII were redesigned helmets, mobile neurosurgical units near battle zones, and the military use of penicillin.[31,32] Before the United States had joined the war, the Infantry Board initiated a quest to find a better helmet design. A visor and skirt-like extensions were added to protect the back and sides of the skull, and a suspension system and adjustable liner elevated the helmet from the head.[18] Twenty-two million of these helmets were produced.

During the early years of WWII, exercise-based programs for motor difficulties were the only TBI rehabilitation available, while those with cognitive or behavioral impairments were sent to mental institutions.[9] Mortality from brain wounds dropped to $\sim$12%, which meant more casualties in need of rehabilitation. Rehabilitation in the United States military was later expanded into an integrated, comprehensive multidisciplinary program, largely because of the efforts of Howard Rusk.[19] In 1943, Rusk established the first Air Force rehabilitation center for airmen who had sustained physical and psychological injuries.[19] During the remainder of the war, 12 similar centers were opened by the air force and later across all of the armed services.[18,19] In 1943, a speech disorder unit was established at Brooke General Hospital Fort Sam Houston, which included a multidisciplinary treatment program of physical therapy, physiotherapy, vocational therapy, and occupational therapy, and by 1945, there were 13 more similar units.[9] After the war, Rusk persuaded President Truman to give an official position to rehabilitation medicine within the military and Veterans Administration.[19]

Korean War 1950–1953

The Korean War occurred when the United States military was downsizing. Following WWII, medical departments were understaffed,[33] and when the United States entered the war, there were only 156 medical corps officers in the Eighth Army. The need for medical providers led physicians to be prematurely pulled from training programs and put directly into combat. A national blood banking system was developed and included a highly organized blood-transfusion service that provided banked blood obtained in the United States and flown to Tokyo, and then to Korea, within 7 days.[33–35]

There were significant advances that impacted organization and guidelines for neurosurgical management of TBI.[33] It was recognized that the key to reducing mortality was the rapid evacuation of intracranial hematomas, and division level mobile teams were deployed to provide neurosurgical intervention very early after closed and penetrating head injuries.[36] This was facilitated by the creation of Mobile Army Surgical Hospitals (MASH).[33–35] Mobile Army Surgical Hospitals (MASH) units were positioned within close proximity of the forward battle locations in order to get the casualty to neurosurgical care as quickly as possible. The first MASH neurosurgical team performed 126 craniotomies in 26 days. The standard practice included removal of all bone fragments, hair, blood, and nonviable brain, followed by a watertight closure of the dura.[33,37] If postoperative radiographs revealed retained bullet or bone fragments, the patient underwent additional operations to remove them.[7] Wallace and Meirowsky described 540 consecutive penetrating injuries for which the dural defect was closed with a graft using fascia lata from the thigh, and reported only 30 cases of new infection following surgery.[37]

It is debatable whether the travel time to definitive care was effected by helicopter transportation during this time.[33,38] Mechanical and personnel issues and technology constraints limited helicopters' effectiveness and kept them grounded. In addition, military policy prohibited rescues from the front line. Most of the missions involved interhospital transfers. As a result, helicopters did not appreciably decrease the average time from injury to surgical care, and were not used for the evacuation of a significant number of casualties.[38] Psychiatric interventions conducted near the battlefield allowed casualties to return to duty (RTD), whereas earlier in the conflict, they would have been evacuated and rarely returned to duty.[33]

Vietnam War 1968–1974

One of the key observations during the Vietnam War was that most direct gunshot wounds to the head were lethal. Carey et al. observed that bullet wounds to the head were more frequently fatal than shrapnel wounds, clinically significant intracranial blood clots were not commonly associated with penetrating injuries, and the helmets used during that war did not offer protection against bullets.[39] In one of his series, Carey et al. noted that 77 of 89 consecutive SMs with penetrating cranial wounds operated on in 1 year were from shrapnel fragments and not from bullets.[40]

A major advancement during the Vietnam War was improved protocols for the evacuation and triage of large numbers of casualties. Helicopters were widely available for casualty evacuation and made a significant difference in time from injury to the operating room. For example, during WWI, it typically took 12–18 h to get a casualty to the operating room, but during the Vietnam War, definitive surgical care was often available within 1.5–2 h.[41] The increased speed of evacuation and surgical care led to a significant reduction in mortality rates, which declined from 4.7% in WWII, to 2% during the Korean War, and finally to 1% during the Vietnam War.[7]

As with previous wars, the use of aggressive procedures for thorough surgical debridement of penetrating brain injuries near the war front was advocated.[42] Type-specific or O-positive low titer whole blood was available for resuscitation and during surgery.[43] Those with penetrating head wounds typically had three-dimensional skull films taken, and then a craniotomy within 90 min of injury.[41] A water-tight dural closure and re-operation for retained metal and bone fragments were standard, and the early use of mannitol was common.[7] In a study of 37 SMs from the Vietnam War with infected craniocerebral trauma, brain abscesses were most often observed 2–3 weeks following injury, and were typically attributed to incomplete debridement of the intracranial wound associated with retained bone fragments.[26]

Additional achievements included improvements in the management of brain abscesses, use of antibiotics and anticonvulsants, and the development of diagnostic criteria for PTSD.[42] Diagnostic criteria for PTSD was added to the third edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM),[22] which was greatly influenced by the experiences and conditions of the SMs from the Vietnam War.

The Vietnam Head Injury Study (VHIS) was a longitudinal study conducted to gather long-term data on penetrating TBI.[42] It enrolled and followed 1221 Vietnam veterans 40 years post-injury and beyond, and was conducted in four phases focusing on long-term clinical, neuropsychological, and genetic characteristics. The study found that penetrating TBI significantly increased the risk for post-traumatic epilepsy (PTE) and cognitive impairment, which may not present until decades later.[42] It also led to the establishment of several government programs for TBI including the Defense and Veterans Head Injury Program (DVHIP), which is now known as the Traumatic Brain Injury Center of Excellence (TBICoE) under the Defense Health Agency (DHA). The DVHIP was formed as a collaborative effort between the DoD, the VA, the Brain Injury Association of America (BIAA), and the International Brain Injury Association (IBIA). At that time, this inter-agency program was primarily focused on post-acute treatment and rehabilitation, with a disease management system integrating education, prevention, clinical care, follow-up, and research programs.[44]

GWOT 2001–2021

Blast injuries were the predominant mechanism of injury during the GWOT, and approximately two thirds of army war zone evacuations were for blast.[45,46] Penetrating brain injuries occurred in only 12% of 433 SMs with TBI who were evacuated to Walter Reed Army Medical Center (WRAMC) early in the GWOT.[47] However, even among those with penetrating brain injuries, ~70% of these injuries were caused by blast shrapnel and only 30% were from gunshot wounds.[48] Improvements in protective equipment resulted in increased survival from blast injuries, but also in more SMs with blast-related brain injuries.[46] During the last two decades, blast-related TBI has become the most common type of brain injury in the military, and extensive federal resources have been expended to better understand and treat this injury. A standardized system-wide approach to the evidence-based management of TBI patients has been codified and disseminated through the VA and DoD Clinical Practice Guidelines.[49]

A timeline documenting some of the most significant advances over the past 20 years is shown in Figure 1. This figure highlights key TBI-focused events within the DoD and VA, and congressional laws and mandates (e.g., DODIs, mandates for screening and assessments, clinical recommendations, and guideline developments).

