Title

Feasibility and Utility of a Flexible Outcome Assessment Battery for Longitudinal Traumatic Brain Injury Research: A TRACK-TBI Study.

Journal

Journal of Neurotrauma, 40(3-4)

Authors

Bodien, Yelena
Barber, Jason
Taylor, Sabrina
et al.

Publication Date

2023-02-01

DOI

10.1089/neu.2022.0141

Peer reviewed

Journal of Neurotrauma
40:337–348 (February 2023)

DOI: 10.1089/neu.2022.0141

Journal of Neurotrauma

ORIGINAL ARTICLE CLINICAL STUDIES

Feasibility and Utility of a Flexible Outcome Assessment Battery for Longitudinal Traumatic Brain Injury Research: A TRACK-TBI Study

Yelena G. Bodien,[1–3] Jason Barber,[4] Sabrina R. Taylor,[5] Kim Boase,[4] John D. Corrigan,[6] Sureyya Dikmen,[4] Raquel C. Gardner,[5] Joel H. Kramer,[5] Harvey Levin,[7] Joan Machamer,[4] Thomas McAllister,[8] Lindsay D. Nelson,[9] Laura B. Ngwenya,[10] Mark Sherer,[7,11] Murray B. Stein,[12] Mary Vassar,[5] John Whyte,[13] John K. Yue,[5] Amy Markowitz,[5] Michael A. McCrea,[9] Geoffrey T. Manley,[5] Nancy Temkin,[4] and Joseph T. Giacino[1–3,*]; and the TRACK-TBI Investigators[**]

Abstract

The effects of traumatic brain injury (TBI) are difficult to measure in longitudinal cohort studies, because disparate pre-injury characteristics and injury mechanisms produce variable impairment profiles and recovery trajectories. In preparation for the Transforming Research and Clinical Knowledge in TBI (TRACK-TBI) study, which followed patients with injuries ranging from uncomplicated mild TBI to coma, we designed a multi-dimensional Flexible outcome Assessment Battery (FAB). The FAB relies on a decision-making algorithm that assigns participants to a Comprehensive (CAB) or Abbreviated Assessment Battery (AAB) and guides test selection across all phases of recovery. To assess feasibility of the FAB, we calculated the proportion of participants followed at 2 weeks (2w) and at 3, 6, and 12 months (3m, 6m, 12m) post-injury who completed the FAB and received valid scores. We evaluated utility of the FAB by examining differences in 6m and 12m Glasgow Outcome Scale-Extended (GOSE) scores between participant subgroups derived from the FAB-enabled versus traditional approach to outcome assessment applied at 2w. Among participants followed at 2w ($n = 2094$), 3m ($n = 1871$), 6m ($n = 1736$), and 12m ($n = 1607$) post-injury, 95–99% received valid completion scores on the FAB, in full or in part, either in person or by telephone. Level of function assessed by the FAB-enabled approach at 2w was associated with 6m and 12m GOSE scores (proportional odds $p < 0.001$). These findings suggest that the participant classification methodology afforded by the FAB may enable more effective data collection to improve detection of natural history changes and TBI treatment effects.

[1]Massachusetts General Hospital, Boston, Massachusetts, USA.
[2]Harvard Medical School, Boston, Massachusetts, USA.
[3]Spaulding Rehabilitation Hospital, Charlestown, Massachusetts, USA.
[4]University of Washington, Seattle, Washington, USA.
[5]University of California, San Francisco, San Francisco, California, USA.
[6]The Ohio State University, Columbus, Ohio, USA.
[7]Baylor College of Medicine, Houston, Texas, USA.
[8]University of Indiana School of Medicine, Indianapolis, Indiana, USA.
[9]Medical College of Wisconsin, Milwaukee, Wisconsin, USA.
[10]University of Cincinnati, Cincinnati, Ohio, USA
[11]TIRR Memorial Hermann, Houston, Texas, USA.
[12]University of California San Diego, La Jolla, California, USA.
[13]Moss Rehabilitation Research Institute, Elkins Park, Pennsylvania, USA.
**The TRACK-TBI Investigators may be found at the end of this article.

*Address correspondence to: *Joseph T. Giacino, PhD, Department of Physical Medicine and Rehabilitation, Spaulding Rehabilitation Hospital, 300 First Avenue, Charlestown, MA 02114, USA E-mail:* jgiacino@mgh.harvard.edu

Keywords: assessment; feasibility; outcome assessment; traumatic brain injury

Introduction

Effective treatment of patients with traumatic brain injury (TBI) remains one of the greatest unmet needs in public health, as evidenced by three decades of negative neuroprotection clinical trials.[1] Multiple factors have been hypothesized to account for this problem.[2,3] The need for more precise outcome assessment has recently been emphasized in TBI reviews [3,4] and by federal funding agencies.[5] Traditional approaches to outcome assessment have generally been ''one size fits all.'' The same battery of measures typically is administered to all participants at all time points, regardless of functional status or context. This approach does not account for the marked variability in pre-injury status, injury mechanisms, impairment profiles, and recovery rates associated with TBI.[6,7]

Longitudinal outcome studies that include patients with a broad spectrum of injury severity are particularly challenging given that participants with more severe cognitive dysfunction cannot be assessed with the same measures as those with less severe impairment. This problem has been recognized for nearly 80 years[8] and has been addressed by excluding patients who are unable to undergo standardized neurocognitive testing, assigning these patients to a single ''untestable'' group,[9,10] or using an outcome measure that covers a range of functioning too broad to detect subtle group distinctions. With the exception of an early article by Levin and associates,[10] which found a close relationship between participant testability and outcome at six months, this association has been generally neglected.

Heterogeneity of TBI further complicates longitudinal outcome assessment. While most people who have had a TBI experience some degree of spontaneous recovery over the course of the first year post-injury,[11–13] rates of recovery vary considerably, even among patients who fall within the same injury severity category. Global outcome measures designed to track level of function across the course of injury typically require major changes in functional status to demonstrate progress.[14] Domain-specific measures of function are subject to floor and ceiling effects, which can result in skewed score distributions. These circumstances are exacerbated by the absence of decision-making guidance concerning test selection in TBI studies that enroll a broad spectrum of patients.

Transforming Research and Clinical Knowledge in TBI (TRACK-TBI) is a multi-center prospective observational study, the first phase of which (TRACK-TBI U01) aimed at examining outcome across the first year post-injury in level I trauma center patients with injuries ranging from uncomplicated mild to severe TBI. The study's Outcomes Core was charged with developing an assessment battery that could evaluate participants who were too cognitively impaired to undergo standardized tests of cognition, psychological health, social participation, and quality of life along with those capable of doing so. To that end, we developed the TRACK-TBI Flexible outcome Assessment Battery (FAB) to enable assessment of patients at all levels of TBI severity across multiple domains of function through all phases of recovery.

We administered the FAB in person to participants at 2 weeks (2w), 6 months (6m), and 12 months (12m) post-injury, and by telephone at 3 months (3m) post-injury.[7] We reasoned that all participants would fall into one of three levels of function—disturbance in consciousness, post-traumatic confusional state (PTCS), and non-confused/oriented. We reviewed measures that were developed specifically to assess patients at these levels of function and used a consensus-based approach to select TBI Common Data Elements (CDEs).[15] In the absence of CDEs, we selected measures with the strongest psychometrical characteristics. Finally, we developed a decision tree that guides examiners in selecting the appropriate measures for each study participant (Fig. 1).

The FAB is comprised of three components: a Screening Protocol administered to all participants, an Abbreviated Assessment Battery (AAB) for participants with disorders of consciousness (DoC, i.e., coma, vegetative state [VS], minimally conscious state [MCS], and PTCS), and a Comprehensive Assessment Battery (CAB) for those able to undergo extended standardized neuropsychological testing. Overall, the FAB consists of 23 standardized instruments (see Supplementary Table S1 for a description of each measure), providing coverage across the seven domains of function described in the TBI CDEs—level of consciousness, cognition, psychological health, physical/sensory symptoms, participation, quality of life, and global level of function.

