A Novel Repairable Wireless Blast Anthropomorphic Test Device

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Abstract. The Wireless Blast Anthropomorphic Test Device (WBATD) is a novel untethered, field-maintainable, and highly repeatable anthropomorphic test device capable of collecting meaningful data enabling evaluation of personal protective equipment (PPE) blast attenuating performance. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) designed and developed the WBATD, which includes blast-specific components (i.e. WBATD Headform, WBATD Torso, and WBATD Neck) that are integrated with arms, legs, pelvis, and neck of the Humanetics Hybrid III 50th Male Pedestrian dummy. The blast specific components contain sensors and wireless data acquisition systems to record blast relevant metrics, while the extremities allow the system to be postured in operationally realistic positions, PPE to be donned fully and functionally, motion resulting from blast overpressure to be realistic (enabling meaningful kinematic data collection), and modular parts to be easily accessible and replaceable without specialized tools or fabrication methods. The WBATD was developed with sufficient anatomical fidelity and instrumentation to enable comparison with other blast injury surrogates and to support ongoing and future blast injury research and modeling efforts. Since development of this novel surrogate, JHU/APL has executed laboratory testing of the blast-specific components, as well as live-fire field testing of the full system. Laboratory testing of the WBATD was conducted under varying blast exposure levels, ATD orientations with respect to the shockwave, and PPE configurations. This testing showed the system to have satisfactory sensitivity between test configurations and high repeatability when exposed to the same test condition. Live-fire testing of the WBATD full system under varying postures, orientations, and PPE configurations, at a number of bomb-suit-relevant blast doses demonstrated the sensitivity, durability, and usability of the system. Future plans include biomechanics-matched field testing of the WBATD in order to develop injury risk curves relevant to the test device.

1. INTRODUCTION

To better protect warfighters, there is an interest in assessing the performance of PPE such as explosive ordnance disposal (EOD) suits in comparison to previous designs, and across suit configurations. The primary function of an EOD suit is to protect the wearer from the possibility of blast-induced injury. Of the four components of blast injury, primary blast injury (resulting from the blast overpressure of an explosion) is potentially the most dangerous. Unfortunately, this injury mechanism is also the least well understood, and first article testing of warfighter PPE does not include a standard for blast overpressure attenuation performance.

A validated surrogate system for predicting risk of primary blast injury does not currently exist. ATDs which have been used for blast testing have several limitations that restrict their widespread adoption. These limitations include cumbersome and delicate external cables and data acquisition systems that restrict mobility, lack of sufficient sensors to capture important metrics in the context of armored blast exposure, and lack of anthropometry to allow for realistic postures, donning of PPE, and blast-induced motion. Other, more biofidelic surrogates are inappropriate for first article testing because their complexity means repair or maintenance can have a significant impact on system repeatability or delay test efforts. Existing ATDs that have been used to study the effects of blast include the Blast Test Device (BTD) and updated Anthropomorphic Blast Test Device (ABTD) [1], a Hybrid III-50M (HII) crash test dummy modified to house pressure transducers [2], the recently developed Blast Overpressure Mannequin (BOPMAN) [3] and Brain Injury Protection Evaluation Device (BIPED) [4], as well as the Human Surrogate Head Model (HSHM) [5] and Human Surrogate Torso Model (HSTM) [6]. While these systems differ greatly in terms of biofidelity, repairability, usability, etc., they all suffer from one or more of the previously listed limitations, and would not be appropriate systems for the first article testing of bomb suits.

To address these limitations, the aim of this work was to design, fabricate, and verify operation of an untethered, field-maintainable, and highly repeatable ATD capable of collecting meaningful data for the evaluation of the blast attenuating performance of personal protective equipment. Through inspiration from existing blast ATDs, collaboration with external institutions with expertise in blast injury research, and leveraging advanced manufacturing and low-size, -weight, and -power (SWaP) electronics, JHU/APL developed a novel, fully integrated WBATD that provides vastly improved usability, operational costs, performance, and applicability to injury risk assessment over existing blast ATDs.

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2. DESIGN AND DEVELOPMENT

2.1 System Requirements

Meetings with other institutions with expertise in blast injury research (DEVCOM Soldier Center, Walter Reed Army Institute of Research, Army Research Laboratory, Aberdeen Test Center) were held in order to draft a set of requirements for the surrogate with regard to use cases, system performance, usability, and repairability.

