ABSTRACT  Clinical research advances in traumatic brain injury (TBI) and behavioral health have always been restricted by the quantity and quality of the data as well as the difficulty of collecting standardized clinical elements. Those barriers, together with the complexity of evaluating TBI, have resulted in serious challenges for clinicians, researchers, and organizations interested in analyzing the short- and long-term effects of TBI. In an effort to raise awareness about existing and cost-effective ways to collect clinical data within the Department of Defense, this article describes some of the steps taken to quickly build a large-scale informatics database to facilitate collection of standardized clinical data and obtain trends of the longitudinal outcomes of service members diagnosed with mild TBI. The database was built following the Defense of Health Agency guidelines and currently has millions of longitudinal clinical data points. Department of Defense-wide clinical data for service members diagnosed with mild TBI to support population studies, and multiple built-in analytical applications to enable interactive data exploration and analysis.

INTRODUCTION
The pathophysiological changes in the brain following traumatic brain injury (TBI) remain poorly understood. Post-traumatic alterations in the brain have been difficult to quantify in part because of the lack of standardization across clinical disciplines, the frequency of incomplete data collection efforts, and the lack of unique metrics to measure changes after TBI events.1 Clinical practice guidelines recommend examining TBI patients with physical, cognitive, behavioral, imaging, and neuropsychological evaluations,2 which results in a large collection of data elements that should be analyzed collectively to better establish an understanding of the patient’s condition.

Despite the existence of detailed clinical practice guidelines for managing patients with mild TBI (mTBI),2–4 most clinical evaluations still rely heavily on behavioral observations such as the Glasgow Coma Scale and on the patient’s subjective recall of post-traumatic amnesia and loss of consciousness. Since these assessment tools depend on environmental and subjective recollections, they often yield highly variable ratings that can complicate the evaluation process by potentially adding uncertain or conflicting information to the patient record.

The complexity, heterogeneity, and often subjective properties of the data elements related to mTBI, combined with the shortage of HealthIT systems to support the data collection, standardization, and analysis of mTBI data, have created significant challenges. First, in order to develop a comprehensive understanding of the patient’s condition, providers must integrate many multimodal measurements and current clinical systems do not facilitate the collection and analysis of the widely disparate data obtained during the evaluation of TBI. Second, researchers typically must use their own data collection strategies to build a database to facilitate their research. The resulting datasets are not integrated with other researchers, potentially limiting the scope and applicability of some findings.

In general, a key factor that has limited research and innovation in mTBI across the Department of Defense (DoD) has been the lack of standardized large-scale databases integrated with the clinical workflow where hundreds of clinical variables can be collected, analyzed simultaneously, and used to discover new complex patterns.

A 2014 memorandum by the assistant Secretary of Defense for Health Affairs (Woodson J: Guidance for the Management of Registries in the Military Health System. Affairs ASoDfH, ed 2014) provides specific guidance about how DoD registries should employ reusable interfaces and data service. In an effort to show how those guidelines can be followed to enable the development of cost-effective data repositories, this article describes a large-scale database that was designed to collect multidisciplinary clinical elements from dozens of external sources and medical devices. The data registry, which combines DoD-wide TBI clinical data with multiple built-in analytical applications, was designed in partnership with the Defense of Health Agency (DHA) with the goal that other organizations or individuals under the
DoD could leverage the concept, technology, and systems to quickly create their own large-scale data repositories or registries.

BACKGROUND
Clinicians and researchers face several challenges when trying to diagnose patients that have sustained concussions. During the last decade, a significant amount of attention has been given to the acquisition of clinical data from patients who have suffered from mTBI and/or psychological health (PH) conditions. In addition, the DoD as well as many other government and private organizations have been leading efforts to raise awareness about the long-term effects of concussions. This has both increased and influenced the collection and the quality of the data being collected.

To provide a comprehensive interdisciplinary treatment for service members diagnosed with mTBI, the DoD supports several organizations that perform extensive clinical evaluations of patients diagnosed with TBI/PH. At organizations such as the National Intrepid Center of Excellence (NICoE), active duty service members diagnosed with mTBI and PH conditions undergo a 4-week intensive treatment program by a team of experts, including weekly appointments with interns and approximately 105 encounters with diverse clinical staff. This dedicated process produces an extensive amount of data points and measurements that must be collected and used to create rich research datasets.