The aims of the current study were to: (1) evaluate the rate of valid completion of the FAB at each time point (i.e., feasibility), (2) identify factors responsible for invalid completion of specific FAB measures (i.e., feasibility), and (3) investigate whether the FAB-enabled approach to outcome assessment applied at 2w identifies subgroups of participants with distinct Glasgow Outcome Scale Extended (GOSE)[16] outcomes at 6m and 12m that would not otherwise be detected on traditional assessment (i.e., utility).

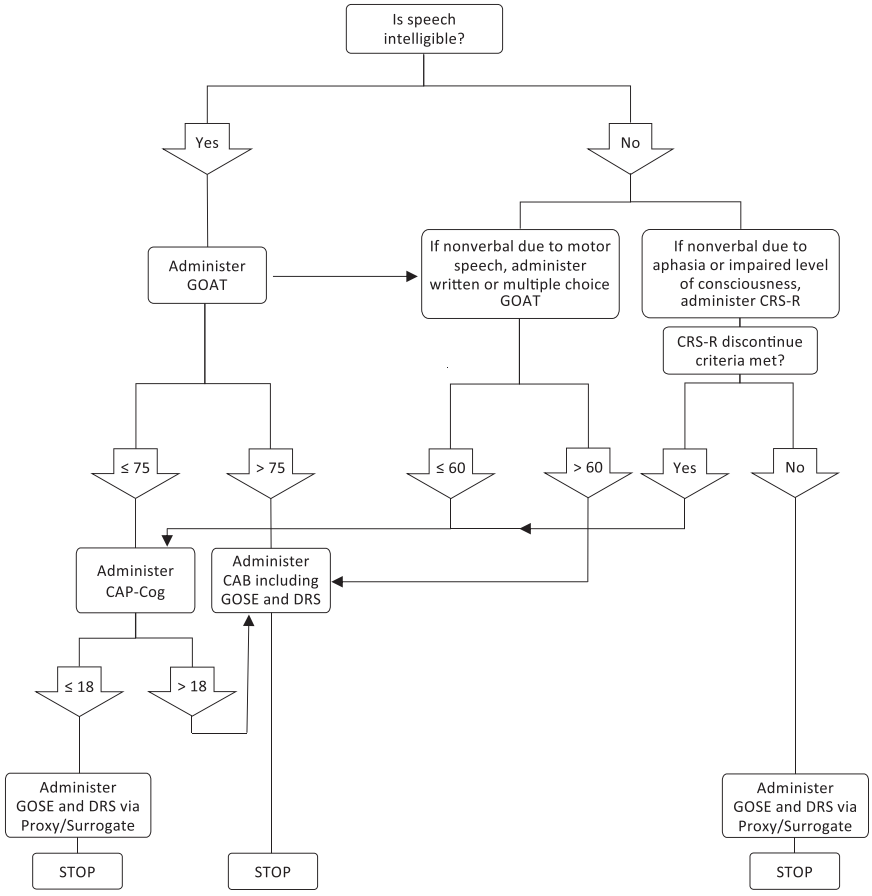

FIG. 1. Flexible Assessment Battery (FAB) decision tree. The examiner begins the FAB by administering a Screening Protocol (SP), which comprises a verbal expression task to ensure that the participant is not aphasic and can speak intelligibly, and the Galveston Orientation and Amnesia Test (GOAT) to assess for ongoing post-traumatic amnesia (PTA). If speech is intelligible and the total GOAT score is >75, the participant progresses to the Comprehensive Assessment Battery (CAB). If speech is intelligible but the participant remains in PTA based on the GOAT (total ≤75), the Cognitive Impairment subscale of the Confusion Assessment Protocol (CAP-Cog) is administered to assess for post-traumatic confusion. If the CAP-Cog score is in the non-confused range (>18), the participant progresses to the CAB. If the CAP-Cog score is in the confused range (≤18), the Glasgow Outcome Scale Extended (GOSE) and Disability Rating Scale (DRS) are completed by the surrogate, concluding the assessment. If the participant is nonverbal because of aphasia or disturbance in consciousness, the Coma Recovery Scale-Revised (CRS-R) is administered. If CRS-R discontinuation criteria are met (Auditory subscale = 4 and Communication subscale = 2 and Arousal subscale = 3), the CAP-Cog is administered and the assessment proceeds as described above. If CRS-R discontinuation criteria are not met, the surrogate completes the GOSE and DRS and the follow-up concludes. At each subsequent follow-up, participants begin with the same battery they were assigned to previously and follow the decision tree, unless there is evidence of a decline in function as judged by the examiner, in which case assessment begins with the SP. The FAB decision tree facilitates assessment of participants across the spectrum of severity, providing examiners with clear guidelines for administration of standardized measures that are appropriate to the participant's current level of function. Additional details about each measure are available in Supplementary Table 1 and by accessing the online TRACK-TBI Standard Operating Procedure (SOP) Manual for Outcome Assessment.[17]

Methods

Participants and study design

TRACK-TBI (clinicaltrials.gov NCT02119182) enrolled 2697 adult and pediatric patients with TBI at 18 level I trauma centers between February 26, 2014, and August 8, 2018. Inclusion and exclusion criteria are presented in Supplementary Table S2. Briefly, inclusion criteria were: (1) presentation to a participating study site within 24 h post-injury, (2) documented acute TBI as defined by the American Congress of Rehabilitation Medicine criteria, and (3) order placed for cranial CT scan. Exclusion criteria were: (1) polytrauma, including spinal cord injury, that could interfere with outcome assessment, and (2) pre-injury debilitating psychiatric disorder or neurological disease. Data collected include clinical indicators, imaging, proteomic and genomic biomarkers, and multi-dimensional outcome data.

For the current study, we excluded participants who were under 18 years of age at enrollment ($n = 145$), withdrew consent ($n = 97$), died before the 2w follow-up ($n = 87$), missed all four follow-up assessments ($n = 158$), or were never assigned to a battery group ($n = 1$) (Fig. 2).

The study was approved by the Institutional Review Board of each enrolling institution and was led by the University of California, San Francisco. Participants or their legally authorized representatives provided written informed consent.

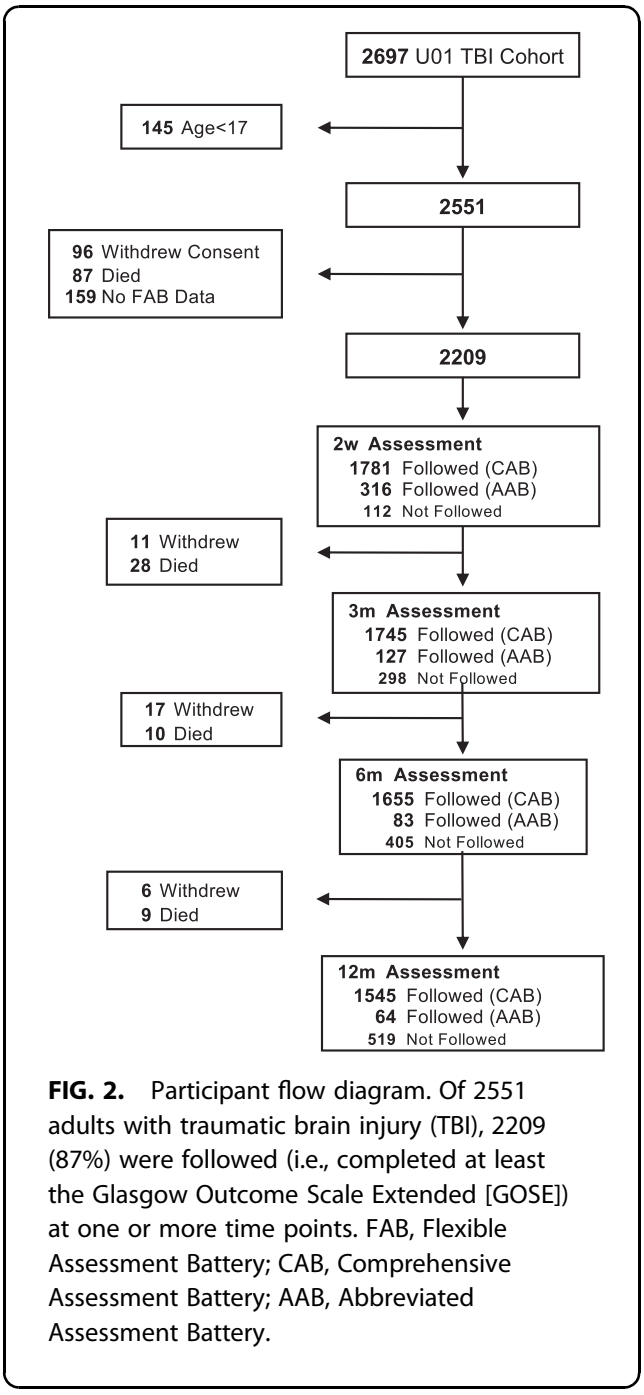

FIG. 2. Participant flow diagram. Of 2551 adults with traumatic brain injury (TBI), 2209 (87%) were followed (i.e., completed at least the Glasgow Outcome Scale Extended [GOSE]) at one or more time points. FAB, Flexible Assessment Battery; CAB, Comprehensive Assessment Battery; AAB, Abbreviated Assessment Battery.