Modularity and flexibility of surrogate configurations (e.g. component vs integrated testing), environments (laboratory, live-fire (LF)) and tethered and untethered testing modes were identified as critical requirements for the system, as well as the ability to test in multiple postures, orientations, and PPE configurations. It was determined that, in order for data from the WBATD to properly capture the full blast attenuating properties of PPE, baseline bare tests should be completed at whichever blast doses were used to evaluate said PPE, meaning the system must be robust enough to survive relevant blast doses unarmored.

In order to support future metrics of blast injury prevention, it was determined that the system must capture data with high enough fidelity to align with ongoing efforts to develop injury risk models, while having high repeatability and reproducibility.

Usability and repairability criteria were outlined to enable operational deployment for first article testing, including ease of use and operational cost. Additionally, repairability, and part replacement requirements were set, with the goal that high-risk repairs can happen on-site without specialized tools or manufacturing facilities.

2.2 System Overview

Based on these requirements, a robust and modular design was developed for the WBATD. A priority was placed on using COTS parts so that any part that might need repair could be accessed and replaced without any specialized tools or fabrication methods. The three blast-specific components (headform, neck, and torso) were designed to integrate with the HIII-50M Pedestrian (PED) arms, legs, pelvis, and neck. This allows the system to be postured in operationally realistic positions, PPE to be donned fully, and motion to be simulated during a blast test, enabling meaningful kinematic data collection. As the HIII-50M PED is a widely used ATD, many biomechanics test facilities already have spare HIII-50M PED parts at their disposal, allowing rapid replacement of damaged components. A fully on-board data acquisition system (DAS) and battery were incorporated into the design, eschewing the need for external cabling, amplifiers, etc., which can become damaged during the course of a test and interfere with blast-induced motion. Special consideration for the usability of the surrogate was also given. For example, reducing the number of disassembly steps required to reach critical components while maintaining their protection during blast events. Additionally, *armed* status and *power* status of the DAS can be determined externally after the system has PPE installed and postured for a blast event. Finally, the system was made to be modular and repairable: head and torso systems can be tested together or separately, the components in each system can be replaced with spare parts without the need for specialized tools. The three blast-specific assemblies, headform, neck, and torso, as well as the instrumentation and data acquisition system, are detailed in the following sections.

The fully assembled WBATD system is shown in **Figure 1.** Overview of the WBATD system showing blast-specific assemblies (head, neck, and torso) integrated with the HIII-50M PED model (cut away to show the WBATD Torso) This image shows the headform, neck, and torso as well as the integration with the remaining HIII-50M PED parts. As shown in this image, the WBATD incorporates an external geometry similar to the HIII-50M PED, allowing for both accurate incorporation of blast protective equipment as well as comparison to previously tested data using the HIII-50M PED.

The torso neck plate can interface with either the WBATD neck natively or the HIII-50M PED neck with the inclusion of an adapter plate. The torso design interfaces with the HIII-50M PED shoulder and arm assembly at a custom reinforced collar joint. The HIII-50M PED chest jacket fits over the internal torso assembly (**Figure 1.** Overview of the WBATD system showing blast-specific assemblies (head, neck, and torso) integrated with the HIII-50M PED model (cut away to show the WBATD Torso)similar to that of the HIII-50M torso, and acts as an easily replaceable protective covering. The electronics base plate is located at the base of the torso and interfaces with the HIII-50M PED lumbar spine, which can act as a mount for shocktube testing, or be installed onto the HIII-50M PED pelvis and legs, so it can be positioned and postured for LF blast testing. The battery and DAS are mounted to the electronics bracket, the access point for these electronics are located at the break of the torso and the pelvis.

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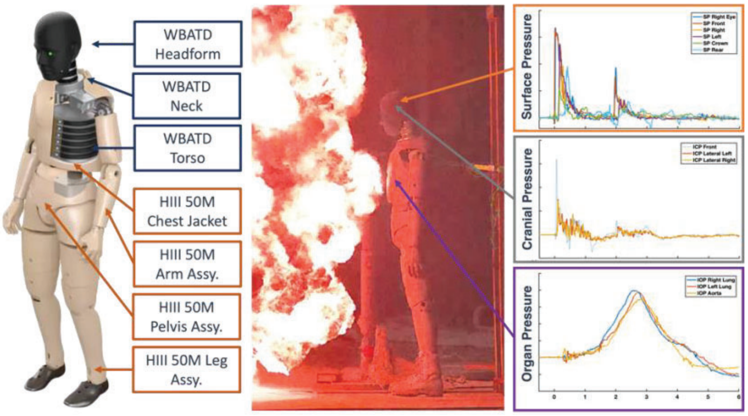

