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Development of a Procedure

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Introduction

The human toll from AP mines is large. The United Nations estimates that there are over 100 million AP mines deployed worldwide (U.N. 2000). An estimated 20,000 civilians die each year from landmine explosions. Thousands more are wounded and maimed. As there is still no inexpensive and reliable mechanical technique for removing AP mines, human deminers will be used in the foreseeable future to protect the general population from the menace of landmines.

To decrease the human toll from demining, protective equipment should be used. For comprehensive protection, the demining ensemble may include head-face protection, torso protection and extremity protection, including gloves and boots as shown in Figure 1. This ensemble offers the potential for substantial protection against fragments, blunt force trauma, burns and other consequences of mine blasts. However, without some objective procedure to evaluate the design of such demining equipment is guesswork. Without some objective procedure to evaluate the design of such demining equipment is guesswork. Indeed, without an effective injury evaluation technique, protective equipment may exacerbate certain types of injury. For example, the introduction of body armor in Northern Ireland for protection against blast fragments may have increased the potential for blast lung injuries (Mellor 1989).

One technique that has been shown to be effective in the automobile industry is the use of an instrumented surrogate (dummy) to evaluate the risk of injury from blunt trauma in automobile crashes. Elements of this technique include the following:

- Biofidelic surrogate - A dummy that is robust, and the response of a human in that crash scenario. This dummy response may be used in an injury model to assess the risk of injury for that crash scenario. The tools used in the automobile industry, however, may not be directly applicable to mine blasts for two reasons. First, automobile crashes and mine blasts are substantially different physical phenomena. While both automobile crashes and mine blasts may involve blunt head and chest trauma, mine blasts may have substantial shock wave effects, burns and other blast phenomena. Second, the events may occur on significantly different time scales. Injuries in mine blasts may occur 10 to 100 times faster than those in automobile crashes. These timescales have an effect on dummy response, and the timeliness of mine blast injuries may be outside the validity of the injury models used in the automobile industry. So, tools used in the automobile industry must be adapted for use in mine blast testing to effectively assess the risk of injury while wearing protective ensembles.
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- Injury risk evaluation - A correlation between an engineering measurement and some injury model. For example, in frontal thoracic blunt impacts, an injury threshold of 60 times the force of gravity is used in the automobile industry.
- Validation by injury model - A correlation between the injury risk evaluation and a physical model of injury. 1) Epidemiology or physical reconstruction of an actual injury event; 2) An animal injury model; or 3) A cadaver human injury model as shown in Figure 2. Development of Surrogate Injury Model [Figure 2]

Widespread use of this technique has saved thousands of lives per year in the automobile industry. As there are similarities in human blunt trauma in an automobile crash and in a blast event, this technique may be adapted to evaluate injury from mine blasts.

Development of Procedure

The goal in the current study is to develop a procedure to evaluate injuries from mine blasts, borrowing tools from existing techniques when appropriate. This approach will result in an objective test criterion for the evaluation of the injury risk of a human wearing a protective demining ensemble. It will allow this injury risk evaluation for protected or unprotected subjects and will indicate the relative levels of protection for subjects wearing different protective equipment.

For decades, work has been performed on human injury from blunt trauma in the automobile field. Simulated automobile crashes are performed, and the response of the dummy is taken to represent the response of a human in that crash scenario. This dummy response may be used in an injury model to assess the risk of injury for that crash scenario.

Focus

Fatal Injuries Sustained in Demining Incidents (Landmine 2000) [Figure 3]

- Head Injuries
- Chest Injuries
- Hemorrhagic Shock
- Presuming Condition
- Unknown

Percentage Fatalities (%) [Figure 3]
Simulation of a realistic test condition is especially important in mine blast testing. A high-speed photograph of a simulated mine blast with two dummies is shown in Figure 4. The force on a human chest or head is related to the pressure from the blast waves. Since pressure falls as the inverse cube of the distance from the blast, the dummy position in the blast is vitally important in a realistic simulation. A field survey found that 91 percent of detonating blast incidents occur with the victim within one meter of the mine (Landmine 2000). It is clear, however, that close enough to a large mine blast there may be substantial injury using any PPE. So, a balance must be maintained between the desire for test realism and the desire to evaluate the worst case in mine blast injuries.