Description of the FAB

To accommodate participants enrolled in TRACK-TBI across all levels of function, we designed the FAB to include two batteries: the AAB for those who cannot complete standardized neuropsychological assessment because of disturbance in consciousness or confusion and the CAB for those able to complete standardized neuropsychological assessment.

The AAB and CAB components of the FAB include different measures to address these differences in level of function. The AAB incorporates two performance-based standardized measures that quantitatively assess level of consciousness and basic elements of cognition. The CAB is composed of performance-based tests of cognition (i.e., attention, memory, information processing speed, executive function), and patient-reported assessment of mood (i.e., depression, anxiety, post-traumatic stress), social participation, and subjective well-being.

Details about administration and scoring of each measure are available by accessing the online TRACK-TBI Standard Operating Procedure (SOP) Manual for Outcome Assessment.[17] A decision tree (Fig. 1) that relies on cut-scores is used to assign participants to either the AAB or CAB (see Supplementary Methods) and to guide battery and test selection when follow-up assessments are conducted. The decision tree also includes skip and stop rules to improve battery efficiency and provides a systematic approach to transitioning from the AAB to the CAB for participants who demonstrate basic cognitive function.

The TRACK-TBI outcome examiners completed extensive in person and virtual training on administration of each measure, as well as use of the decision tree. After data collection, all data forms were curated by a

central site, and queries were sent to individual sites to complete missing data or reconcile data inconsistencies[18] (see Supplementary Methods for details). The GOSE served as the primary outcome measure in TRACK-TBI. For purposes of this study, we used the ''GOSE-TBI'' scoring method, which reflects disability specifically caused by the effects of the TBI.[19]

Data analysis

FAB feasibility. In Aim 1, we calculated the proportion of participants who were followed and received a valid score on each CAB or AAB measure at the 2w, 3m, 6m, and 12m follow-up visits. Examiners applied Test Completion Codes (TCC, see Supplementary Table S3), adapted from a previous clinical trial,[20] to each measure in the battery to indicate whether the measure was completed and valid, completed but invalid, attempted but not completed, or not attempted. The TCCs specify the reason(s) individual tests were not attempted or not completed according to standard procedures (i.e., invalid) and enable analysis of data that are missing for non-random reasons.[8,21]

We operationally defined participants as ''followed'' when the primary outcome measure, the GOSE, was attempted, regardless of whether it was completed. For participants who died, a GOSE score of ''1 = Dead'' was assigned. At each time point, we divided the number of participants who received a valid score on each measure by the number of participants who were followed at that time point. For example, if the GOSE was attempted by 2000 participants at the 2w visit and 1990 participants received a valid score in person or by telephone, the proportion of valid test completions would equal 99.5%.

Finally, we calculated the proportion of participants who received valid scores on all FAB measures and the proportion of measures that were assigned valid scores at each time point. The formulas used to calculate these metrics and additional analytic details are provided in the Supplementary Methods. In Aim 2, we used the TCCs to identify factors contributing to incomplete or invalid assessments. For each measure, and each TCC, we calculated the proportion of participants for whom the measure was either attempted but not completed, or not attempted.

FAB utility. We investigated the utility of the FAB by examining whether the FAB-enabled approach to outcome assessment applied at 2w identifies subgroups of participants with distinct GOSE outcomes at 6m and 12m that would not otherwise be detectable through traditional outcome assessment. To reflect the traditional approach to assessment, we assigned participants to the AAB or CAB groups based on ability to undergo standardized neuropsychological testing. Participants who were too impaired for standardized testing based on results of the screening examination at 2w were assigned to the AAB and the remainder to the CAB.

Employing the FAB-enabled assessment approach at 2w allowed us to test all traditionally ''untestable'' participants using either the Coma Recovery Scale-Revised (CRS-R)[22] or Confusion Assessment Protocol Cognitive Impairment Subscale (CAP-Cog).[23,24] The findings from these measures provided diagnostic information, revealing four subgroups with distinct levels of function within the AAB group (Table 1).

Table 1. Description of Participants in the Traditional and Flexible Outcome Assessment Battery-Enabled Outcome Assessment Groups

Assessment approach	*Group name*	*Description*
Traditional	AAB	Too impaired to undergo standardized neuropsychological testing and assigned to the AAB, based on results of the screening examination
	CAB	Able to undergo standardized neuropsychological testing and assigned to the CAB, based on results of the screening examination
	Group name	***Description***
FAB-enabled	$ComaVS_{AAB}$	Unconscious (criteria for coma or vegetative state [VS][22] met on CRS-R)
	$MCS\text{-}_{AAB}$	Conscious with no evidence of language function (criteria for minimally conscious state *minus* [MCS-][21] met on CRS-R[23])
	$MCS+_{AAB}$	Conscious with evidence of language function (criteria for MCS *plus* [MCS+][21] met on the CRS-R)[23]
	$PTCS_{AAB}$	Conscious with evidence of language function but confused (criteria for post-traumatic confusional state [PTCS] met on CAP-Cog)
	CAB	Conscious, able to undergo standardized neuropsychological testing and assigned to the CAB, based on results of the screening examination

AAB, Abbreviated Assessment Battery; CAB, Comprehensive Assessment Battery; VS, vegetative state; CRS-R, Coma Recovery Scale-Revised; MCS-, minimally conscious state minus (MCS without evidence of language function); MCS+, minimally conscious state plus (MCS with evidence of language function; FAB, Flexible Outcome Assessment Battery; PTCS, post-traumatic confusional state; CAP-Cog, Confusion Assessment Protocol-Cognitive Impairment Subscale.

Table 2. Comparison of Demographic and Acute Injury Characteristics by Battery Assignment