Figure 1. Overview of the WBATD system showing blast-specific assemblies (head, neck, and torso) integrated with the HIII-50M PED model (cut away to show the WBATD Torso)

2.3 WBATD Headform

The WBATD headform was designed with sufficient anatomical fidelity and instrumentation to enable comparisons with other blast injury head surrogates, as well as support continued development of future injury models. Additionally, the headform was designed to be modular and facilitate repair, consisting of multiple replaceable sub-assemblies; the crown, brain surrogate, midface, DAS, jaw, and chin insert, and kinematic DAS. The headform can be integrated into the full system, as shown in **Figure 1.** Overview of the WBATD system showing blast-specific assemblies (head, neck, and torso) integrated with the HIII-50M PED model (cut away to show the WBATD Torso)or used independently to evaluate headborne PPE.

The WBATD headform combines two existing external headform geometries. The first, which defines the crown of the WBATD headform, matches that of the large Multi-Sized Headform (LG-MSH). The remainder of the headform external geometry was derived from the Visible Human geometry. Facial features, such as ear geometries, were slightly modified to enable the donning of ear and eye PPE. While outer cranial geometry was derived from the LG-MSH, the interior cranial geometry (and therefore brain surrogate geometry) were driven by skull thickness, which was set to match literature values for the average male cranium, and ranges from 5mm to 9mm thick. The interior of the crown incorporated channels for routing sensor cables into the midface, where the DAS is located.

The midface of the WBATD headform interfaces with the crown and jaw components, and houses the headform DTS SLICE NANO (DTS, Seal Beach, CA) DAS and associated heat sink, the DAS status LED and controller, a 2200 mAh battery, sensors, as well as a shielded data connection and DAS cable ingress for wired connection during laboratory or fully integrated tests. These internal components can be accessed by removing the jaw, without removing the headform from the surrogate neck. The chin insert houses the DTS Dynamic Data Recorder (DDR) kinematics sensor and is molded into the chin insert with a silicone material to keep its placement consistent and secure during testing, and can be quickly removed from the jaw for charging, data download, and re-arming. The headform was designed to have similar mass properties as the HIII-50M PED, with a total mass of 4.44 kg, and principal moment of inertia in the mid-sagittal plane of 249 kg*cm2. The headform neck plate shares the interface of the HIII-50M system, which enables the WBATD headform to be used with a number of surrogate necks, including the Hybrid III and all previous JHU/APL surrogate necks.

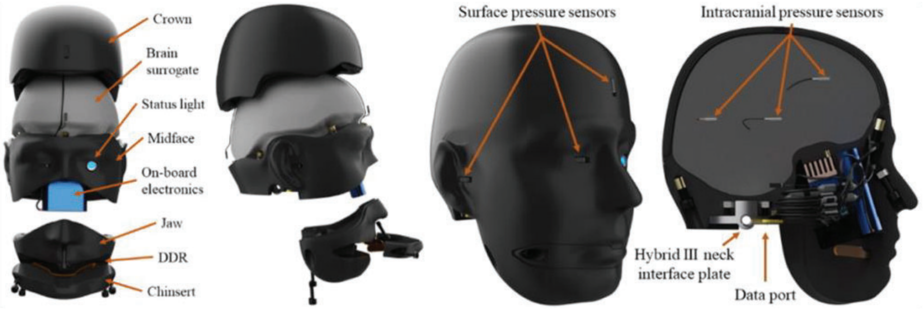

Figure 2. WBATD components

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The crown, midface, jaw, and chin insert components are fabricated through Selective Laser Sintering (SLS) of glass-filled nylon, which has historically been used as a bone surrogate [10], and then surface-dyed black to resist discoloration during LF testing. The brain surrogate is molded from Sylgard 527 gel (Dow, Midland, MI) and is molded separately from the cranium. A thin, tougher silicone (P-656, Silicones Inc., High Point, NC) layer surrounds the brain surrogate. This silicone layer has two functions; first, it contains the Sylgard gel in the event of temperature-based volumetric and viscosity changes, and Second, it enables the brain surrogate to be stored, handled, and assembled into the WBATD headform. In the event of damage to the brain surrogate, or during routine maintenance, the brain can be removed from the headform and replaced, rather than de-molded.

2.4 WBATD Torso

JHU/APL developed the WBATD torso surrogate system to assess the blast attenuating properties of PPE worn on the torso. The torso is instrumented with sensors that enable it to take measurements relevant to primary blast injury and align with ongoing blast injury research and modeling efforts. The torso was designed to be modular and facilitate repair, and consists of multiple replaceable sub-assemblies: spine, collar, ribs, thorax assembly, and electronics bracket, which houses the SLICE NANO DAS and on-board battery. The WBATD torso is blast-specific, but interfaces with the HIII-50M PED lumbar spine, pelvis, legs, and arms to enable fully integrated, full-body blast testing.