Despite the efforts to support more acquisition of clinical data, there are still many challenges and questions about how to collect standardized data while not disrupting the clinical workflow and avoiding the clinical staff to enter the same information multiple times in different systems. Currently, most of the attention has been given in creating centralized databases where researchers, once they collect the different clinical elements, can share the data with other collaborators and organizations. However, the question about cost-effective approaches to collect standardized data from providers without disrupting the clinical workflow remains open.

There are four well-known databases that are currently assembling clinical information from TBI patients: “Traumatic Brain Injury Model Systems (TBIMS), Federal Interagency Traumatic Brain Injury Research (FITBIR),” the “Center for Neuroscience and Regenerative Medicine Database (CNRM),” and the Gemini program.” Given the limited information publicly available about the technical and engineering design of each of those databases, an in-depth comparison of the databases is not within the scope of this article.

The TBIMS program is funded by the U.S. Department of Education’s National Institute on Disability and Rehabilitation Research, to examine the course of recovery and outcomes following a moderate or severe TBI. The program operates a database that receives information from 16 different centers around the country. The primary objective of the database is to generate new and useful knowledge about the short- and long-term effects of TBI based on 327 clinical elements that are collected during inpatient rehabilitation and after discharge.

To address some of the existing gaps surrounding TBI, the National Institutes of Health, in partnership with the DoD, is building a centralized database for TBI research named the FITBIR database. The primary objective of FITBIR is to serve as a central repository for TBI data to enable the comparison of results across studies. Since the data going to FITBIR will come from individual federally funded research projects that might not be collecting the same data elements or might not share the data until the end of the project, it may take years to produce a database with sufficient homogeneity and quantity to perform some of the desired population-based studies. To mitigate a prolonged period before a return on investment, strategies are being implemented, such as the development of common data elements (CDEs) to reduce variability in data element reporting and incentives to collect legacy data.

A similar effort is being driven by the CNRM, which is a federal medical research program operated by the Uniformed Services University of the Health Sciences that brings together clinicians and scientists across different disciplines for innovative TBI research, including approaches for diagnosis and recovery. Internally, CNRM maintains a comprehensive database with de-identified information regarding study participants. The clinical and research elements that are incorporated into the database are predominantly driven by clinical research protocols conducted within the organization.

Finally, the “Gemini” program is a project under One Mind for Research focusing on exchanging and gathering data from different organizations performing research with patients who have TBI. The “Gemini” program employs the principle of open science to collect data from different funded projects with the goal of making them available to the broader population. This database faces the same challenges as other systems as well as the challenge of obtaining data from third-party organizations collecting the information.

Recently, there have been other efforts to build additional large-scale databases such as the Department of Defense and Department of Veteran Affairs Psychological Health & Traumatic Brain Injury registry that is scheduled to be operational by fiscal year 2017. Despite the great work that has been done on repositories to store clinical data on TBI patients, there are many challenges with the design and development of many of the existing databases. First, most of the current databases depend on individually funded projects that, as part of their project deliverables, have agreed to contribute their data with one of the existing databases before the completion of the project. Since funding can vary between different clinical disciplines, the focus of research programs can change on an annual basis, research protocols have a specific target population, and different research studies can collect distinctive clinical data; combining and comparing the data produced by individual research studies will be extremely challenging. Second, most of the data
collection and analysis is focused on particular aspects of TBI (e.g., neuropsychological, neuroimaging, sleep, vestibular, etc.) and not necessarily on comprehensive datasets that can enable research on multivariate approaches to model the complex biological state of mTBI patients. Third, none of the existing databases have been incorporated with the clinical workflow. Fourth, most of the existing databases assume that organizations or researchers have data collection mechanisms compatible with existing case report forms such as those used by CNRM or that have e-forms that follow the CDEs suggested for TBI. Fifth, none of the existing databases provide built-in analytical techniques that can be used to analyze, model, forecast, and mine the heterogeneous data. Finally, the existing databases do not incorporate population data such as DoD-wide clinical data for TBI patients.