	All participants	*AAB at 2w*	*CAB at 2w*	p
Subjects	2097	316	1781	
Age				
Mean (SD)	40.7 (17.4)	42.4 (17.7)	40.4 (17.4)	0.066
Sex				
Male	1445 (69%)	247 (78%)	1198 (67%)	<0.001
Female	652 (31%)	69 (22%)	583 (33%)	
Race				
A - White	1625 (78%)	252 (81%)	1373 (77%)	0.846
B - Black	337 (16%)	43 (14%)	294 (17%)	
C - Asian	72 (3%)	11 (4%)	61 (3%)	
D - Native Hawaiian/Pac. Isl.	7 (0%)	1 (0%)	6 (0%)	
E - Alaska Native/ Inuit	2 (0%)	0 (0%)	2 (0%)	
F - Indian	5 (0%)	1 (0%)	4 (0%)	
G - Mixed race	37 (2%)	5 (2%)	32 (2%)	
Unknown	12	3	9	
Hispanic				
No	1656 (79%)	242 (78%)	1414 (80%)	0.494
Yes	431 (21%)	69 (22%)	362 (20%)	
Unknown	10	5	5	
Insurance				
A - Insured	1306 (65%)	165 (58%)	1141 (66%)	0.048
B - Medicare/ Medicaid/ Other	278 (14%)	46 (16%)	232 (13%)	
C - Uninsured	433 (21%)	72 (25%)	361 (21%)	
Unknown	80	33	47	
Living situation				
A - Independent living	1631 (80%)	218 (73%)	1413 (81%)	0.001
B - Living with others	392 (19%)	73 (24%)	319 (18%)	
D - Homeless	6 (0%)	2 (1%)	4 (0%)	
E - Other	15 (1%)	6 (2%)	9 (1%)	
Unknown	53	17	36	
Previous TBI history				
0 - None	1545 (80%)	231 (87%)	1314 (78%)	0.004
1 - ED visit	241 (12%)	20 (8%)	221 (13%)	
2 - Hospital stay	155 (8%)	14 (5%)	141 (8%)	
Unknown	156	51	105	
Drug history				
A - No	1352 (68%)	168 (64%)	1184 (68%)	0.002
B - Yes, no trouble	552 (28%)	68 (26%)	484 (28%)	
C - Yes, reported trouble	97 (5%)	25 (10%)	72 (4%)	
Unknown	96	55	41	
Psychiatric history				
A - No history	1368 (65%)	222 (70%)	1146 (64%)	0.042
B – Rec'd professional help	368 (18%)	53 (17%)	315 (18%)	
C - Used meds regularly	291 (14%)	29 (9%)	262 (15%)	
D - Hospitalized	68 (3%)	12 (4%)	56 (3%)	
Unknown	2	0	2	
Cause of injury				
A - Road traffic	1204 (58%)	185 (59%)	1019 (57%)	0.737
B - Fall	551 (26%)	77 (25%)	474 (27%)	
C - Other accident	113 (5%)	15 (5%)	98 (6%)	
D - Violence	144 (7%)	22 (7%)	122 (7%)	
E - Other	78 (4%)	15 (5%)	63 (4%)	
Unknown	7	2	5	
GCS ED				
Mean (SD)	13.1 (3.7)	6.9 (4.2)	14.2 (2.3)	<0.001
Severe (3–8)	272 (13%)	192 (65%)	80 (5%)	<0.001
Moderate (9–12)	106 (5%)	52 (18%)	54 (3%)	
Mild (13–15)	1671 (82%)	51 (17%)	1620 (92%)	
Unknown	48	21	27	
Initial CT				
Negative	1066 (53%)	9 (3%)	1057 (61%)	<0.001
Positive	954 (47%)	290 (97%)	664 (39%)	
Unknown	77	17	60	
ISS non-head/neck				
Mean (SD)	6.0 (7.4)	8.4 (9.4)	5.4 (6.7)	<0.001
Unknown	471	5	466	
Major extracranial inj.				
No	1685 (80%)	203 (64%)	1482 (83%)	<0.001
Yes	412 (20%)	113 (36%)	299 (17%)	
Highest level of care				
A - ED	453 (22%)	1 (0%)	452 (25%)	<0.001
B - Ward	731 (35%)	5 (2%)	726 (41%)	
C - ICU	913 (44%)	310 (98%)	603 (34%)	

AAB, Abbreviated Assessment Battery; CAB, Comprehensive Assessment Battery; w, week; SD, standard deviation; TBI, traumatic brain injury; ED, Emergency Department; GCS, Glasgow Coma Scale; CT, computed tomography; ISS, Injury Severity Score; ICU, intensive care unit.

We compared the median GOSE scores at 6m and 12m between participants assigned to subgroups using the FAB-enabled versus traditional approach to outcome assessment at 2w. We used proportional odds logistic regression to investigate the relationship between level of function at 2w (as determined by the FAB) and GOSE outcome at 6m and 12m.

Results

Participant characteristics

The sample included 2,209 participants: mean (standard deviation [SD]) age 41.4 (17.6) years, predominantly male ($n = 1445$, 69%), and Caucasian ($n = 1625$, 78%). Of surviving participants, 72% and 64% were followed at 6m and 12m, respectively. Outcome data at 2w were available for 2097 of 2209 (95%) participants, of whom most had a mild injury ($n = 1671$, 82%), followed by severe ($n = 272$, 13%), moderate ($n = 106$, 5%) and injury of unknown severity ($n = 48$, 2%). Outcome data were available for 1872 (84%) participants at 3m, 1738 (77%) at 6m, and 1609 (68%) at 12m. Demographic and acute injury characteristics for the AAB and CAB cohorts at 2w are compared in Table 2.

FAB Feasibility

Aggregate completion rates for the CAB and AAB at each follow-up visit are presented in Table 3. Among participants followed (i.e., GOSE attempted), 98–100% of both cohorts (AAB and CAB) received a valid GOSE score (primary outcome measure) across all time points. Among the remaining self- or surrogate-reported

Table 3. Rate of Valid Test Completion by Battery and Outcome Domain among Participants Followed

CAB	2w n = 1780	3m n = 1740	6m n = 1650	12m n = 1543
Measures that can be administered in person or by telephone				
Global outcome				
GOSE	100%	100%	100%	100%
E-DRS-PI	97%	98%	99%	98%
TBI Symptoms				
RPQ	98%	98%	98%	98%
PROMIS-PAIN	96%	97%	97%	97%
ISI	97%	97%	97%	97%
Participation and QOL				
QOLIBRI	97%	98%	98%	97%
MPAI4	97%	98%	98%	98%
SWLS	96%	97%	97%	97%
SF-12	98%	98%	98%	98%
Psychological health				
PCL-5	95%	97%	97%	97%
BSI-18	97%	98%	97%	97%
PHQ-9	96%	97%	97%	97%
Measures that can be administered only in person				
Cognition				
WAIS-IV PSI	83%	—	83%	75%
TMT	83%	—	84%	75%
RAVLT	85%	—	85%	76%
NIH Toolbox	67%	—	69%	64%
AAB	**2w n = 314**	**3m n = 131**	**6m n = 86**	**12m n = 64**
Measures that can be administered in person or by telephone				
Global outcome				
GOSE	98%	98%	99%	100%
E-DRS-PI	97%	96%	99%	100%
Measures that can be administered only in person				
Consciousness/Cognition				
CRS-R/CAP-Cog	72%	—	36%	34%

Percentages represent the proportion of participants followed who completed assigned measures in a valid manner at each time point.

w, week; m, month; CAB, Comprehensive Assessment Battery; AAB, Abbreviated Assessment Battery; GOSE, Glasgow Outcome Scale Extended; E-DRS-PI Expanded Disability Rating Scale Post-Acute Interview; TBI, traumatic brain injury; RPQ, Rivermead Post-Concussion Questionnaire; PROMIS PAIN, Participant Reported Outcome Measurement Information System Pain Intensity and Interference Instruments; ISI, Insomnia Severity Index; QOLIBRI, Quality of Life After Brain Injury–Overall Scale; MPAI4, Mayo-Portland Adaptability Inventory; SWLS, Satisfaction With Life Scale; SF-12, Short Form 12; PCL-C, Post Traumatic Stress Disorder Checklist; BSI-18, Brief Symptom Inventory 18; PHQ-9, Participant Health Questionnaire- 9; WAIS-IV PSI, Wechsler Adult Intelligence Scale Processing Speed Index; TMT, Trail Making Test; RVLT Rey Auditory Verbal Learning Test II; NIH, National Institutes of Health; CRS-R, Coma Recovery Scale- Revised; CAP-Cog, Confusion Assessment Protocol-Cognitive Impairment Subscale.

measures, valid scores were obtained in person or by telephone for at least 95% of participants at all time points. Valid completion rates were generally lower for performance-based measures requiring in person administration (CAB: 64–85%; AAB: 34–72%) and lowest for the NIH Toolbox (CAB) and CRS-R/CAP-Cog (AAB).

Valid completion rates by battery among participants followed are shown in Table 4. The proportion of participants with valid completion on all measures ranged from 34% to 94% for the AAB and from 62% to 95% for the CAB, depending on follow-up time point. Battery duration was longest for the CAB at the 2w time point (mean [SD] = 90 [20] min), and for the AAB at 12m (mean [SD] = 28 [15] min).