Within the HIII-50M PED chest jacket, the WBATD torso is comprised of the spine, neck interface plate, collar assembly, thorax assembly, and base plate (**Figure 3**). The neck interface plate installs onto the spine and interfaces with the WBATD neck, or, with the addition of an adapter plate, the HIII-50M PED neck. The collar component interfaces the HIII-50M PED arm assemblies with the torso. The thorax assembly is composed of six rib pairs that surround the torso organ surrogates. Rib geometry was based heavily on HIII-50M PED rib geometry to facilitate use of the COTS HIII-50M PED chest jacket as the exterior torso covering. To balance biofidelity with repairability, the torso has three rib sizes for the six rib levels. The ribs are fabricated by SLS of Nylon 11, which was selected for its excellent toughness. The remaining hard parts were machined from glass-filled Nylon billet for strength.

Figure 3. Exploded WBATD torso components (left) and cutaway view of the torso (right)

The ribs surround the thorax components. A silicone (P-656) back-fill component acts as a surrogate for the musculature of the back. The thorax assembly is composed of the silicone (P-656) thorax liner and liner cap, and contains the silicone foam (Soma-Foama 25, Smooth-On, Inc Macungie, PA) lung surrogate, and three sensor plugs, one for each of the left lung, right lung, and descending aorta. These intra-organ pressure (IOP) sensor locations were chosen for comparison with ongoing blast injury risk studies. The sensor plugs in which the sensors are embedded are molded from a silicone gel (Silicones, Inc., XP-429) that has historically been used for organ surrogates [8], and fit into the foam lung surrogate, which fits into the thorax liner, and is sealed and supported by the thorax liner cap. The HIII 50M PED abdominal insert, which sits in the cavity of the HIII 50M PED pelvis, protects the electronics bracket, which attaches to the base of the HIII 50M PED lumbar spine, and houses the DAS and a 4400 mAh battery.

The WBATD torso components were designed for easy repair. For example, if a rib fractures during a test, the rib design allows for easy removal of just the broken rib to be replaced with a new rib. For internal repair, the base plate and thorax cap can be removed to access the lung assembly and aorta sensor plug. The sensor plugs were designed such that they may be removed individually for calibration, repair, or replacement without the need of remolding the entire lung surrogate.

2.5 WBATD Neck

In previous work, JHU/APL designed and fabricated a surrogate neck to attach the HSHM to the HSTM. The objective of this previous effort was to develop a simplified neck surrogate with (1) improved reproducibility of fabrication and repeatability over previous custom neck surrogates, and (2) improved head kinematic response more similar to postmortem human subjects under relevant blast loading conditions than the HIII neck, while remaining robust enough for LF blast testing. More details on the development of this surrogate neck are available in Vignos (2022) [8].

In this current work, JHU/APL adopted and updated this design to include two additional functionalities: (1) the ability for neck rotation for proper posturing in low-crawl, or prone, position, and (2) the provision of a protected pass-through for the SLICE NANO daisy-chain cable to connect headform and torso DASs for integrated tests (Figure 4). Additionally, a steel tension cable was added to improve robustness. To achieve rotational functionality, the neck was bonded to a base plate (Figure 4) with a captured pin that can be pulled to rotate 25 degrees in both left and right direction for low-crawl posturing.

The WBATD neck consists of three layers of molded Shore 60A silicone (Silicones Inc., P-60) separated by and bonded to aluminum (6061) discs. Sitting atop the neck is the head interface plate and Shore 50A nodding blocks (Silicones Inc., P-50). This plate matches the geometry and mounting modality of the HIII neck—a pin connection between head and neck. The nodding blocks were molded and bonded to this plate, and are fit such that there is a slight pre-compression of the nodding blocks when the WBATD headform is mounted to the surrogate neck.