GWOT: Neurosurgical advances

Since the end of the Vietnam War, computed tomography (CT) and magnetic resonance imaging (MRI) technologies have been introduced and refined. The availability of CT scanners in far-forward military treatment facilities (MTF) enabled the precise characterization of intracranial injuries and skull fractures close to the point of injury, allowing neurosurgical interventions to be better informed and more effective. In the post-acute period, MRI and endovascular technology have provided key information about subtle brain and vascular injuries. Decompressive craniectomy, cerebral angiography, transcranial Doppler (TCD) imaging, and hypertonic resuscitation fluids were introduced and widely used in the GWOT.[50] Decompressive craniectomy was introduced as a ''damage-control'' procedure—injuries that in previous conflicts would have been considered lethal were aggressively decompressed at a far-forward Combat Support Hospital (CSH) and patients were then transferred to Walter Reed National Military Medical Center (WRNMMC) (formally known as WRAMC) for definitive care. [51–53] Between April 2003 and October 2008, a total of 188 decompressive craniectomies were performed within hours after injury (154 for penetrating head injury, 22 for closed head injury, and 12 for unknown injury mechanism) and then transferred to WRNMMC.[54] Timing of the craniectomy appeared to make a difference, and in one study of 213 SMs who underwent the procedure, post-operative mortality was significantly lower when craniectomy was initiated within 5.33 h of injury than when surgery was performed later.[55] As would be expected, the presence of neurosurgeons in far-forward MTFs also led to improved outcomes.[56] However, large decompressive craniectomies, particularly those involving perinasal sinuses and the skull base, have presented significant challenges for reconstruction surgery and cranioplasty.

The acute and subacute study of the cerebral vasculature with angiography and Doppler imaging has revealed that severe blast injury can cause pseudoaneurysms and vasospasm, leading to delayed neurological deterioration.[50] In one study of 90 TBI patients admitted to the neurosurgery service of WRNMMC who underwent daily TCD studies, 12% were found to have severe vasospasm.[57] Contemporary neurosurgical training often includes experience with endovascular procedures, and during the GWOT, military neurosurgeons, and radiologists successfully applied those endovascular skills to

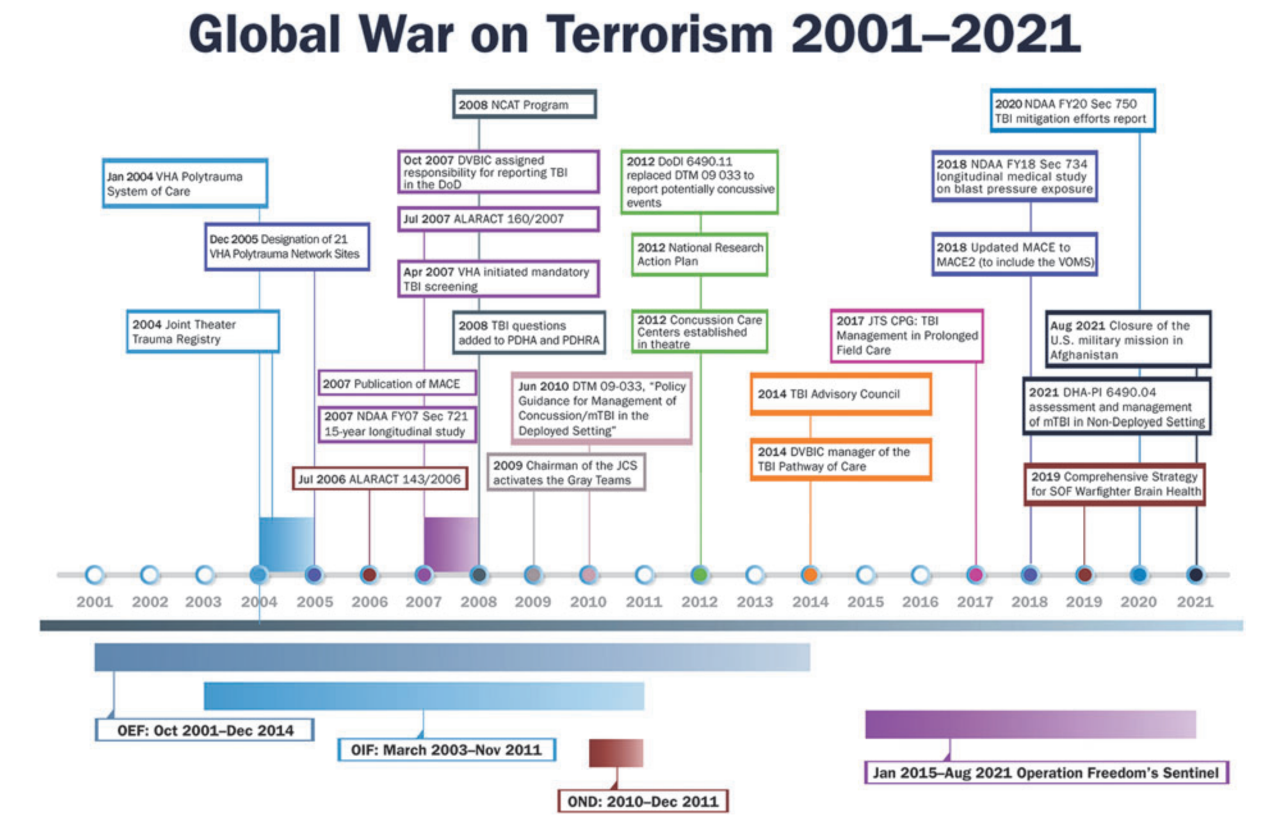

FIG. 1. Global War on Terrorism 2001–2021 timeline. VHA, Veterans Health Administration; MACE, Military Acute Concussion Evaluation; NDAA, National Defense Authorization Act, ALARACT, All Army Activities; NCAT, neuro-cognitive assessment testing; DVBIC, Defense and Veterans Brain Injury Center; PDHA, Post Deployment Health Assessment; PDHRA, Post-Deployment Health Reassessment; JCS, Joint Chiefs of Staff; DTM, directive-type memorandum; DoDI,Department of Defense Instruction; JTS, Joint Trauma System; CPG, Clinical Practice Guideline; VOMS, Vestibular Ocular Motor Screening; DHA-PI, Defense Health Agency-Procedural Instructions, SOF, special operating forces; OEF, Operation Enduring Freedom; OIF, Operation Iraqi Freedom, OND, Operation New Dawn.