Table 4. Valid Completion Rates by Battery among Participants Followed

	Battery assigned	Measures assigned n	Measures with valid completion Mean (%)	Participants with valid completion of full battery n (%)
2w	CAB	16	14.9 (93)	1076 (63)
	AAB	3	2.7 (90)	207 (70)
3m	CAB	12	11.8 (98)	1598 (95)
	AAB	2	1.94 (97)	116 (94)
6m	CAB	16	15.0 (94)	1103 (69)
	AAB	3	2.3 (78)	29 (36)
12m	CAB	16	14.7 (92)	930 (62)
	AAB	3	2.3 (77)	21 (34)

w, week; m, month; CAB, Comprehensive Assessment Battery; AAB, Abbreviated Assessment Battery.

Reasons for incomplete or invalid assessment

Logistical factors (TCC 3.6, Supplementary Table 3) were the most common cause of failure to achieve valid completion. This code was most often applied to performance-based measures when the participant was not available for in person assessment and when technical (e.g., setting up or running the NIH Toolbox) or scheduling problems occurred. Factors such as test refusal, medical issues, and examiner error were recorded in less than 1% of participants per measure. The frequency with which each TCC was recorded for each measure at each time point is presented in Supplementary Tables S4–S7.

Because we were interested in determining whether incomplete or invalid scores were attributable to the burden of the test battery, rather than extraneous circumstances concerning the participant, examiner, or site, we performed a secondary analysis including all followed participants, removing measures with TCCs indicating interference from logistical issues. For each measure, we recalculated the proportion of followed participants who received a valid score. This increased valid completion rates for all performance-based measures to 90% or above at all time points, except for the NIH Toolbox at 2w (87%) (Supplementary Table S8).

FAB utility

The proportion of participants in each of the eight GOSE outcome categories using the traditional approach (untestable participants collapsed into one group) at 2w is compared with the FAB-enabled approach (untestable participants separated into four subgroups) in Figures 3 (6m) and 4 (12m).

While 44% of AAB participants deemed ''untestable'' at 2w by the traditional approach fell in the Lower Moderate Disability (LMD) category or better at 6m (Fig. 3,

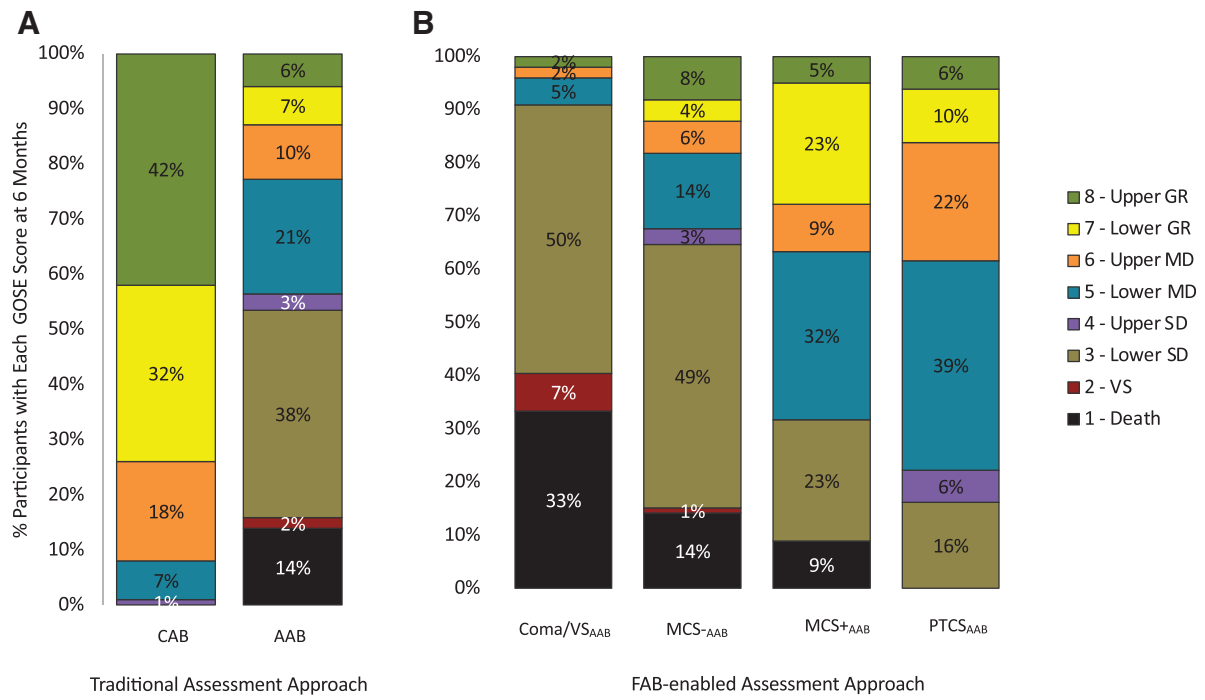

FIG. 3. Proportion of participants' 6-month Glasgow Outcome Scale Extended (GOSE) scores by category based on the traditional and Flexible Assessment Battery (FAB)-enabled approaches to assessment at two weeks post-injury. The FAB-enabled approach to assessment generated four distinct subgroups with marked differences in GOSE outcome at 6m. (**A**) When participants who were unable to be assessed using standard neuropsychological testing were assigned to the Abbreviated Assessment Battery (AAB) at 2w and combined into a single group (i.e., traditional approach), the median 6m GOSE score was 3 (Lower Severe Disability), which is 4 points lower than the median score for participants assigned to the Comprehensive Assessment Battery (CAB) group (7- Lower Good Recovery). (**B**) When AAB participants were classified by level of function into four subgroups using the Coma Recovery Scale-Revised (CRS-R) and Confusion Assessment Protocol (CAP-Cog) measures in the FAB, the median 6m GOSE score for the minimally conscious state plus (MCS with evidence of language function (MCS+$_{AAB}$) and post-traumatic confusional state (PTCS$_{AAB}$) subgroups was 2 points higher (5- Lower Moderate Disability) than the 6m GOSE score estimated using the traditional approach (3- Lower Severe Disability). GR, good recovery; MD, moderate disability; SD, severe disability; VS, vegetative state; MCS-, minimally conscious state minus (MCS without evidence of language function).

Panel A), the FAB-enabled approach parsed the ''untestable'' group into four discrete subgroups showing markedly different outcomes (Fig. 3, Panel B) at the same time points. Among participants in the coma/VS$_{AAB}$ subgroup, 9% fell into the LMD category or better at 6m, compared with 69% and 77% of those in the MCS+$_{AAB}$ and PTCS$_{AAB}$ subgroups, respectively. At 12m, the findings were similar (Fig. 4). Mean and median GOSE scores for the four FAB-enabled subgroups and for the traditionally assessed group are presented in Table 5. At 6m, median GOSE scores were 2 points higher for the MCS+ and PTCS subgroups compared with median scores obtained using the traditional approach.

Proportional odds logistic regression indicated that when the FAB-enabled subgroups defined at 2w were used to characterize outcome at 6m and 12m, GOSE scores differed significantly among the four AAB subgroups (6m $p<0.001$, 12m $p<0.001$). For example, GOSE scores were significantly higher at 6m and 12m for both the MCS+ and MCS- subgroups relative to the coma/VS subgroup, and for the PTCS subgroup relative to the MCS- subgroup (see Table 6 for odds ratios for each between-group comparison).