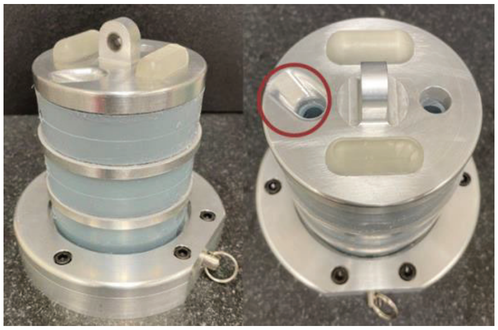

Figure 4. WBATD Neck with daisy-chain cable pass-through circled in orange

2.6 Data Acquisition & Electronics

The midface of the headform, and the lumbar electronics bracket of the torso each house an identical DTS SLICE NANO DAS. The DTS SLICE NANO is a modular, low-SWaP (26×31 mm footprint) DAS that has the capability of operating as a standalone system, collecting and storing high-frequency measurements in an untethered configuration, making it ideal as a DAS for blast ATDs [11]. Both SLICE NANO systems consist of one Base+ SLICE, a battery SLICE, and three bridge SLICEs, configured with a 100-kHz anti-aliasing hardware filter. The sampling rate of the SLICE NANO system scales with the number of channels collected, and can collect data at 300 kHz when the maximum nine sensors are connected (three per bridge SLICE), and up to 500 kHz if fewer sensors are connected. In the wired "lab-mode," the SLICE NANO receives external power and remains connected to a computer during testing. Lab-mode facilitates external triggering of the SLICE NANO for syncing with another DAS, as well as faster data downloading and system re-arming. For LF tests, the DAS operates in "wireless-mode," powered by an on-board rechargeable lithium-ion battery (a smaller, 2200-mAh battery housed in the midface for headform-only testing, or a larger, 4400-mAh battery housed in the torso for integrated testing) (Tenergy Power, Fremont, CA). In wireless-mode, the system operates on a circular buffer, with a signal-based trigger that is typically set to one of the surface-pressure (SP) sensors, enabling the recording of the full blast event, including pre-trigger data. A MagSafe-style quick-disconnect data connection port located under the right ear allows the user to connect a computer to the DAS via USB between tests. Using the DTS SLICEWare software, test data from the WBATD can be downloaded, system diagnostics can be run, and the system can be re-armed for the next test, before disconnecting this external cable.

For integrated headform and torso testing, a daisy-chain cable runs from the headform DAS, internally through the WBATD neck and the WBATD torso spine, and connects to the torso DAS. This allows the two systems to act in a parent-child configuration, where the headform DAS can trigger the

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torso DAS, and data can be downloaded from both systems simultaneously via the headform data connection port. Additionally, in this configuration, the single larger battery housed in the torso powers both DASs.

The WBATD Left Eye houses an LED indicator that communicates DAS power and armed status, visible even when the WBATD is equipped with EOD PPE. The LED indicator is blue when the DAS is powered on, and green once the system is armed and ready to collect data. A custom LED controller was designed at JHU/APL to interface with the DAS and is installed on top of the DTS SLICE NANO stack.

The torso DAS and battery are housed in protective aluminum covers mounted to the base of the lumbar spine (**Figure 3**). The electronics are further protected by the HIII-50M PED abdominal insert, which can be easily removed during testing for electronics access. The torso DAS operates in the same way as the head system, allowing testing to be done independently on each of the components, or in conjunction with one another in the case of integrated testing.

2.7 Instrumentation

The WBATD headform is outfitted with a number of sensors to enable repeatable dynamic measurements of surface pressure (SP), intracranial pressure (ICP), and linear and angular acceleration (Figure 5). The DTS DDR (DTS, Seal Beach, CA) is a self-contained, battery-powered, low-SwaP kinematic sensor equipped with a 3-axis linear accelerometer, and 3-axis angular accelerometer. It is capable of recording these six sensors at a sample rate of 5.5 kHz. This system operates independently from the SLICE NANO DAS. Since the SLICE NANO sampling rate is limited by channel count, the DDR was selected as an alternative sensor package to collect the six kinematic channels without sacrificing the number of pressure sensor channels or their maximum sampling rate. Similar to the way in which the SLICE NANO system is triggered by a surface-pressure threshold, the DDR recorder is triggered by head motion and captures and stores head kinematic data. DDR data download and arming is separate from the SLICE NANO system; however, these processes can be completed simultaneously.

The headform is instrumented with 10 total pressure sensors; 6 SP sensors (Kulite LPS-LHT-145-1000A, Kulite, Leonia, New Jersey), bonded to the external surface of the crown and midface components of the headform, and 4 ICP sensors (Kulite XCL-100-500A) imbedded in the brain surrogate. The DAS can collect nine channels per test, and the selected channel configuration can be switched (by way of connectors accessible in the midface) for a given test or test series. SP sensors were placed across the surface of the head and face in areas of interest related to blast injury (e.g., eyes and ears), as well as regions that are commonly under head-borne PPE. The SP locations are described as Right Eye, Forehead, Left Ear, Right Ear, Crown, and Nape. SP sensors are bonded with a semi-permanent adhesive, and can pass through the midface without severing any wires, allowing the sensors to be removed for calibration, repair, or replacement. The locations for the four intracranial pressure sensors were selected to match ongoing blast injury risk studies; and are described as Anterior-Superior, Lateral Left, Lateral Right, and Posterior. Like the SP sensors, the ICP sensor cable routing is removable and non-permanent. All SP sensors are oriented normal to the surface at the location they are bonded. All intracranial pressure sensors are oriented in the anterior direction.