The primary focus of our work was to fill the gap between the clinical workflow and existing repositories by building a system that follows the DHA guidelines and can be seamlessly integrated with the clinical workflow, used to collect standardized clinical elements, and provide a platform where clinical staff, researchers, and administrators can analyze, explore, and review large collections of interdisciplinary data of mTBI patients.

All of the different components that were used to create our database are owned and operated by the DoD and are available to any other organization that might be interested in leveraging them to create their own database. To disseminate information and help researchers learn about how existing DHA guidelines can be used to create cost-effective systems to collect clinical data, this article describes some of the steps that were taken to quickly build a large-scale informatics database to enable in-depth analysis of patients diagnosed with mTBI. Note that the article describes a platform and database system that was built using applications, technologies, and resources that the DoD currently has available at the enterprise level. Given the rapid changes and evolution of HealthIT systems, some of the design and/or technologies might evolve; however, the overall framework has been designed flexible enough to support any potential changes.

**APPROACH**

Instead of relying on investigators to collect and contribute data or on researchers to extract information from clinical notes, we created a clinical repository that automatically receives and integrates data from disparate clinical sources. Figure 1 shows a diagram of our large-scale database. The diagram is divided into two sections to the left of Figure 1 (gray-shaded areas) are the "producers"—those systems that can generate clinical data—and to the right (green-shaded areas) are the "consumers"—those systems that can use the clinical data.

**Producers**

To develop the comprehensive database, we first identified the different sources of information that can produce clinical and

**FIGURE 1.** Diagram illustrating the overall design of our large-scale informatics system to support research and innovation in mTBI. The system is capable of aggregating clinical information from DoD-approved systems as well as from local data repositories. AHTLA, Armed Forces Health Longitudinal Technology Application; CHCS, Composite Health Care System; CDR, Clinical Data Repository; DEERS, Defense Enrollment Eligibility Reporting Systems.)
research data for patients diagnosed with mTBI. The different sources of clinical data were divided into two groups: “trusted clinical sources” and “external/unharmonized” sources.

**Trusted Clinical Systems**

Clinical data collected from electronic health records (EHRs) such as the Armed Forces Health Longitudinal Technology Application (AHLTA) or the Composite Health Care System (CHCS) that have a provider, organization, and/or individual signing the information and is accountable for the accuracy of the data. Those systems cannot be altered, thus the data should be considered as accessible information from a known “trusted source.” Other data coming from additional DoD sources such as the MHS Mart (M2), Pharmacy Data Transaction Service (PDTS), Clinical Data Repository (CDR), Defense Enrollment Eligibility Reporting Systems (DEERS), and TRICARE Encounter Data Institutional (TED_I) should also be considered secure and trusted information.13

The DoD has multiple systems used to capture and integrate data from different “trusted” clinical sources. Three of the most popular databases are the Health Services Data Warehouse (HSDW),14 the Medical Data Repository,15 and the COHORT Database.16 After considering the flexibility, scalability, and capabilities of the different systems, we partnered with HSDW to provide us access to the data from different clinical sources. Currently, following the DHA registry guidelines, HSDW is becoming the adopted warehouse to provide clinical information to DHA (Woodson J: Guidance for the Management of Registries in the Military Health System. Affairs ASoDfH, ed 2014).

HSDW is a DHA effort to create a repository of the DoD health information. The system uses multiple internal and commercial tools to quickly integrate and query data from different sources. Typically, EHRs contain billions of data records as well as significant amounts of sensitive information. Due to the size of the data and the necessity of combining data from multiple sources, the clinical data in HSDW flows from different databases to a temporary database where the data is transformed into a star schema that consist of multiple fact tables referencing many different dimension tables. The benefits of the star schema include enabling simple queries, simplified logic, fast performance, and quick aggregations.

Currently, HSDW has connectivity to over 12 different data sources including DEERS, M2, CHCS, COHORT, Picture Archiving and Communication System, and PDTS. Figure 2 lists some of the data sources currently available through HSDW. From those sources we can obtain patient and encounter level information such as demographics, deployment information, type of encounters, diagnosis, procedures, and medication changes. Such information has proven to be valuable for epidemiology studies, trending information, and to obtain indirect measurements of outcomes.17 HSDW has over 9 billion records containing clinical information and metadata of all encounters that have taken place since 2006.