Discussion

We followed a large cohort of TRACK-TBI study participants with mild to severe TBI across the first year post-injury using a novel multi-dimensional flexible outcome assessment battery (''FAB'') designed to accommodate

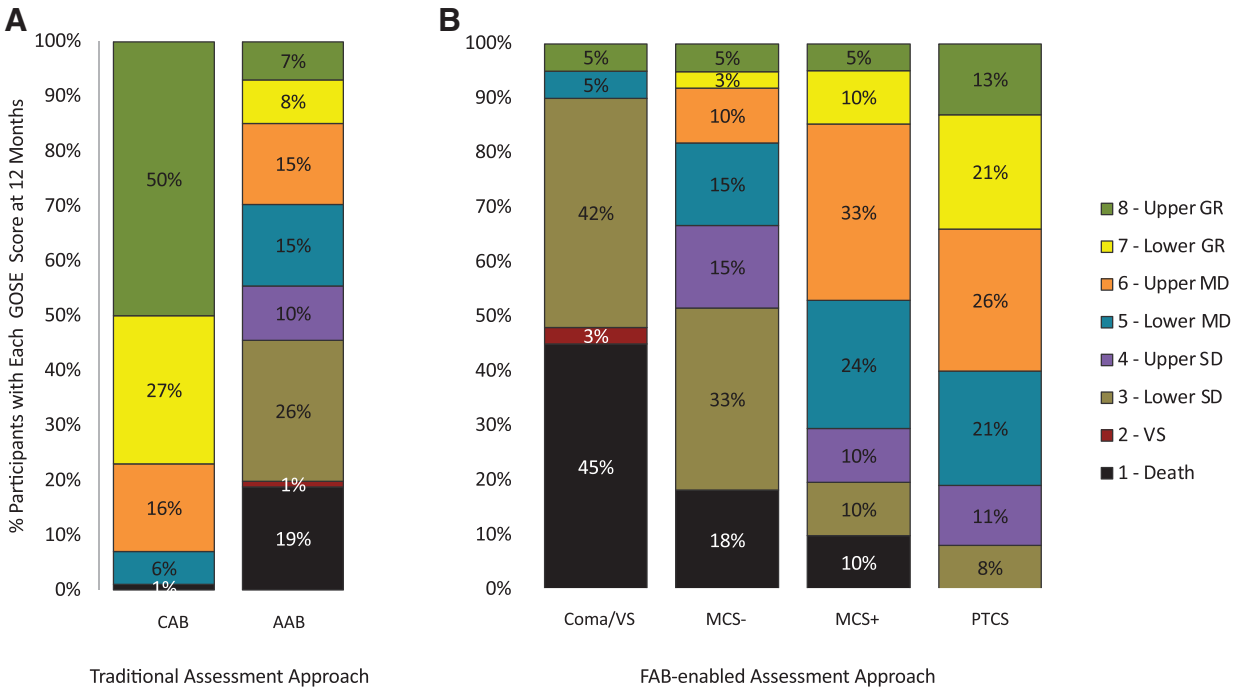

FIG. 4. Proportion of participants' 12-month Glasgow Outcome Scale Extended (GOSE) scores by category based on the traditional and Flexible Assessment Battery (FAB)-enabled approaches to assessment at two weeks post-injury. The FAB-enabled approach to assessment generated four distinct subgroups with marked differences in GOSE outcome at 6m. (**A**) When participants who were unable to be assessed using standard neuropsychological testing were assigned to the Abbreviated Assessment Battery (AAB) at 2w and combined into a single group (i.e., traditional approach), the median 12m GOSE score was 4 (Upper Severe Disability), which is 3 points lower than the median score for participants assigned to the Comprehensive Assessment Battery (CAB) group at 2w (7- Lower Good Recovery). (**B**) When AAB participants were classified by level of function at 2w into four subgroups using the Coma Recovery Scale-Revised (CRS-R) and Confusion Assessment Protocol (CAP-Cog) measures in the FAB, the median 12m GOSE score was 1 point higher for the minimally conscious state plus (MCS with evidence of language function ($MCS+_{AAB}$) subgroup (5- Lower Moderate Disability) and 2 points higher for the post-traumatic confusional state ($PTCS_{AAB}$) subgroup (6- Upper Moderate Disability) when compared with the 12m GOSE score estimated using the traditional approach (4- Upper Severe Disability). GR, good recovery; MD, moderate disability; SD, severe disability; VS, vegetative state.

Table 5. Comparison between 6- and 12-Month Glasgow Outcome Scale Extended Scores Obtained Using the Traditional and Flexible Outcome Assessment Battery-Enabled Outcome Assessment Approach

		6m GOSE score			*12m GOSE score*		
Assessment Approach at 2w		**n**	***Mean (SD)***	***Median [IQR]***	***N***	***Mean (SD)***	***Median [IQR]***
Traditional approach	AAB	184	4.0 (2.0)	3 [3,5]	157	4.1 (2.1)	4 [3,6]
FAB-enabled approach	$Coma/VS_{AAB}$	42	2.5 (1.5)	3 [1,3]	38	2.4 (1.8)	3 [1,3]
	$MCS-_{AAB}$	71	3.8 (2.0)	3 [3,5]	60	3.8 (1.9)	3 [3,5]
	$MCS+_{AAB}$	22	4.9 (2.0)	5 [3,7]	21	5.0 (1.8)	5 [4,6]
	$PTCS_{AAB}$	49	5.2 (1.4)	5 [5,6]	38	5.8 (1.4)	6 [5,7]
CAB[a]		1199	7.1 (1.0)	7 [6,8]	1048	7.2 (1.1)	7 [7,8]

[a]Participants in the CAB were included in both the traditional and FAB-enabled approaches.

w, weeks; GOSE, Glasgow Outcome Scale Extended; SD, standard deviation; IQR, interquartile range; AAB, Abbreviated Assessment Battery; VS, vegetative state; FAB, Flexible Outcome Assessment Battery; MCS-, minimally conscious state minus (MCS without evidence of language function); MCS+, minimally conscious state plus (MCS with evidence of language function); PTCS, post-traumatic confusional state; CAB, Comprehensive Assessment Battery.

Table 6. Odds Ratios for Glasgow Ootcome Scale Extended Outcome Scores at 6m and 12m across Groups Using the Flexible Outcome Assessment Battery-Enabled Outcome Assessment Approach

	Group comparison	*OR*	*95% CI*	p
6m	All groups	NA	NA	< 0.001
	$MCS-_{AAB}$ $Coma/VS_{AAB}$	4.24	(1.98, 9.08)	< 0.001
	$MCS+_{AAB}$ $Coma/VS_{AAB}$	15.68	(5.64, 43.61)	< 0.001
	$PTCS_{AAB}$ $Coma/VS_{AAB}$	20.17	(8.44, 48.22)	< 0.001
	$MCS+_{AAB}$ $MCS-_{AAB}$	3.70	(1.54, 8.90)	0.004
	$PTCS_{AAB}$ $MCS-_{AAB}$	4.75	(2.38, 9.50)	< 0.001
	$PTCS_{AAB}$ $MCS+_{AAB}$	1.29	(0.53, 3.14)	0.581
12m	AAB group	NA	NA	< 0.001
	$MCS-_{AAB}$ $Coma/VS_{AAB}$	4.81	(2.18, 10.65)	< 0.001
	$MCS+_{AAB}$ $Coma/VS_{AAB}$	18.56	(6.47, 53.19)	< 0.001
	$PTCS_{AAB}$ $Coma/VS_{AAB}$	36.76	(14.03, 96.32)	< 0.001
	$MCS+_{AAB}$ $MCS-_{AAB}$	3.86	(1.56, 9.51)	0.003
	$PTCS_{AAB}$ $MCS-_{AAB}$	7.64	(3.48, 16.78)	< 0.001
	$PTCS_{AAB}$ $MCS+_{AAB}$	1.98	(0.77, 5.11)	0.157

OR, odds ratio; CI, confidence interval; m, month; NA, not applicable; MCS-, minimally conscious state minus (MCS without evidence of language function); AAB, Abbreviated Assessment Battery; VS, vegetative state; PTCS, post-traumatic confusional state; MCS+, minimally conscious state plus (MCS with evidence of language function).

participants across the full spectrum of injury severity. Feasibility testing indicated that valid completion rates were high for the battery overall. Although this finding is generally consistent with previous literature,[9] rates were highest for telephone-administered self-report measures and lowest for performance-based measures requiring in person assessment. The CRS-R (AAB), CAP-Cog (AAB), and NIH Toolbox (CAB) had the lowest valid completion rates.

Valid completion rates were as low as 34% on some measures at the 6m and 12m follow-ups among participants with the most severe disability. This is unsurprising because patients with severe TBI often have significant physical limitations, recurrent medical instability, and insufficient insurance coverage for transportation. In line with this observation, we found that logistical problems (e.g., inability to return to the study site, scheduling problems, need for disability accommodations) accounted for most failures to complete assigned measures in a valid manner. Our protocol did not allow us to determine which logistical reasons accounted for participant failure to complete in person measures.