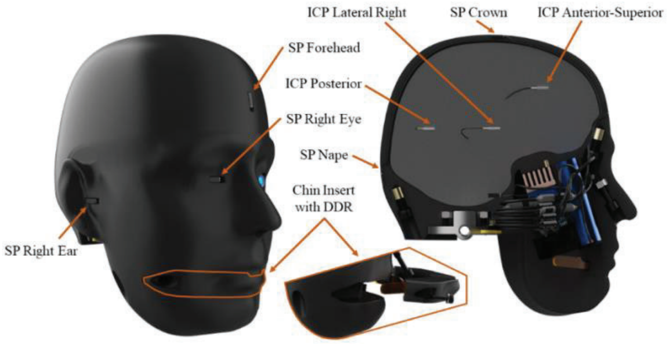

Figure 5. Location of SP sensors, ICP sensors, and the DDR kinematics sensor (SP Left Ear and ICP Left Lateral not pictured)

The WBATD torso is outfitted with sensors to enable repeatable dynamic measurements of intra-organ pressure (IOP) and thorax deformation. The locations for the three IOP sensors (Kulite XCL-100-500A) were selected to match ongoing blast injury risk studies: Left Lung, Right Lung, and Descending Aorta. Additionally, the torso can be equipped with 12 strain gauges (KFWB-2-350-C1-11 M609, Kyowa, Tokyo, Japan) arranged and wired as 6 half-bridge pairs at symmetric locations around the left and right ribs at the 4th rib level. This rib level was selected because it is at a similar height to the HIII and HSTM chest deflection measurement systems. By wiring the strain gauges in a half-bridge configuration, the strain measurement is isolated to the bending strain experienced by the rib. An algorithm to synthesize the data from these six strain gauges into a measurement of thorax deflection, analogous to an External Peripheral Instrument for Deformation Measurement (EPIDM) [9] was developed (Figure 6). This strain-based thorax deformation measurement system can be swapped for a pair of kinematics sensor packages located on the sternum and spine of the torso (2x Endevco 7264C-2k accelerometers, 1x DTS ARS PRO-18K angular rate sensor, oriented orthogonal).

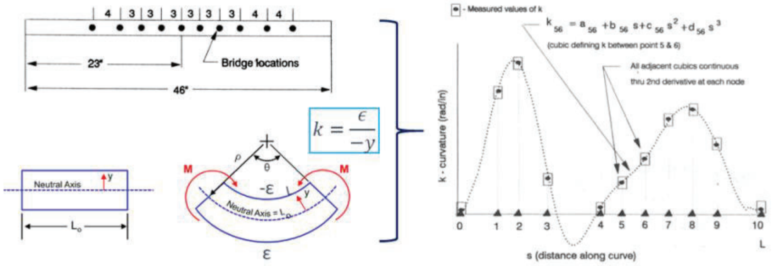

Figure 6. Overview of strain-based thorax deflection measurement

3. OPERATION & PERFORMANCE

Following fabrication and shock tube checkout testing, LF tests of the integrated WBATD system (head, neck, torso, and HIII-50M PED components) were performed at the ATC within Aberdeen Proving Ground. The primary objective of this test series was to determine the durability and usability of the WBATD when exposed to EOD-suit-relevant blast doses in standing and prone postures in a forward-facing orientation, with and without PPE. The test matrix was designed such that the blast dose would increase over the course of the test week with the goal of finding at what charge weights and standoff distances electrical or mechanical failure might occur. Testing the WBATD in bare and armored conditions would also inform the usability of the WBATD, namely the ability to quickly and easily doff and don PPE and re-posture the surrogate, as well as connect to, download data from, and re-arm the on-board DAS. The secondary objective of this test series was to determine usability of the surrogate in the side-facing, standing configuration, as well as the forward-facing, kneeling configuration. Both of these objectives were achieved through the execution and analysis of the tests performed at ATC.