Modeling the mine blast itself is a complicated issue. Nominally identical mines may have widely different behavior, and blast characteristics may change considerably, depending on soil and environmental conditions. Also, real mines may be difficult to obtain in quantity and to handle safely. To develop an objective test procedure, we want a test condition that is realistic, yet repeatable—a balance that limits the number of tests and cost necessary to effectively characterize the performance of protective equipment. This argument suggests that mines should be simulated with a relatively well-characterized plastic explosive and should be implanted in a well-characterized soil. Several blast energies may be used to simulate the range of energies expected with actual mines. The selection of simulated mine blast energy should be done on ongoing efforts to correlate blast properties of actual and simulated mines (Bergeron 2000).

Several dummies exist that may be appropriate for mine blast testing. One widely validated dummy that may be particularly useful in estimating the risk of frontal blast trauma is the Hybrid III dummy shown in Figure 5. The dummy pictured is the size of an average U.S. male, but scaled dummies exist for the small female and large males. Used in automobile crash testing, this dummy is widely validated in frontal blast impacts for both head and chest injuries. It may be positioned using articulated joints. The Hybrid III may be instrumented with accelerometric sensing and force-sensing transducers. Though the dummy does not have a completely biofidelic response, the data from these transducers may be used with accepted injury thresholds and risk functions to determine the risk of injury in a given test condition. As changes in anthropometry may change risk of injury, for an accurate response, the dummy selected should be representative of the population modeled. Worldwide anthropometry of the average male is shown in Figure 6 (Jurgens 1998). If the distance of the body to the mine when detonating is taken to be roughly proportional to the mean reach (arm length), the average Southeast Asian male is approximately 70 mm closer to the blast than the average North American male. This distance may substantially increase the risk of head or thorax injury in demining for the average Southeast Asian male dummies. As there are large numbers of mines in West Africa and Southeast Asia where the people have relatively short arms and/or of small stature, the small Hybrid III dummy should be incorporated into mine protective equipment testing.

To summarize, essential elements in the development of a procedure for evaluating the risk of injury while wearing demining protective equipment are:

- A robust dummy with established and applicable injury criteria positioned in a realistic manner in position representative of demining (i.e., kneeling, prone, standing, etc.).
- Robust instrumentation—data handling consistent with the response.
- Accurate positioning—distance to mine must be consistent and quantifiable.
- Repeatable, quantifiable threat (mine) with fixed burial and soil characteristics.

Each of these elements acts to provide an objective criterion for injury risk while ensuring that the resulting criterion is as applicable as possible to the conditions experienced in the real world.

**Existing Human Injury Criteria**

Preliminary tests were performed using dummies with protective ensembles and simulated mines. The mines were plastic explosive with 20g C-4, 100g C-4, and 50g C-4. These devices were found to be comparable in blast energies to a wide range of existing mine types (Bergeron 2000). The dummy used was a Hybrid III 50th percentile male dummy or equivalent.

From the database of existing injuries, the types of injuries evaluated should be blunt head trauma, blunt neck trauma, blunt thorax trauma, blast lung, blast-induced hearing damage and burns. Blast injuries can also evaluate the potential for "fall" type injuries caused by whole body displacement from blasts. All of these injury types except burns were evaluated in the preliminary test series.

**Blunt Trauma Head Injuries**

As discussed above, fatalities from head injuries are very significant in mine blasts. These injuries may be caused by direct blast impingement on the head.

One simple surrogate for the risk of head injury from force experienced by the dummy head is the peak acceleration at the center of the dummy head. This surrogate has the advantage of being easily measured, and existing injury criteria use this measurement.

One injury criterion commonly used with the Hybrid III dummy head/neck complex in frontal impacts is the Head Impact Criterion (HIC) for comminutive head injury (Versace 1971). HIC includes the effect of head acceleration and duration; a HIC value of 1000 is specified as the level for onset of severe head injury. Physically, HIC predicts that large accelerations may be tolerated for short times. HIC is based on human cadaver and animal impact data with durations that are usually one millisecond or greater.