the treatment of blast-induced pseudoaneurysms, carotid-cavernous fistulas, and vasospasm, both at WRNMMC and at far-forward MTFs.[58–60]

GWOT: Changes within the TBI landscape

During the early years of GWOT, retired United States Army General Surgeon John Holcomb observed a critical disconnection between communication on the ground and trauma care facilities. He pioneered the development of a trauma care system, which resulted in the Joint Trauma System (JTS) and the DoD Trauma Registry.[61] Today, the JTS focuses on all components of trauma care from prevention to acute care, rehabilitation and RTD, and supports combat casualty care conferences and multiple other programs to educate and train military providers. With the influx of complex combat-related injuries and mTBI, the need for more specialized medical care and comprehensive rehabilitation for returning SMs became paramount. In 2005, the United States Congress allocated funding to the VA to establish the Polytrauma System of Care.[62] This program is designed to balance access with specialized expertise in TBI, and is made up of four components: polytrauma rehabilitation centers, polytrauma network sites, polytrauma support clinic teams, and polytrauma points of contact. Today, the Polytrauma System of Care stretches across the United States with widespread access throughout the country.[63]

Blast injury research within the DoD began to increase by 2003, peaking near 2008. Between 2007 and 2008, Congress allocated > \$600,000,000 in funding for TBI and PTSD research.[64,65] Almost half (42.6%) of all blast injury research was composed of TBI-related research during this time.[64] In 2006, the DoD Directive 6025.21E was issued by the secretary of the army to establish policies and responsibilities for medical research on the prevention, mitigation, and treatment of blast injuries.[65] The same year, Congress passed the National Defense Authorization Act (NDAA) for fiscal year 2007 (Public Law 109-364), which called for a 15-year, longitudinal study of TBI incurred by veterans of Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF). The NDAA also established a 15-member panel of experts to develop a family caregiver curriculum (FCC) to assist caregivers with the challenges of caring for SMs with disabilities related to moderate and severe TBIs. The TBI-CoE is the office of responsibility for conducting the 15-year projects (providing periodic reports to Congress) as well as producing the Family Caregiver Curriculum. Table 1 summarizes the key NDAAs from the last 20 years, and their impact on the Military Health System (MHS).

During the first 5–10 years of GWOT there was increasing concern that a higher frequency of mTBIs were occurring, but were unrecognized by first responders or command. Blast appeared to cause ''invisible'' injuries that left SMs with headaches, sleep problems, and PTSD. There was additional concern that failure to recognize blast-induced mTBI might risk SMs returning to duty too soon and sustaining more TBIs before fully recovering from the first. Suicide rates were increasing, and during 1 year it was observed that more SMs died from suicide than from enemy assaults.

The DoD introduced numerous policies between 2006 and 2010 to increase concussion screening of SMs on the battlefield, in-theater neurological testing, and TBI reporting and tracking.[66] The All Army Activities

Table 1. National Defense Authorization Act (NDAA) Requirements Related to TBI and PTSD, 2001–2022

Fiscal Year	*Section*	*Description*
2001	732	Teleradiology demonstration project; hub and spoke concept, CONUS
2005	723	Study of mental health services; focus on improving mental healthcare
2005	734; 738	Medical care and tracking and health surveillance in the AOR; mandated medical record- keeping
2006	721, 722	PTSD programs; designed for early diagnosis and treatment
2006	735	AHLTA; a single EHR across the services
2007	721	15-year study of TBI
2007	735; 741	Mental health task force; PTSD projects; look at specific needs of those deployed to OIF/OEF
2007	744	Family caregiver guide for TBI patients
2008	708	TRICARE payment for mental healthcare
2009	725	Conduct basic science and translational research on TBI to test efficacy of clinical approaches, including pharmacological agents
2009	733	Suicide task force
2010	711	Comprehensive policy on pain management
2010	714	Increase DoD mental health capabilities
2010	723	Clinical trial on cognitive rehabilitative therapy for military veterans with TBI
2010	726	Study of PTSD
2011	722	Comprehensive policy on consistent neurological cognitive assessments of SMs before and after deployment.
2011	723	Assessment of PTSD
2012	711; 723	Mental health; PTSD
2012	724	Report on implementation of policy for management of concussion/mTBI in the deployed setting; the effectiveness of policy in identifying and treating blast-related concussive injuries; and the effect of policy on operational effectiveness in theater
2013	725-730	Mental health
2013	739	Plan to eliminate gaps and redundancies in programs of the DoD on psychological health and TBI
2014	704	Pilot program on investigational treatment of SMs with TBI and PTSD
2014	723	Report on memorandum on how the secretary identifies, refers, and treats TBI with respect to SMs who served in OEF/OIF before the effective date in June 2010 of the DTM 09–033, regarding using a 50-m distance from an explosion as a criterion
2015	728	Evaluation of specific tools, processes, and best practices to improve the identification of and treatment by SMs of mental health conditions and TBI; report on the MACE and PDHA; the DoDI 6490.11
2015	731	A report that assesses the transition of care for PTSD and TBI
2016	730	Eliminate performance variability of healthcare provided by the DoD
2017	707; 708	Establish a joint trauma system within the DHA that promotes improved trauma care to SMs, veterans, and beneficiaries; establish standards of care for trauma services provided at MTFs; coordinate the translation of research; incorporate lessons learned from the trauma education and training partnerships into clinical practice; establish a joint trauma education and training directorate
2018	703	HBO2 may be furnished if prescribed by a physician for treatment of TBI
2018	734	Longitudinal medical study on blast pressure exposure of members of the armed forces
2019	719	Improvements to trauma center partnerships
2020	742	Modification of requirements for longitudinal medical study on blast pressure exposure of members of the armed forces and collection of exposure information
2020	750	A meta-analysis of evidence-based TBI mitigation efforts, and a road map for implementation across the MHS of measures that address the process for receiving treatment, patient outcomes, cost, and patient and command satisfaction
2022	722	Cross-functional team for emerging threat relating to anomalous health incidents