3.1 Test Setup

The WBATD was positioned on the blast pad, along with a HIII-50M torso and headform modified for blast testing, at equal distances from the charge at a roughly 135° angle, to minimize reflections between the test articles (**Figure 7**). The torso and head of the HIII-50M were both equipped with a triaxial accelerometer (Endevco 7264D). The headform of the HIII-50M was additionally equipped with two pressure gauges (Endevco 8530C-100), at the crown and ear locations. Next to each test article was a pencil probe (PCB 137A24), positioned 71cm from the center of the test article, oriented directly toward the charge line, and with the center of the pressure sensor at the same standoff distance as the test article.

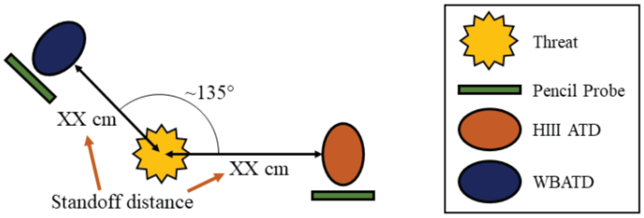

Figure 7. Live-fire blast pad configuration

Six different charge weight and standoff configurations were used for this test series (**Table 1.** Live-fire charge weights and standoffs). These conditions were selected in order to reflect a wide range of

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relevant blast doses. ConWep was used to estimate the peak incident pressure for planning purposes. Each test used a spherical charge of C4 hung 137 and 76 cm off the ground, for standing and prone/kneeling postures, respectively, in order to simulate a free-field air blast. To achieve the proper standoff for the HIII, a measurement was taken between the charge line and the most anterior point of the surrogate chest. Because of the differences in WBATD postures, standoff was measured as the distance from the charge line to the nearest midline sensor (Table 1).

Table 1. Live-fire charge weights and standoffs

Method	Charge [kg]	Standoff Distance [cm]	ConWep Estimated Peak [kPa]
4 lb – 68 in	1.81	173	482.6
4 lb – 60 in	1.81	152	648.1
4 lb – 55 in	1.81	140	792.9
NGABS	4.55	183	896.3
4 lb – 50 in	1.81	127	979.1
Euro 1	1	100	1119.7

For the standing and kneeling postures, the National Institute of Justice (NIJ) Integrity Test Stand was used to support the surrogate in position (Figure 8). By biasing the surrogate slightly forward when standing or kneeling, and tethering it to the NIJ Integrity Test Stand, the surrogate successfully remained in the set posture until charge detonation. The stand served a secondary purpose as well, preventing the surrogate from falling completely to the steel blast pad, which could damage the headform or associated SP sensors in the bare configuration. Use of the stand does not interfere with capturing the initial surrogate acceleration kinematics directly caused by the blast.

Two PPE conditions were tested. For bare tests, the surrogate was virtually unarmored, with only boots worn for a more stable standing base. For armored tests, the surrogate was donned in a Generation 1 Advanced Bomb Suit (ABS Gen 1), including trousers, groin panel, jacket, back panel, and helmet. Figure 8 shows the various postures and PPE conditions.

Figure 8. Various orientations, postures and PPE conditions (not shown) were tested. The WBATD is free-standing prior to the shot. The NIJ Integrity Test Stand prevents it from falling to the steel pad.

4. DISCUSSION

Check-out tests in APL's Blast Overpressure Simulation System (BOSS) [11] and a small series of LF tests at ATC were completed to do an initial evaluation of the repeatability, usability, durability, and repairability of the WBATD. In general, the system showed good repeatability, with the variation in measured pressure metrics from BOSS testing similar to the variation in the generated shockwave. At a high level, the majority of the objectives set during the development process regarding usability, durability, and repairability of the system were met. Following this first LF test series a number of improvements were incorporated into the design, which are discussed in the subsections below.

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4.1 Usability

The testing team was pleased with the usability of the system in the field based on verbal feedback from the APL and ATC testing teams given during the test week. The battery life for the system was regarded as impressive, often lasting over half of a test day, and it is estimated based on per-test voltage drop that the battery could last a full test day if the time the system was armed between tests was minimized. Additionally, there was easy access to the battery, even with the jacket donned. With or without PPE, the battery was able to be swapped in under 5 minutes by an experienced operator.