**FIGURE 2.** A table showing some of the data sources available within HSDW. The existing data sources include the Military Health System Mart (M2), Medical Data Repository (MDR), COHORT Database, Armed Forces Health Longitudinal Technology Application (AHLTA), Integrated Clinical Database (ICDB), TRICARE Encounter Data - Institutional (TED_I), TRICARE Encounter Data - Non-Institutional (TED_NI), Comprehensive Ambulatory Provider Encounter Record (CAPER), TRICARE Management Activity (TMA), Defense Enrollment Eligibility Reporting Systems (DEERS), Clinical Data Repository (CDR), Air Force Corporate Health Information Processing Service (AFCHIPS), Pharmacy Data Transaction Service (PDTS), Standard Inpatient Data Record (SIDR), and the Composite Health Care System (CHCS).

Table I illustrates the magnitude of the data that is currently available in HSDW. It is important to note that these numbers are DoD-wide numbers, not only for those patients diagnosed with mTBI. Although encounter metadata and coding information have proven to be beneficial in many population studies, there are also many limitations regarding the uncertainty of the data and the validity of translating coding information into research data.18 In addition, standardized information or CDEs must be collected within every discipline to successfully accomplish research in mTBI that cannot be done by simply relying on International Classification of Diseases (ICD) or Current Procedural Terminology (CPT) codes. In general, detailed information need to be collected through standardized forms.

To create electronic forms that can be used by providers to collect clinical and research data, the system must be integrated with the clinical workflow and should not add any burdens to the providers. In general, the primary concerns of incorporating standardized forms within clinical settings.

**TABLE I.** Sample List to Illustrate the Comprehensive Data Available Through Health System Data Warehouse

<table>
<thead>
<tr>
<th>Type of Records</th>
<th>Number of Records (2006–2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encounters</td>
<td>2,295,080,000</td>
</tr>
<tr>
<td>Diagnosis</td>
<td>4,092,881,000</td>
</tr>
<tr>
<td>Lab</td>
<td>225,709,110</td>
</tr>
<tr>
<td>Radiology</td>
<td>35,695,174</td>
</tr>
<tr>
<td>Detailed S/O Notes</td>
<td>1,409,000,000 (Between7/13–7/14)</td>
</tr>
<tr>
<td>(Split by MEDCIN)</td>
<td></td>
</tr>
</tbody>
</table>
include the potential of workflow disruptions, concerns about security and privacy, lack of incentives for additional effort that might be required to collect or input the data, the learning curve required to learn a new system, potential of dual entry, and the lack of interoperability between different systems.\textsuperscript{19}

In the DoD, the primary outpatient EHR has been AHLTA and most providers are required to write a clinical note for every encounter. To document the subjective (S) and objective (O) portion of an encounter, AHLTA S/O notes use MEDCIN terminology.\textsuperscript{20} MEDCIN is a commercial product employed in AHLTA that uses a hierarchical structure to enhance the codification of information in EHRs. Aside from MEDCIN terms, AHLTA supports Alternate Input Method (AIM) forms that are templates that can be used to document S/O notes.\textsuperscript{21} AIM forms can be built around a theme, a diagnosis, or a symptom.

To enhance the data collected by HSDW, we built AIM forms for multiple disciplines including Neurology, Nursing, Social Workers, Audiology, Speech, Vestibular, Complementary Alternative Medicine, and other disciplines. By using AIM forms the S/O notes are not just a text field where providers can write free-form text, but instead standardized forms where each button, field, and checkbox has a corresponding MEDCIN term. Figure 3 shows some screenshots of an existing AHLTA AIM forms. Figure 3A shows a screenshot of the Audiology AIM form. The form has different tabs across the top as well as different discrete fields within each tab that have unique MEDCIN terms associated with them. The benefit of using AIM forms is that the providers complete their S/O notes using a form that has specific and standardized data elements. When providers submit a clinical note, each button, checkbox, and text field has a

FIGURE 3. (A and B) Sample screenshots of existing Alternative Input Method (AIM) forms used to standardize the collection process within the Armed Forces Health Longitudinal Technology Application (AHLTA).
particular MEDCIN term associated with them, thus making the parsing and querying of the data possible.