TBI, traumatic brain injury; PTSD, post-traumatic stress disorder; CONUS, continental United States; AHLTA, Armed Forces Health Longitudinal Technology Application; EHR, electronic health record; OIF, Operation Iraqi Freedom; OEF, Operation Enduring Freedom; DoD, Department of Defense, SM, service member; DTM, directive-type memorandum; MACE, Military Acute Concussion Evaluation; PDHA, Post-Deployment Health Assessment; DoDI, Department of Defense Instruction; MTF, military treatment facility; HBO2, hyperbaric oxygen.

(ALARACT) 143/2006 and ALARACT 160/2007 resulted in an increased rate of reporting TBIs by threefold. In 2006, the Military Acute Concussion Evaluation (MACE) was created, and in 2008 it was introduced into theater mTBI care. Currently, MACE 2 is the standard concussion screening tool used by the DoD.

Important components of the symptoms and signs of blast-related concussion were cognitive deficits and slowing of reaction time. During the first decade of GWOT, the DoD worked closely with the University of Oklahoma to develop and refine the Automated Neuropsychological Assessment Metrics (ANAM) test, which is a computerized neurocognitive assessment tool (NCAT) administered on a laptop computer with a mouse. Section 1673 of the 2008 NDAA required pre-deployment neurocognitive testing of all SMs, and this requirement was codified in the DoDI 6490.13, which mandated the use of the ANAM for neurocognitive testing. As a result of this mandate, baseline ANAM test results are currently available for comparison with post-concussive ANAM tests for all deployed SMs.

In 2012, President Obama issued an executive order directing the DoD, VA, Department of Health and Human Services (HHS), and Department of Education, to develop a national research action plan (NRAP) on PTSD, other mental health conditions, and TBI ''to improve the coordination of agency research into these conditions and reduce the number of affected men and women through better prevention, diagnosis, and treatment.'' The NRAP continues to be used as a blueprint for coordinating DoD-sponsored TBI research.

GWOT: Gray Team assessments in the Gulf Region

In 2009, the chairman of the Joint Chiefs of Staff was concerned that more needed to be done to better identify and treat TBI and psychological illness among deployed SMs. His chief medical advisor, Christian Macedonia, organized a team of medical experts with representatives from each of the service branches to spend ~10 days traveling to different medical outposts in Afghanistan and Iraq. The team surveyed the TBI and mental health care provided, and identified problems or needs that deployed providers had. This team was called the Gray Team, and the director of the TBICoE was designated as the co-leader to evaluate and provide recommendations for in-theater mTBI care. Because of the success of this first expedition, three subsequent Gray Teams returned to Iraq and Afghanistan to monitor the implementation of their recommendations (personal communication; COL [ret.] Macedonia, 2021).

Gray Team I (February, 2009) found that concussion care in both OIF and OEF was haphazard; there were serious deficiencies in virtually all aspects of in-theater mTBI care. Few medics or corps personnel had been trained in mTBI evaluation. Less than 5% had heard of the MACE, and the use of the MACE to screen potential concussion victims was inconsistent.[67] The RTD rate exceeded 95%, but members of the Gray Team raised concerns that some SMs might be returning to active duty too soon. In their final report, the Gray Team members recommended more medical provider concussion training and a systematic approach to managing concussions.

Gray Team II deployed August 2009 and noted significant improvements in concussion evaluation of warfighters exposed to blast, but remained concerned that many SMs were still not adequately screened. The Gray Team II report had a number of recommendations, including a systems-wide approach to concussion care. They recommended the establishment of centers strategically placed in theater to provide enhanced education and treatment of SMs with concussion in an effort to optimize treatment and RTD of SMs when cleared for full duty. At these concussion care centers (CCC), RTD was used as the sole indicator for clinical success without any follow up measures. Directive-Type Memorandum (DTM) 09-033 was produced as a result of the concerns of Gray Team II about screening blast-exposed SMs for TBI. This directive held line leaders responsible for the identification and treatment of blast victims in the deployed setting, and set criteria for mandatory screening in specified situations. In particular, it required that all SMs within 50 m of a blast must be evaluated for concussion. This became known as the ''50 meter rule.'' Refer to Table 2 for detailed criteria of the ''50 meter rule.'' In addition, the DTM mandated detailed medical recordkeeping on blast-exposed SMs.

In January 2011, a third Gray Team was deployed and found the emergence of an organized system of mTBI care, which was one clear improvement since the first Gray Team. However, there was no standard approach to implementing DTM 09-033. The 50 meter rule was considered arbitrary by some leaders and likely resulted in more SMs having to be removed from duty than was necessary. Some locations demonstrated improvements in early recognition of mTBI/concussion in an exposed individual, with more consistent application of the MACE, and clinical evaluation for concussion at the level of corps personnel (pre-Role I). There was an urgent need for a diagnostic test battery to reliably diagnose concussion soon after the trauma, independent of the SMs' self-report. An additional need was to develop a standardized protocol for RTD based upon objective assessments (e.g., neuropsychological testing, reaction time) and functional metrics (e.g., weapons maintenance and firing in general, shooting simulators, driving simulation for drivers, improvised explosive device [IED] detection for road clearance patrols). Many soldiers were returned to varying degrees of duty even while experiencing significant symptoms (minimal, impairing, and disabling).