The LED light designed to alert the team to the armed and power status of the DAS before the test was visible even from under the EOD helmet, and was generally visible from ATC's live remote camera of the range. The original communication port and DDR were accessible with just the removal of the head-borne PPE, and the panel cover successfully protected the communication port from damage, even in the high-dose, unarmored test. It was found, however, that the panel cover could be challenging to fasten, because of the AM threads, and that the EOD suit itself can get in the way of plugging in the communication cable and removing the chin insert to access the DDR. For these reasons, the communications port was redesigned to the MagSafe-style connector now in use (including a magnetic panel cover), and the chin insert was angled up to its current location. It was found the original nape design was too short to fully catch the posterior helmet strap, and so this was extended down 5mm in the updated design. Additionally, after this test series, the original rotating neck design was updated to be much simpler, with the locking mechanism moved to the front, as it is more accessible here with current PPE designs.

Post-test, it generally took the team under 10 minutes to connect to the SLICE NANO, remove and connect to the DDR, download the test data from each DAS, run diagnostics on and rearm both systems, reinstall the DDR, and disconnect from the surrogate. The majority of time spent preparing the WBATD between tests was in doffing and/or donning the full EOD suit and posturing the surrogate for the next test. Repeatable posturing methods were made more efficient over the course of the test week, and were recorded in the WBATD User Guide. Generally, the doff-don-posturing process took 10 minutes for the simplest case (re-posturing the bare surrogate) and up to 40 minutes for the most complex case (doffing damaged PPE, donning new PPE, re-posturing the surrogate). This process was made difficult by both the cumbersome nature of EOD suits and the high number of degrees of freedom of the HIII-50M PED pelvis and legs, which sometimes required multiple operators working in tandem to achieve a targeted position. Further development of these components could make this process quicker and more repeatable.

4.2 Durability and Repairability

As expected, blast exposure limits of various WBATD components were found over the course of the test week, and updates to the design were made to address these limits. Generally, given the violence and potential for overmatch of the blast event the WBATD was exposed to, it was assessed that the durability of the system was sufficient. Specifically, the system survived the 'NGABS' dose unarmored without being damaged. Additionally, design features that enabled the system to remain in use in the case of damage worked as intended, as when, for example, the rear intracranial pressure sensor stopped functioning, and the channel was made use of by switching it to the left ear SP (this issue also led to the use of more robust internal connectors in the current design).

The original WBATD neck design failed in tension during a bare prone test, which led to the addition of the internal tension cable to the current design. In this case, the ability of the WBATD design to integrate with the HIII neck allowed the test week to continue without delay, by swapping in that part.

The highest dose charge configuration, in the unarmored configuration, was chosen as the last test, in order to better understand any mechanical weaknesses of the original design. During this test (1.8 kg – 127 cm), the four HeliCoils connecting the headform to the neck interface plate failed, causing the headform to fall from the surrogate, break the DAS communication cable, and impact the steel blast pad. While this caused internal rupture of the brain surrogate at the location where the ICP sensor cables exit, the GF Nylon exterior of the WBATD headform did not crack, and none of the electronics in the headform failed. It is likely that if this occurred in the middle of a test week, and a backup sensorized brain surrogate were on hand, the headform could be repaired within a few hours. As a result of this failure, the original neck plate design (and jaw-midface attachment design) was changed to use captured nuts rather than Helicoils. Additionally, the ICP cable egress from the brain surrogate was moved to the inferior surface rather than anterior surface to make that surrogate more robust, and the NANO SLICE backup battery was incorporated into the DAS stack.

While no major issues were found with Torso durability during the testing, the original hard support plate design was changed to the current strap design to allow for more realistic torso compression with a

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hard plate, and the DAS and battery were moved from their previous location on this support plate to the current location lower on the lumbar spine base, where those components are out of the way and better protected by the HIII abdominal insert.

5. CONCLUSIONS

The Wireless Blast Anthropomorphic Test Device (WBATD) is a modular and repairable system that enables measurement of internal and external pressure, kinematics, and thorax deflection during blast events. By incorporating recent advancements in low-SWaP data acquisition systems and integrating with existing COTS ATD parts, it is the first blast-specific ATD that can be postured realistically and tested fully wirelessly, capturing data relevant to both primary and tertiary blast injury. Additionally, by taking advantage of state-of-the-art additive manufacturing of durable thermoplastics, this system is robust enough to survive EOD-suit relevant blast doses unarmored, allowing for baseline 'bare' testing and therefore full evaluation of PPE blast-attenuating performance. Usability and repairability considerations were taken into account through the design process, resulting in a system that can be reset quickly between tests, and repaired within hours, reducing risk to crucial live-fire test series. Initial laboratory testing has indicated excellent repeatability; and initial live-fire testing showed sufficient durability of the original design, which has been updated to the current iteration to address components that failed during overmatch. Future match-pair testing, and solicitation of feedback from other blast test experts is planned, in order to develop an injury-linked dataset and further optimize the design.

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