In collaboration with DHA, we added a new data source and comprehensive database to HSDW—"CDRMart." The CDRMart contains all the S/O notes written in AHLTA, each note can be linked to a specific encounter, and the text of each note can also be split into the corresponding MEDCIN terms. This new functionality currently allows us to pull encounter information (e.g. date, ICD, CPT, etc.) and augment that information with clinical notes either collected through AIM forms or as free-form text. A combination of parsing and natural language processing (NLP) techniques are used to extract relevant clinical information from unstructured data sources. For example, an AIM form containing an injury tab, like the one illustrated in Figure 3B, enables the collection of standardized injury information following the CDE recommendations by seamlessly integrating the forms to the system that all providers use to document their encounters.

In the design and development of the AIM forms, we partnered with the Tri-Service Workflow—a DHA team of clinicians and information technology professionals that standardize clinical documentation and workflows while enhancing provider efficiency and patient safety. All of the AIM forms that were created as part of this project are currently in the enterprise and available to anyone with an AHLTA account and can be easily recreated in other commercial electronic health records (EHRs).

**External Sources**

In addition to trusted sources such as EHRs, hospital organizations, and clinics always have other sources of clinical data that are used by the clinical staff, but often the data does not make it into the patient records. For example, sleep studies, neuropsychological evaluations, and audiologic examinations are some of the assessments that employ specialized devices to test patients. Each of the individual computer system collects a number of measurements about patients and often generates summary reports with overall findings. Generally, providers review the aggregate reports and write a subjective description of the findings and diagnosis. Frequently, the data collected by the individual devices or the individual reports are not included in the patient records. Those systems that do not have a connection to the EHRs are considered as "external/unharmonized" sources.

In order to build a comprehensive dataset that can be used to explore the short- and long-term effects of mTBI, data generated by different clinical devices or external sources must be collected. In our approach, we connect medical devices and external data collection sites to a “data augmentation” database that works as an external database to enhance the information collected from HSDW. The augmentation database also works as a temporary platform where parsing, filtering, and standardization of the data produced by different systems that are not connected to any EHR takes place. Figure 1 shows the overall concept of the augmentation system used to collect external data.

Some of the sample external sources that have been incorporated into our augmentation database include data from independent DoD databases such as CarePoint and the Wounded, Ill, and Injured Registry (WIIR).

CarePoint is a centralized platform and hosting environment owned and operated by DHA that was built on top of Microsoft Office SharePoint Services to consolidate multiple DoD applications such as the Military Health Service Population Health Portal or other web-based applications. To provide clinical staff and researchers dynamic forms with built-in decision rules and interactive interfaces that AHLTA AIM forms cannot provide, we designed multiple clinical forms in CarePoint. Figure 4A shows a referral form that was developed to collect in-depth historical information from TBI patients before they attend the NICoE program. Figure 4B shows an interdisciplinary form that was created to effectively collect information from multiple providers belonging to different disciplines.

In addition, data from medical devices such as polysomnogram, actigraphy, and audiogram devices are being pulled and incorporated into the augmentation database. Similarly, to create a comprehensive database that can benefit different researchers and providers interested in understanding the effects of mTBI, many other databases and clinical devices that do not have connectivity to AHLTA have been incorporated into the augmentation database.

Given the importance of collecting short- and long-term outcome measures, within the DoD there are several systems that can be used to collect standardized questionnaires including the Behavioral Health Data Portal, the WIIR, mCare, After Deployment website, and many others. We partnered with the Army Analytics Group in developing a module on the WIIR that can be used to collect longitudinal information from patients that receive treatment at the NICoE. The decision of using the WIIR was made given that it was a very cost-effective and flexible system that could be quickly incorporated into our clinical workflow to collect outcome data directly from the patients. The WIIR, a system owned and operated by the DoD, has many unique features including all the information assurance (IA) certifications, a Common Access Card-enabled interface for providers, reachable from any MTF, and accessible to patients regardless what network, computer, phone, or tablet device they use. The NICoE environment within the WIIR currently has over 30 standardized surveys including PCL-M, NSI, GAD-7, and AUDIT-C. Currently, our clinical staff requests specific surveys to be completed at different time intervals, the patients are automatically notified and/or reminded about the pending surveys, on submission the surveys are scored by the system, standardized plots and tables are generated to show changes, and the clinical staff is notified that the information is available for their review. The use of the WIIR...
FIGURE 4. (A) A referral form that was developed within CarePoint to collected in-depth historical information from TBI patients before they attend the NICoE program. (B) An interdisciplinary form that was created in CarePoint to effectively collect information from multiple providers belonging to different disciplines.
has significantly improved our ability to collect outcomes data without adding any significant burden to the patients or providers. The data collected from the WIIR are automatically transferred to our augmentation database and can then be merged with any other clinical element. Figure 5 (left) shows a screenshot of the WIIR module that is currently being used to automatically collect self-reports at the NICOe. Figure 5 (right) lists some of the self-reports that are currently available through the WIIR.