Table 2. Department of Defense (DoD) and Defense Health Agency (DHA) Policies for TBI

Directive	Title	Specific guidance
DoDI: 6490.11 (2012, 2021)	DoD Policy Guidance for Management of mTBI/ Concussion in the Deployed Setting; Reporting guidance, treatment guidance	Events requiring mandatory rest periods and medical evaluations and reporting of exposure of all involved personnel include, but are not limited to: a. involvement in a vehicle blast event, collision, or rollover b. presence within 50 m of a blast (inside or outside) c. a direct blow to the head or witnessed loss of consciousness d. exposure to more than one blast event (SM's commander shall direct a medical evaluation)
DoDI: 6490.13 (2015, 2017)	Comprehensive Policy on TBI-Related Neurocognitive Assessments by the Military Services	Guidance on the use of a computerized neurocognitive assessment tool (ANAM) for the evaluation of SMs with a concussion
Policy Memorandum 19-01 (2019)	Comprehensive Strategy for SOF Warfighter Brain Health	Results from neurocognitive assessment tools, comprehensive histories, and blast exposure monitoring can assist leadership with decision making by providing data for the early detection and treatment of injury. Over the course of an Operators entire career this policy will surveil exposures, objective cognitive performance, subjective symptoms, and objective data on cumulative blast exposure
DHA-PI: 6490.04 (2021)	Required Clinical Tools and Procedures for the Assessment and Clinical Management of mTBI/Concussion in Non-Deployed Setting	Medical personnel will evaluate individuals as soon as possible following a potentially concussive event. Potentially concussive events may include, but are not limited to: a. involvement in a vehicle blast event, collision, or rollover b. presence within 50 m of a blast (inside or outside) c. a direct blow to the head or witnessed loss of consciousness d. exposure to more than one blast event; falls; or sports-related head impacts Medical personnel will perform the following: a. complete the MACE 2 at initial mTBI/concussion evaluation b. initiate a PRA protocol at follow-up and continue to c. monitor/assess the patient regularly until an exertional test is successfully completed and the patient is cleared for return to full duty or normal activity, as applicable. d. track and document required mTBI/concussion patient reported outcome measures using NSI, and other recommended tools as outlined by the TAC to ensure patient outcomes are improving with treatment

mTBI, mild traumatic brain injury; SM, service member; ANAM, Automated Neuropsychological Assessment Metrics; MACE, Military Acute Concussion Evaluation; PRA, Progressive Return to Activity; NSI, Neurobehavioral Symptom Inventory; TAC, TBI Advisory Council.

The last Gray Team deployed September of 2011 and observed a subtle yet profound change in the way TBI was managed. By creating mandatory evaluation criteria, a chain of accountability, and record-keeping, the emphasis shifted from ''self-reporting'' of TBI to ''leadership reporting'' of TBI. This shift reduced stigma by making reporting a leadership responsibility congruent with taking good care of troops rather than leaving it to the individual. There were notable observations in the CCCs. Two of the CCCs had outstanding programs and were identified to serve as models across theater. Sleep and fatigue problems were a paramount issue among SMs, and sleep/rest were the primary treatments for mTBI and combat operational stress. The best CCC environments were conducive to proper sleep hygiene, provided a stress-free environment, optimized delivery of therapy and education, and insured patient confidentiality. Those CCCs reported a >95% RTD, with the leading cause of delayed RTD being mental health issues.

The National Intrepid Center of Excellence (NICoE) was created with funding from The Intrepid Fallen Heroes Fund (IFHF) following a 2007 Congressional mandate that the DoD provide focused care for those with TBI and psychological health concerns.[68] The NICoE building, a facility that includes extensive state-of-the-art diagnostic, treatment, and educational facilities for SMs with complicated post-concussion symptoms and signs, began treating patients in October 2010 on the campus of WRNMMC. During the past 10 years, the IFHF has funded nine other centers, called Intrepid Spirit centers, which are located on major military bases throughout the country. The Intrepid Spirit centers operate using an NICoE-influenced care model with a focus on diagnosis and treatment, and coordination of intensive outpatient programs for those with persistent post-concussion symptoms and signs (A summary of clinical recommendations and clinical practice guidelines over the past 10 years is provided in Table 3)

In summary, some of the most important advances during the GWOT were:

- Recognition of the subtle cognitive and neurological injury caused by blast
- Improved screening for concussion
  - MACE/ MACE 2
  - ANAM, mandatory pre-deployment testing
  - Post Deployment Health Assessment (PDHA) and Veterans Administration (VA) mandatory screening
- Clinical practice guidelines and recommendations for:
  - Acute care of severe TBI
  - Craniotomies by non-neurosurgeons
  - Progressive return to activity
- CCCs in theater

Table 3. Evidence-Based Clinical Recommendations and Clinical Practice Guidelines Produced during the Last 10 Years