Among higher functioning participants assigned to the CAB, challenges to valid test completion most often arose from technical difficulties encountered during in person test administration. Poor internet connectivity, equipment breakdown, and challenges operating the mouse among older age participants complicated valid completion of the NIH Toolbox. These findings highlight the pressing need, exacerbated further by the COVID-19 pandemic, for validated measures of consciousness and cognition that can be administered remotely. The Brief Test of Adult Cognition by Telephone, a standardized cognitive test battery, addresses this need and has been validated against traditional paper-and-pencil tests in TRACK-TBI.[25] The TRACK-TBI investigators are also currently conducting validation studies on telephone-based versions of the CRS-R and CAP-Cog.

To establish the utility of the FAB, we investigated whether the FAB-enabled approach to outcome assessment could identify subgroups of participants at 2w with distinct GOSE outcomes at 6m and 12m that would not otherwise be detected using the traditional assessment approach. The FAB-enabled approach allowed us to parse participants lumped together as ''untestable'' by the traditional approach into four distinct subgroups characterized by discernibly different levels of function. The median GOSE score at 6m and 12m was as much as two categories higher in some cases when the FAB-enabled approach was compared with the traditional approach.

Consistent with previous evidence showing that level of consciousness is predictive of outcome,[26,27] we also found that the odds of being in a higher GOSE category at 6m and 12m increased as level of consciousness at 2w, as measured by the FAB, increased. These findings suggest that the FAB may unmask meaningful differences in outcome that would otherwise be overlooked by collapsing ''untestable'' participants into a single group and support previous studies suggesting that broad outcome categories decrease the precision of outcome assessment.[21,28–30] The FAB-enabled approach to outcome assessment offers investigators a methodology to systematically assess research participants across the full range of TBI severity, accommodate changes in function over time, and avoid underestimation of outcome in clinical trials.

This study has some limitations. While our overall follow-up rates of 72% and 64% at 6m and 12m, respectively, are lower than the 80–90% follow-up rates reported in some previous multi-center TBI studies,[9,31,32] this may reflect differences in eligibility criteria and how ''follow-up'' was defined. We did not systematically collect data on the reasons why participants did not attend follow-up visits, in part because many participants were not reachable after hospital discharge. Thus, we do not know whether the content or duration of the FAB contributed to missed follow-ups. Our interest was primarily in assessing how well participants tolerated the FAB, which required their presence during phone-based or in-person study visits.

The TCCs provided detailed information about factors contributing to incomplete and confounded assessment in participants who were followed. It should be noted that the TCCs used here, and in previous studies,[7,10,20,23,33,34] have not been psychometrically validated. In addition, although TRACK-TBI enrolled 314 participants with severe injury, findings may differ in a larger sample.

Our results lay the groundwork for use of a flexible outcome battery in TBI clinical trials and provide opportunity for future studies to extend and validate the findings. The difference in GOSE scores observed between the MCS+ and MCS- subgroups suggests the need for TBI outcome measures with an extended floor. Previous studies support the premise that inclusion of these subgroups can effectively extend the floor of existing global outcome measures[14,26,33,35]

Future research should also consider alternate approaches to data analysis, including item response theory,[36] which can account for differences in baseline level of function. This approach would enable integration of data from the AAB and CAB into the same outcome model.

Conclusions

We developed and deployed a flexible outcome assessment battery (i.e., ''FAB'') that enables standardized longitudinal assessment of research participants with very mild to very severe TBI. Use of a FAB is in keeping with a broader movement in neuropsychological assessment across other neurological disease states, as well. Although the FAB was well-tolerated, logistical problems were a common cause of failure to achieve valid completion. Our utility analysis demonstrated that the FAB can identify subgroups of participants traditionally considered ''untestable'' because of severe cognitive impairment who have distinct outcomes at 6m and 12m post-injury. These findings suggest that the FAB can mitigate challenges to outcome assessment associated with TBI heterogeneity and may avoid underestimation of outcome in clinical trials.

Acknowledgments

The authors wish to posthumously acknowledge the monumental contributions made to TBI research and clinical practice by our friend, colleague, and advisor, Harvey Levin, PhD (1946-2022). In addition to the guidance he provided on the design and implementation of the TRACK-TBI Flexible outcome Assessment Battery (FAB), Dr. Levin's remarkable 50-year legacy has left an indelible mark on the field and shaped the careers of hundreds of neuropsychologists worldwide. He will be greatly missed.

TRACK-TBI Investigators

Ramon Diaz-Arrastia, University of Pennsylvania; Adam R. Ferguson, University of California, San Francisco; Ramesh Grandhi, University of Utah; Ruchira Jha, Barrow Neurological Institute; C. Dirk Keene, University of Washington; Frederick K. Korley, University of Michigan; Christopher Madden, UT Southwestern; Randall Merchant, Virginia Commonwealth University; Pratik Mukherjee, University of California, San Francisco, David Okonkwo, University of Pittsburgh; Claudia Robertson, Baylor College of Medicine; David Schnyer, UT Austin; Ross Zafonte, Harvard Medical School

Authors' Contributions

Yelena G. Bodien: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing–Original Draft, Review and Editing, Visualization, Supervision, Project Administration; Jason Barber: Methodology, Validation, Formal Analysis, Data Curation, Writing–Original Draft, Review and Editing; Sabrina R Taylor: Conceptualization, Validation, Investigation, Data Curation, Writing–Review and Editing, Project Administration; Kim Boase: Conceptualization, Methodology, Validation, Data Curation, Writing–Review and Editing, Supervision; John D. Corrigan: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Sureyya Dikmen: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Raquel C. Gardner: Conceptualization, Writing–Review and Editing; Joel H Kramer: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Harvey Levin: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Joan Machamer: Conceptualization, Methodology, Validation, Data Curation, Writing–Review and Editing; Thomas McAllister: Conceptualization, Methodology, Investigation, Writing – Review and Editing; Lindsay D. Nelson, PhD: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Laura B. Ngwenya: Methodology, Investigation, Writing–Review and Editing; Mark Sherer: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Murray B. Stein: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Mary Vassar: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Project Administration; John Whyte: Conceptualization, Methodology, Investigation, Writing–Review and Editing; John K. Yue: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Amy Markowitz: Investigation, Writing–Review and Editing, Project Administration, Funding Acquisition; Michael A. McCrea: Conceptualization, Methodology, Investigation, Writing–Review and Editing; Geoffrey T. Manley, Nancy Temkin: Conceptualization, Methodology, Investigation, Validation, Formal Analysis, Writing–Original Draft, Review and Editing, Funding Acquisition; Joseph T. Giacino: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing–Original Draft, Review,

and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; TRACK-TBI Investigators: Investigation, Writing–Review and Editing

Funding Information

The contents of this publication were developed under grants from: NIH/NINDS (Grant UO1-NS086090) and DoD (Grant W81XWH-14-2-0176).

Author Disclosure Statement

No competing financial interests exist.