Now that we have an enhanced version of HSDW with structured and unstructured clinical information from different EHRs and a comprehensive augmentation database with data collected from external sites or devices, we need to integrate the data so it can be used to better understand the status of our patients and the effects of mTBI. Because of IA regulations, data from external sources should not be merged with clinical data. To comply with these regulations, although avoiding the expense of having to extract, transform, copy, and load data from multiple systems into a single database, we developed, in collaboration with DHA, a “virtual layer.” The uniqueness of the virtualization layer is the ability for multiple data sources to be brought together through a centralized tool. Instead of copying the data from disparate sources, the metadata from different databases is

**FIGURE 5.** (Left) Screenshot of the NICOe environment within the WIIR that is used to collect patients’ self-reports. (Right) Lists of some of the questionnaires that are currently available in the WIIR.

**FIGURE 6.** To show the value of our database, the clinical diagnosis of a large DoD population of 89,840 service members that have sustained an mTBI between 2007 and 2014 was analyzed to better understand the differences in symptoms prior and post mTBI. Eight symptoms commonly associated with mTBI are presented with the corresponding percentage of patients with such a clinical diagnosis prior and post their brain injury. It is important to note the significant changes that are apparent in headaches, sleep, neurological disorders, and depression.
copied, the virtual layer hides system-specific data schemes, and during the query process, the data are brought together. The virtual layer has proven to be a very cost-effective way to scale our large-scale informatics database given that additional sources of data can be added at very minimum expense or impact to the system.

Consumers

Figure 1 shows the virtual layer as the gate to consumption of the multimodal clinical data coming from different database systems. The two primary ways the data are consumed by users are (a) as “queries” or (b) by “business intelligence (BI) dashboards.” Queries can be written using a variety of applications and tools that can connect, communicate, and query the virtual layer, which connects to many different databases. In addition, the BI Dashboards are created using a combination of popular tools including Statistical Analysis System (SAS), Microsoft Power BI, or Tableau.27,28 The results section will discuss some cases where the data from our large-scale repository were quickly used to extract new knowledge about mTBI.

RESULTS

The database described above has been used to support multiple clinical and research studies about the effects of mTBI.29–31 While the main objective of this article is to describe the process that was followed to create a large-scale informatics databases for mTBI patients and encourage other organizations to follow a similar approach, this section will briefly describe some of the results that we have been able to obtain from the database.

Some of our preliminary results include findings in speech and pathology data, neurology, audiology, vestibular, observations about neuroimaging lesions, validation of some self-reports, and the description of the short- and long-term effects of TBI. In addition, comprehensive dashboards have been developed to assist with program evaluation, longitudinal outcomes analysis, analyze DoD-wide trends, and determine organizational metrics.

As an example of the effectiveness of the database, a research query was done to quickly look at the speech-language pathology findings. A total of 485 patients (age \( M = 32.47, \ SD = 8.60 \)) were found with all the information needed for the study. Then, by leveraging the technology of our database system, we were able to immediately estimate that 67% of our patients complained of word-finding difficulties and that the average scores for cognitive evaluations that are related to verbal memory were low or below average while those related to prospective, visual, and spatial memory show strengths among the same service members. The results of combining different databases provide objective support that verbal memory and new learning are consistently the most frequent area of weakness in formal speech-language pathology assessment and that there is a significant difference between verbal and visual memory that becomes more evident among patients who have sustained a concussion.