Name of CR/CPG	Author/Org	Focus	Innovations
Indications and Conditions for In-Theater Post-Injury Neurocognitive Assessment Tool (NCAT) Testing_2011	TBICoE	Guidance on when to recommend a computerized neurocognitive assessment following a concussion	Mandated 12 months before deployment, provides a reference point for neurocognitive testing following TBI
Indications and Conditions for Neuroendocrine Dysfunction Screening Post Mild Traumatic Brain Injury_2012	TBICoE	Guidance for primary care providers in identifying patients with mTBI who may benefit from endocrine evaluation and care	NED should be a considered when symptoms remain >3 months and/or patient becomes symptomatic up to 36 months post-injury
Management of Headache Following Concussion/Mild Traumatic Brain Injury: Guidance for Primary Care Management in Deployed and Non-Deployed Settings_2016	TBICoE	Guidance for the characterization of post-traumatic headaches, and the most appropriate non-pharmacological and pharmacological treatments for each	Emphasize non-pharmacological treatment
Assessment and Management of Oculomotor Dysfunctions Associated with Traumatic Brain Injury_2016	Vision Center of Excellence	Accepted practices for rehabilitation and treatment strategies for oculomotor dysfunctions	Improve the speed, accuracy and integration of oculomotor functions
Traumatic Brain Injury Management in Prolonged Field Care_2017	Joint Trauma System	Care of TBI in austere environments	Techniques for preventing secondary brain injury; recognizing red flags
Catastrophic Non-Survivable Brain Injury_2017	Joint Trauma System	Guidance for the identification and characterization of severe TBI, and for hemodynamic stabilization of the patient	Guidance for Role 2 and Role 3 facilities
Joint Trauma System Clinical Practice Guideline: Traumatic Brain Injury Management in Prolonged Field Care_2017	Joint Trauma System	Focus on NS care at Role 3 MTFs	Decompressive craniectomy; 3% HTS; ICP monitoring
VA/DoD Clinical Practice Guideline for the Management of Posttraumatic Stress Disorder and Acute Stress Disorder_2017	VA/DoD	Provide evidence-based information on diagnosis, treatment, and follow-up care of PTSD and related conditions	Emphasize the use of patient-centered care
Emergency Life-Saving Cranial Procedures by Non-Neurosurgeons in Deployed Setting_2018	Joint Trauma System	Provision of specific and tailored guidelines for the performance of cranial procedures by non-neurosurgeons	Codification of safe processes and procedures for emergency, life-saving cranial surgery by non-neurosurgeons
Cognitive Rehabilitation for Service Members and Veterans Following Mild to Moderate Traumatic Brain Injury_2019	TBICoE	Guidance for when concussed patients might benefit from cognitive rehabilitation, and what forms of cognitive rehabilitation are most appropriate	To improve functional difficulties defined by self-reported complaints and concerns
VA/DoD Clinical Practice Guideline for the Assessment and Management of Patients at Risk for Suicide_2019	VA/DoD	Provide evidence-based information on the assessment and management of suicide risk	Use team approach to improve care coordination, involve family/caregivers, and encourage culture shift to reduce stigma
Management of Sleep Disturbances Following Concussion/mTBI: Guidance for Primary Care Management in Deployed and Non-Deployed Settings_2020	TBICoE	Guidance on the recognition of the most common types of sleep disturbances seen in the military, and the most effective treatment of each	Emphasis on non-pharmacological treatments
Military Acute Concussion Evaluation 2 (MACE 2)_2021	TBICoE	The steps for the initial evaluation of SM with possible concussion	Mandated by the DoD for initial evaluation
Use of TBI Plasma Biomarkers after a Potentially Concussive Event_2021	Joint Trauma System	Guidance on using the portable i-STAT TBI Plasma Cartridge with the i-STAT Alinity System to detect an abnormal CT	Plasma biomarkers for identifying those at risk for intracranial injury or hematomas
Progressive Return to Activity Following Concussion/Mild TBI_2021	TBICoE	Guidance for primary care providers for safely returning concussed SMs to duty	Evidence-based protocol for gradual increase in activity level prior to full RTD
VA/DoD Clinical Practice Guideline for the Management and Rehabilitation of Post-Acute Mild TBI_2021	VA/DoD	Guidance for primary care providers on the post-acute (> 1 week) care of SMs with persistent post-concussive symptoms	Evidence-based recommendations for outpatient programs for care of post-concussive symptoms
Joint Trauma System Clinical Practice Guideline: Use of a Traumatic Brain Injury Plasma Biomarkers after a Potentially Concussive Event_2021	Joint Trauma System	Guidance for use of TBI plasma biomarkers after a potentially concussive event	Highly controlled rollout of the TBI biomarker
Assessment and Management of Dizziness and Visual Disturbances following Concussion/Mild TBI_2021	TBICoE	Guidance for characterization and treatment of mild vestibular and visual symptoms following mTBI	Focuses on the neurological links between vestibular and visual disturbances
Neuroimaging Following Concussion/mTBI Clinical Recommendation_2022	TBICoE	Guidance on when to consider a CT or MRI following a concussion	Pending

CR, clinical recommendation; CPG, clinical practice guideline; TBI, traumatic brain injury; TBICoE, Traumatic Brain Injury Center of Excellence; NS, neurosurgical; MTF, military treatment facility; HTS, ICP, intra-cranial pressure; VA, Veterans Administration; DoD, Department of Defense; PTSD, post-traumatic stress disorder; SM, service member; CT, computed tomography; RTD, return to duty; MRI, magnetic resonance imaging.

- Neurosurgical advances
  - Early and aggressive endovascular interventions
  - Rapid decompressive craniectomy with limited brain debridement
- Specialty care centers for TBI in multiple United States locations (Intrepid Spirits, NICoE)

Next Steps: Future Military TBI Needs

Despite continued counterterrorism efforts in the United States over the past two decades, terrorist groups will likely remain a threat. Forecasting the landscape of asymmetric threats involving terrorist groups is difficult, because of their use of unconventional weapons and tactics. We may anticipate near-peer threats in the future as well. Collectively, these groups may use new forms or types of aggression that are beyond our conventional thinking about the etiology of TBI.

Since 2016, some United States DoD and Canadian government personnel have reported a series of sudden and troubling sensory events such as sounds, pressure, or heat concurrently or immediately preceding the sudden onset of symptoms. These have been characterized as anomalous health incidents (AHI), and involve mechanisms that are poorly understood. In addition, the reported clustering of symptoms seem to resemble those of mTBI—although this does not meet exact criteria for a mTBI diagnosis. Because it is not associated with a discrete traumatic incident, it has been referred to as ''acquired idiopathic neurological syndrome.'' The mechanisms and source of these incidents needs to be understood to help protect our fighting force and create effective prevention and treatment strategies.

Military health operations also need to be prepared and agile for injuries occurring in urban areas, as well as in remote locations where medical evacuations may be delayed. Advanced technologies that aid in the objective and rapid diagnosis and characterization of TBI are paramount. To aid in operational decisions in theater, this type of technology must be compact, able to withstand extreme temperatures, effective in noisy environments, and must provide quick (i.e., within seconds or minutes) and reliable results. Genomic and biomarker research may also assist in determining if certain populations (i.e., gender, age, ethnic background) are more vulnerable to TBI and/or poor outcomes post-TBI. Findings of these studies may identify objective measures for RTD decisions. This includes understanding the effects of subconcussive injuries from blast exposures and weapons training, as well as effects of multiple exposures and multiple mTBIs over time. Identifying effective treatments or techniques for improving sleep, especially during times of stress, will help optimize the readiness and resilience of the warfighter.

Conclusion

Advances in military care are driven by the lessons learned from previous military conflicts. These advances have evolved since the time of the United States Civil War to present day, and have shaped our current military health system. Congressional mandates have helped direct and prioritize research efforts and have resulted in innovations and best practices by healthcare providers directing care for warfighters and their families. For future military engagements, it will be important to optimize the performance and recovery of our fighting force, as well as to promote psychological resilience. Advances in future technology may assist in identifying and categorizing higher-risk military occupations and training activities, as well as optimizing the use of wearable technologies to measure exposure and utilizing biomarkers to identify and classify subconcussive injuries and more severe TBI.

Acknowledgments

The authors thank CAPT Scott Cota and Dr. Emma Gregory for their support, and Mr. Thomas Jones for the graphic design of the GWOT timeline.

The views expressed in this manuscript are those of the authors and do not necessarily represent the official policy or position of the Defense Health Agency (DHA), Department of Defense (DoD), or any other United States government agency.