Supplementary Material

Supplementary Methods
Supplementary Table S1
Supplementary Table S2
Supplementary Table S3
Supplementary Table S4
Supplementary Table S5
Supplementary Table S6
Supplementary Table S7
Supplementary Table S8

References

1. Maas AI, Roozenbeek B, Manley GT. Clinical trials in traumatic brain injury: past experience and current developments. Neurotherapeutics 2010; 7(1):115–126; doi: 10.1016/j.nurt.2009.10.022
2. Maas AI, Menon DK, Lingsma HF, et al. Re-orientation of clinical research in traumatic brain injury: report of an international workshop on comparative effectiveness research. J Neurotrauma 2012;29(1):32–46; doi: 10.1089/neu.2010.1599
3. Menon DK, Maas AI. Traumatic brain injury in 2014. Progress, failures and new approaches for TBI research. Nat Rev Neurol 2015;11(2):71–72; doi:10.1038/nrneurol.2014.261
4. Stein DG. Embracing failure: what the Phase III progesterone studies can teach about TBI clinical trials. Brain Inj 2015;29(11):1259–1272; doi:10.3109/02699052.2015.1065344
5. Saatman KE, Duhaime AC, Bullock R, et al. Classification of traumatic brain injury for targeted therapies. J Neurotrauma 2008;25(7):719–738; doi:10.1089/neu.2008.0586
6. Tversky A, Kahneman D. Judgment under uncertainty: heuristics and biases. Science 1974;185(4157):1124–1131; doi:10.1126/science.185.4157.1124
7. Bodien YG, McCrea M, Dikmen S, et al. Optimizing outcome assessment in multicenter TBI trials: perspectives from TRACK-TBI and the TBI Endpoints Development Initiative. J Head Trauma Rehabil 2018;33(3): 147–157; doi:10.1097/HTR.0000000000000367
8. Ruesch J, Moore, BE. Measurement of intellectual functions in the acute stage of head injury. Arch NeurPsych 1943;50(2):165–170; doi:10.1001/archneurpsyc.1943.02290200065005
9. Scheibel RS, Levin HS, Clifton GL. Completion rates and feasibility of outcome measures: experience in a multicenter clinical trial of systemic hypothermia for severe head injury. J Neurotrauma 1998;15(9):685–692; doi:10.1089/neu.1998.15.685
10. Levin HS, Gary HE Jr, Eisenberg HM, et al. Neurobehavioral outcome 1 year after severe head injury. Experience of the Traumatic Coma Data Bank. J Neurosurg 1990;73(5):699–709; doi:10.3171/jns.1990.73.5.0699
11. Hammond FM, Giacino JT, Nakase Richardson R, et al. Disorders of consciousness due to traumatic brain injury: functional status ten years post-injury. J Neurotrauma 2019;36(7):1136–1146; doi:10.1089/neu.2018.5954
12. Whyte J, Nakase-Richardson R, Hammond FM, et al. Functional outcomes in traumatic disorders of consciousness: 5-year outcomes from the National Institute on Disability and Rehabilitation Research Traumatic Brain Injury Model Systems. Arch Phys Med Rehabil 2013;94(10):1855–1860; doi:10.1016/j.apmr.2012.10.041
13. Nakase-Richardson R, Whyte J, Giacino JT, et al. Longitudinal outcome of patients with disordered consciousness in the NIDRR TBI Model Systems Programs. J Neurotrauma 2012;29(1):59–65; doi:10.1089/neu.2011.1829
14. Whyte J, Giacino JT, Heinemann AW, et al. Brain Injury Functional Outcome Measure (BI-FOM): A single instrument capturing the range of recovery in moderate-severe traumatic brain injury. Arch Phys Med Rehabil 2021;102(1):87–96; doi:10.1016/j.apmr.2020.09.377
15. Hicks R, Giacino J, Harrison-Felix C, et al. Progress in developing common data elements for traumatic brain injury research: version two–the end of the beginning. J Neurotrauma 2013;30(22):1852–1861; doi:10.1089/neu.2013.2938
16. Wilson JT, Pettigrew LE, Teasdale GM. Structured interviews for the Glasgow Outcome Scale and the extended Glasgow Outcome Scale: guidelines for their use. J Neurotrauma 1998;15(8):573–585; doi:10.1089/neu.1998.15.573
17. TRACK-TBI Resources for Researchers. Available from: https://tracktbi.ucsf.edu/researchers [Last accessed: October, 21, 2021].
18. Boase K, Machamer J, Temkin NR, et al. Central curation of Glasgow Outcome Scale-Extended data: lessons learned from TRACK-TBI. J Neurotrauma 2021;38(17):2419–2434; doi:10.1089/neu.2020.7528
19. Wilson L, Boase K, Nelson LD, et al. A manual for the Glasgow Outcome Scale-Extended interview. J Neurotrauma 2021;38(17):2435–2446; doi:10.1089/neu.2020.7527
20. Zafonte RD, Bagiella E, Ansel BM, et al. Effect of citicoline on functional and cognitive status among patients with traumatic brain injury: Citicoline Brain Injury Treatment Trial (COBRIT). JAMA 2012;308(19):1993–2000; doi:10.1001/jama.2012.13256
21. Pastorek NJ, Hannay HJ, Contant CS. Prediction of global outcome with acute neuropsychological testing following closed-head injury. J Int Neuropsychol Soc 2004;10(6):807–817; doi:10.1017/s1355617704106012
22. Giacino JT, Kalmar K, Whyte J. The JFK Coma Recovery Scale-Revised: measurement characteristics and diagnostic utility. Arch Phys Med Rehabil 2004;85(12):2020–2029; doi:10.1016/j.apmr.2004.02.033
23. Sherer M, Nakase-Thompson R, Yablon SA, et al. Multidimensional assessment of acute confusion after traumatic brain injury. Arch Phys Med Rehabil 2005;86(5):896–904; doi:10.1016/j.apmr.2004.09.029
24. Sherer M, Katz DI, Bodien YG, et al. Post-traumatic confusional state: a case definition and diagnostic criteria. Arch Phys Med Rehabil 2020; 101(11):2041–2050; doi:10.1016/j.apmr.2020.06.021
25. Nelson LD, Barber JK, Temkin NR, et al. Validity of the Brief Test of Adult Cognition by Telephone in level 1 trauma center patients six months post-traumatic brain injury: A TRACK-TBI study. J Neurotrauma 2021; 38(8):1048–1059; doi:10.1089/neu.2020.7295
26. Giacino JT, Sherer M, Christoforou A, et al. Behavioral recovery and early decision making in patients with prolonged disturbance in consciousness after traumatic brain injury. J Neurotrauma 2020;37(2):357–365; doi:10.1089/neu.2019.6429
27. Luauté J, Maucort-Boulch D, Tell L, et al. Long-term outcomes of chronic minimally conscious and vegetative states. Neurology 2010;75(3):246–252; doi:10.1212/WNL.0b013e3181e8e8df
28. Nelson LD, Brett BL, Magnus BE, et al. Functional Status Examination yields higher measurement precision of functional limitations after traumatic injury than the Glasgow Outcome Scale-Extended: a preliminary study. J Neurotrauma 2020;37(4):675–679; doi: 10.1089/neu.2019.6719
29. Zou LF, Pierce B, Nielson JL. A multi-modal assessment of clinical predictors for traumatic brain injury end-points. J Neurotrauma 2021;38(2): 261–271; doi:10.1089/neu.2020.7222
30. Nelson LD, Ranson J, Ferguson AR, et al. Validating multidimensional outcome assessment using the TBI Common Data Elements: an analysis of the TRACK-TBI pilot sample. J Neurotrauma 2017;34(22):3158–3172; doi: 10.1089/neu.2017.5139
31. Richter S, Stevenson S, Newman T, et al. Handling of missing outcome Ddata in traumatic brain injury research: a systematic review. J Neurotrauma 2019;36(19):2743–2752; doi:10.1089/neu.2018.6216
32. Yue JK, Vassar MJ, Lingsma HF, et al. Transforming research and clinical knowledge in traumatic brain injury pilot: multicenter implementation of the common data elements for traumatic brain injury. J Neurotrauma 2013;30(22):1831–1844; doi:10.1089/neu.2013.2970
33. Thibaut A, Bodien YG, Laureys S, et al. Minimally conscious state "plus": diagnostic criteria and relation to functional recovery. J Neurol 2020; 267(5):1245–1254; doi:10.1007/s00415-019-09628-y
34. Dams-O'Connor K, Sy KTL, Landau A, et al. The feasibility of telephone-administered cognitive testing in individuals 1 and 2 Years after inpatient rehabilitation for traumatic brain injury. J Neurotrauma 2018; 35(10):1138–1145; doi:10.1089/neu.2017.5347
35. Formisano R, Contrada M, Ferri G, et al. The Glasgow Outcome Scale Extended-Revised (GOSE-R) to include minimally conscious state in the vegetative vtate/unresponsive wakefulness syndrome category: a correlation with Coma Recovery Scale-Revised (CRS-R). Eur J Phys Rehabil Med 2019;55(1):139–140; doi:10.23736/S1973-9087.18.05441-2
36. Hambleton RK, Swaminathan H, Rogers HJ. Fundamentals of Item Response Theory. Sage Publications, Inc: Thousand Oaks, CA. 1991