During the last decade, the sequel of symptoms that occurs most commonly after mTBI has been of great interest.1,2 It is known that patients that suffer a brain injury are more likely to suffer from depression,32 headaches,33 sleep disorder, and other conditions. To describe the difference in symptom configuration within patients before and after their TBI, we used our database to quickly pull the symptoms for a large DoD population of 89,840 service members that have sustained an mTBI between 2007 and 2014. Figure 6 shows eight symptoms commonly associated with mTBI and the number of TBI-related healthcare encounters 30 days after mTBI.

![Number of TBI-related Healthcare Encounters 30 days after mTBI](https://example.com/image)

<table>
<thead>
<tr>
<th>Number of Clinical Encounters 30 days after mTBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st mTBI</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>Mean (Std)</td>
</tr>
<tr>
<td>Percentile 25%</td>
</tr>
<tr>
<td>Percentile 50%</td>
</tr>
<tr>
<td>Percentile 75%</td>
</tr>
</tbody>
</table>

FIGURE 7. Another way to utilize our database is to look at health care utilization trends after mTBI and analyze the impact that multiple concussions have on the health care system. This figure shows the average number of TBI-related clinical encounters service members had 30 days after their first, second, third, fourth, and fifth mTBI event. From the results we can see that on average service members have 3.9 encounters 30 days following their first TBI; however, that number goes to 8 encounters 30 days following their third TBI event.
percentage of patients with such a clinical diagnosis prior and post their brain injury. Note the significant changes that are apparent in headaches, sleep, and neurological disorders. From Figure 6, it is also important to see the significant increase that speech and language disorders have after an mTBI.

Health care utilization has been another important topic that has received a significant amount of attention during the last few years. Another way to utilize our database is to look at health care utilization trends after mTBI and analyze the impact that multiple concussions have on the health care system. Figure 7 shows the average number of TBI-related clinical encounters service members had 30 days after their first, second, third, fourth, and fifth mTBI event. From the results shown in Figure 7, we can see that on average service members have 3.9 encounters 30 days following their first TBI; however, that number goes to 8 encounters 30 days following their third TBI event.

Another way to consume data is through dashboards. The dashboards provide a single analytical framework where administrators, clinicians, and researchers can analyze and explore clinical data to better understand the effects of TBI, mTBI, post-traumatic stress disorder, and comorbid PH. Multiple dashboards have been created to better understand the effects of concussion as well as the effects that a specific treatment has on patients diagnosed with mTBI. Figure 8 shows four dashboards generated using the data obtained from our comprehensive mTBI database. Figure 8A shows a dashboard with nine different metrics used to monitor outcome measure and monitor patients that have received a specific treatment. Longitudinal data are automatically pulled from the different databases and shown to providers so they can better understand the effectiveness of different treatments among subjects with mTBI. Figure 8B shows a dashboard illustrating the changes of a specific patient. For this particular patient, the users can interactively explore the data and see that the patient is improving in most of the different dimensions, but the severity of the headache seem to be getting worse. Figure 8C shows a screenshot of an interactive tool to explore the health care utilization of mTBI patients.

FIGURE 8. Screenshots of different interactive dashboards have been created to illustrate some of the information been collected from different databases and integrated by our virtual layer. (A) Dashboard showing nine different outcome metrics and the change pre- and post-treatment. (B) Dashboard illustrating the changes observed within a specific patient. For this particular patient, it shows that the patient is improving in most of the different dimensions, but the severity of the headaches seems to be getting worse. (C) Dashboard illustrating another outcome measures—health care utilization pre- and post-treatment. (D) Executive dashboard used to monitor the incidence of mTBI across the DoD and forecast demand for TBI-related clinical services.
pre- and post-treatment. Figure 8D shows a dashboard used to monitor the incidence of mTBI across the DoD and forecast demand for TBI-related clinical services.

**CONCLUSION**

In an effort to raise awareness about how existing DHA guidelines can help organizations design cost-effective ways to collect clinical data within the DoD, this paper described some of the steps that were taken to quickly build a large-scale informatics database to facilitate collection of standardized clinical data and obtain trends of the longitudinal outcomes of service members diagnosed with mTBI. All the systems, components, and applications that were used to build our large-scale data repository are available to organizations and researchers interested in creating their own data repository and trending applications.

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