Funding Information

This work was prepared under Contract HT0014-21-C-0012 with DHA Contracting Office (CO-NCR) HT0014 and, therefore, is defined as United States government work under Title 17 U.S.C.§101. Per Title 17 U.S.C.§105, copyright protection is not available for any work of the United States government. For more information, please contact dha.TBICOEinfo@mail.mil

This work was prepared under Contract (HT0014-19-C-0004) General Dynamics Information Technology and (W81XWH-16-F-0330) Credence Management Solutions, and is defined as United States government work under Title 17 U.S.C.§101. Per Title 17 U.S.C.§105, copyright protection is not available for any work of the United States government. For more information, please contact: dha.tbicoeinfo@mail.mil.

Author Disclosure Statement

No competing financial interests exist.

References

1. United States Department of Defense. Department of Defense Instruction, Number 6490.11. Policy guidance for management of mild traumatic brain injury/concussion in the deployed setting. November 26, 2019. Available from https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/649011p.pdf. [Last accessed: 3/25/2022].

2. Rigg JL, Mooney SR. Concussions and the military: issues specific to service members. PM R 2011;3(10 Suppl. 2):S380–386.
3. Magnuson J, Leonessa F, Ling GS. Neuropathology of explosive blast traumatic brain injury. Curr Neurol Neurosci Rep 2012;12(5): 570–579.
4. de Lanerolle NC, Kim JH, Bandak FA. Neuropathology of traumatic brain injury: comparison of penetrating, nonpenetrating direct impact and explosive blast etiologies. Semin Neurol 2015;35(1):12–19.
5. Rutkow IM. The medical and surgical history of the War of the Rebellion, 1861-1865. Arch Surg 1998;133(7):783.
6. Weber JW, Hassler WW. American-Civil-War. In: Encyclopaedia Britannica, 8th ed. Encyclopaedia Britannica: Chicago; 2021. https://www.britannica.com/event/American-Civil-War/The-military-background-of-the-war (Last accessed May 9, 2022).
7. Gilhooly J, Siu A, Beare M, et al. Acute management of military-related injury. Handb Clin Neurol 2015;127:379–393.
8. Cirillo VJ. The Spanish-American War and military radiology. AJR Am J Roentgenol. 2000;174(5):1233–1239.
9. Cifu DX, Cohen SI, Lew HL, et al. The history and evolution of traumatic brain injury rehabilitation in military service members and veterans. Am J Phys Med Rehabil 2010;89(8):688–694.
10. Protas M, Yilmaz E, Patel AP, et al. Review of treatment of gunshot wounds to head in late 19th century. World Neurosurg 2018;116:396-401.
11. Slater J. Neurosurgery at war. Annual meeting of the Western Neurosurgical Society. Olympic Valley-Lake Taho, CA. September, 2005.
12. Trunkey DD. History and development of trauma care in the United States. Clin Orthop Rel Res. 2000(374):36–46.
13. Kaufman HH. Treatment of head injuries in the American Civil War. J Neurosurg 1993;78(5):838–845.
14. United States Surgeon-General's Office, Barnes JK, Woodward JJ, et al. The Medical and Surgical History of the War of the Rebellion, 1861-1865. Washington DC: Government Printing Office; 1870–1888.
15. Bollet AJ. Military medicine in the Spanish-American War. Perspect Biol Med 2005;48(2):293–300.
16. Rosengart MR. Critical care medicine: landmarks and legends. Surg Clin North Am 2006;86(6):1305–1321.
17. Pesce A, Palmieri M, Frati A, et al. A forgotten tale from the Great War: General Lorenzo Bonomo and the birth of Italian war neurosurgery. World Neurosurg 2020;140:338–346.
18. Lanska DJ. Historical perspective: neurological advances from studies of war injuries and illnesses. Ann Neurol 2009;66(4):444–459.
19. Lanska DJ. Elaboration of the visual pathways from the study of war-related cranial injuries: the period from the Russo-Japanese War to World War I. Front Neurol Neurosci 2016;38:31–42.
20. Spurling RG, Woodhull B. The surgical volumes of the history of the United Stated Army Medical Department in World War II. Neurosurgery. Arch Surg 1960;80:406–415.
21. Milton J, Rugino A, Narayan K, et al. A case-based review of the management of penetrating brain trauma. Cureus 2017;9(6):e1342.
22. Shively SB, Perl DP. Traumatic brain injury, shell shock, and posttraumatic stress disorder in the military—past, present, and future. Journal Head Trauma Rehabil 2012;27(3):234–239.
23. Grantham EG, Mayfield FH. Dr. Roy Glenwood Spurling, 1894-1968. J Neurosurg 1968;28(6):610–612.
24. Rehder R, Lohani S, Cohen AR. Unsung hero: Donald Darrow Matson's legacy in pediatric neurosurgery. J Neurosurg Pediatr 2015;16(5):483–494.
25. Craig WM. Neurosurgery in World War II. U S Armed Forces Med J 1952;3(1):1–13.
26. Rish BL, Dillon JD, Caveness WF, et al. Evolution of craniotomy as a debridement technique for penetrating craniocerebral injuries. J Neurosurg 1980;53(6):772–775.
27. Medell RJ, Waisel DB, Eskuri SA, et al. Field block for cranial surgery in World War II. Mil Med 1998;163(2):80–83.
28. Bonfield CM, Kumar AR, Gerszten PC. The history of military cranioplasty. Neurosurg Focus 2014;36(4):E18.
29. Flanigan P, Kshettry VR, Benzel EC. World War II, tantalum, and the evolution of modern cranioplasty technique. Neurosurg Focus 2014;36(4):E22.
30. Spurling RG. Neurosurgery in World War II. Bull U S Army Med Dep 1946;6(6):691–695.
31. Stone JL, Patel V, Bailes JE. Sir Hugh Cairns and World War II British advances in head injury management, diffuse brain injury, and concussion: an Oxford tale. J Neurosurg 2016;125(5):1301–1314.
32. Hughes JT. Hugh Cairns (1896-1952) and the mobile neurosurgical units of World War II. J Med Biogr 2004;12(1):18–24.
33. Baker MS. Military medical advances resulting from the conflict in Korea, Part II: historic clinical accomplishments. Mil Med 2012;177(4):430–435.
34. Wright D. Commonwealth surgery in the Korean war. Lancet 1956;271(6941):505–509.
35. Watts JC. War surgery in the Korean campaign. Postgrad Med J 1954;30(339):22–29.
36. Meirowsky AM. Penetrating craniocerebral truma: observations in Korean war. JAMA 1954;154(8):666–669.
37. Wallace PB, Meirowsky AM. The repair of dural defects by graft. An analysis of 540 penetrating wounds of the brain incurred in the Korean War. Ann Surg 1960;151(2):174–180.
38. Barr J, Montgomery S. Helicopter medical evacuation in the Korean War: did it matter? J Trauma Acute Care Surg 2019;87(1S Suppl 1): S10-s13.
39. Carey ME, Sacco W, Merkler J. An analysis of fatal and non-fatal head wounds incurred during combat in Vietnam by U.S. forces. Acta Chir Scand Suppl 1982;508:351–356.
40. Carey ME, Young HF, Mathis JL. The neurosurgical treatment of craniocerebral missile wounds in Vietnam. Surg Gynecol Obstet 1972;135(3):386–389.
41. Eiseman B. Combat casualty management in Vietnam. Journal Trauma. 1967;7(1):53–63.
42. Raymont V, Salazar AM, Krueger F. "Studying injured minds" —the Vietnam head injury study and 40 years of brain injury research. Front Neurol 2011;2:15.
43. Hammon WM. Analysis of 2187 consecutive penetrating wounds of the brain from Vietnam. J Neurosurg 1971;34(2 Pt 1):127–131.
44. Salazar AM, Zitnay GA, Warden DL, et al. Defense and Veterans Head Injury Program: background and overview. J Head Trauma Rehabil 2000;15(5):1081–1091.
45. Warden D. Military TBI during the Iraq and Afghanistan wars. J Head Trauma Rehabil 2006;21(5):398–402.
46. Ling G, Ecklund JM, Bandak FA. Brain injury from explosive blast: description and clinical management. Handb Clin Neurol 2015;127:173–180.
47. Bell RS, Vo AH, Neal CJ, et al. Military traumatic brain and spinal column injury: a 5-year study of the impact blast and other military grade weaponry on the central nervous system. Journal Trauma. 2009;66(4 Suppl):S104–111.
48. Weisbrod AB, Rodriguez C, Bell R, et al. Long-term outcomes of combat casualties sustaining penetrating traumatic brain injury. J Trauma Acute Care Surg 2012;73(6):1525–1530.
49. Ling GS, Ecklund JM. Traumatic brain injury in modern war. Curr Opin Anaesthesiol 2011;24(2):124–130.
50. Ling G, Bandak F, Armonda R, et al. Explosive blast neurotrauma. J Neurotrauma 2009;26(6):815–825.
51. Brandvold B, Levi L, Feinsod M, et al. Penetrating craniocerebral injuries in the Israeli involvement in the Lebanese conflict, 1982-1985. Analysis of a less aggressive surgical approach. J Neurosurg 1990;72(1): 15–21.
52. Rubiano AM, Carney N, Khan AA, et al. The role of decompressive craniectomy in the context of severe traumatic brain injury: summary of results and analysis of the confidence level of conclusions from systematic reviews and meta-analyses. Front Neurol. 2019;10:1063.
53. Ecker RD, Mulligan LP, Dirks M, et al. Outcomes of 33 patients from the wars in Iraq and Afghanistan undergoing bilateral or bicompartmental craniectomy. J Neurosurg 2011;115(1):124–129.
54. Bell RS, Mossop CM, Dirks MS, et al. Early decompressive craniectomy for severe penetrating and closed head injury during wartime. Neurosurg Focus 2010;28(5):E1.
55. Shackelford SA, Del Junco DJ, Reade MC, et al. Association of time to craniectomy with survival in patients with severe combat-related brain injury. Neurosurg Focus 2018;45(6):E2.
56. Breeze J, Bowley DM, Harrisson SE, et al. Survival after traumatic brain injury improves with deployment of neurosurgeons: a comparison of US and UK military treatment facilities during the Iraq and Afghanistan conflicts. J Neurol Neurosurg Psychiatry 2020;91(4):359–365.
57. Razumovsky A, Tigno T, Hochheimer SM, et al. Cerebral hemodynamic changes after wartime traumatic brain injury. Acta Neurochir Suppl 2013;115:87–90.
58. Vadivelu S, Bell RS, Crandall B. Delayed detection of carotid-cavernous fistulas associated with wartime blast-induced craniofacial trauma. Neurosurg Focus 2010;28(5):E6.
59. Bell RS, Ecker RD, Severson MA, 3rd, et al. The evolution of the treatment of traumatic cerebrovascular injury during wartime. Neurosurg Focus. 2010;28(5):E5.

60. Coughlin DJ, Boulter JH, Miller CA, et al. An endovascular surgery experience in far-forward military healthcare–a case series. Mil Med 2020;185(11–12):2183–2188.
61. The Department of Defense Center of Excellence for Trauma. Joint Trauma System History; 2019. Available from https://jts.amedd.army.mil/index.cfm/about/origins (Last accessed January 26, 2022).
62. Lew HL, Poole JH, Vanderploeg RD, et al. Program development and defining characteristics of returning military in a VA Polytrauma Network Site. J Rehabil Res Dev 2007;44(7):1027–1034.
63. United States Department of Veterans Affairs. Polytrauma/TBI System of Care; 2015. Available from: https://www.polytrauma.va.gov/system-of-care/index.asp (Last accessed January 27, 2022).
64. Denny JW, Brown RJ, Head MG, et al. Allocation of funding into blast injury-related research and blast traumatic brain injury between 2000 and 2019: analysis of global investments from public and philanthropic funders. BMJ Mil Health 2020. [Epub ahead of print].
65. Champion HR, Holcomb JB, Young LA. Injuries from explosions: physics, biophysics, pathology, and required research focus. Journal Trauma 2009;66(5):1468–1477.
66. Agimi Y, Regasa LE, Ivins B, et al. Role of Department of Defense policies in identifying traumatic brain injuries among deployed US Service Members, 2001-2016. Am J Public Health 2018;108(5): 683–688.
67. Hamilton R. An Army Buddy's Call For Help Sends A Scientist On A Brain Injury Quest. National Public Radio 2016. https://www.npr.org/sections/health-shots/2016/06/08/480608042/an-army-buddys-call-for-help-sends-a-scientist-on-brain-injury-quest (Last accessed May 9, 2022).
68. Defense Health Agency. History of the NICoE. National Intrepid Center of Excellence (NICoE); 2022. Available from: https://walterreed.tricare.mil/Health-Services/Specialty-Care/National-Intrepid-Center-of-Excellence-NICoE/About/History-of-the-NICoE (Last accessed January 28, 2022).