HIC values obtained in mine blast testing are shown in Figure 7 for mine blast strengths of 50g C-4, 100g C-4, and 200g C-4. Several tests with 20g C-4 showed potentially injurious levels of HIC, one near a value of 10,000, which is presumably a fatal injury. For several tests in this series, however, the duration of the acceleration peak was substantially shorter than the usual value of HIC duration (> one millisecond). This result suggests that the data on which HIC is based must be recalibrated for use with mine blasts and that the resulting injury model must be validated with a physical injury model.
with protective helmets and suits showed potentially injurious levels of neck bending. All but one test that exceeded the injury threshold had the largest simulated mine (200g). The 50g test that showed injurious neck moments may be attributed to a loose Hybrid III neck for that test. Paradoxically, the use of a protective suit and helmet generally resulted in higher neck moments than when no protective equipment was used. This tendency likely is the result of the increase of surface area exposed to the blast when using the protective gear.

**Blunt Trauma Thorax Injuries**

The blast pressure wave and following pressure wave from the detonation of a mine have the potential to produce severe blunt trauma to a human thorax in proximity to the blast. Merris and Gadd (1971) developed acceleration injury criteria for blunt trauma to the human thorax. This injury tolerance is 60g limit over a three ms duration. As with the head, acceleration may be taken as a proxy for the global force experienced by a thorax.

Representative chest accelerations from the preliminary test series are shown in Figure 9. As expected, the most severe chest accelerations occurred with no protective suit while the least severe occurred at the lowest level of mine blast (50g) with the protective equipment. This injury criterion does not include other possibly significant effects, such as chest compression injuries or blast lung injuries. However, these factors may be included when using other measures.

**Blunt Chest Injury Criterion for Surrogate Mines with Hybrid III Dummies**

<table>
<thead>
<tr>
<th>Basic Suit</th>
<th>No Suit</th>
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<tbody>
<tr>
<td>200gm</td>
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<tr>
<td>50gm</td>
<td>50gm</td>
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<tr>
<td>100gm</td>
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</tr>
<tr>
<td>200gm</td>
<td>100gm</td>
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</table>

**Blunt Overpressure Injuries**

There is a substantial risk of blast overpressure injuries, either blast lung or blast-induced hearing injuries, when at a close distance to AP mine blasts. However, the usual instrumentation of the Hybrid III dummy does not include any assessment of the effects of blast overpressure, either in the head or the chest. So, in preliminary testing, a pressure sensor was mounted on the surface of the chest to evaluate the potential for blast lung injuries, and another pressure sensor was mounted in the head at the location of the ear to evaluate the potential for hearing damage. The evaluation of blast wave injuries is important since addition of protective equipment for the thorax may accentuate blast overpressure injuries.

Pressure profiles seen in the preliminary testing are similar to a typical ideal shock wave with a nearly instantaneous rise to peak pressure with exponential decay. Peak external pressure vs. duration for the thorax is shown in Figure 10. This data is compared with the classic threshold, one percent fatal, and 50 percent fatal free field curves taken from classic work by Bowen et al. (1968). While several of the tests with 50g and 100g C-4 show potential lung injuries at the threshold level, only the 200g C-4 simulated mines show greater than one percent fatalities on this scale.

Future tests should incorporate additional pressure sensors in the thorax and head to minimize the potential for spurious pressure results. In addition, as the injurious criterion used is a free field value based on plane wave, an assessment should be made of the effects of differences between the ideal blast wave and local blast shock for AP mines.

**Burns**

As mine blasts involve explosive deflagration, there is a significant potential for burns close to mine blasts. The mechanism for this injury is rapid radiant and convective heat transfer of the injury. Predictive criteria exist for such flash burns; in 1960, the Naval Materials Laboratory developed a skin simulator for evaluating injuries caused by thermal insults (Dockhorn 1960). The technique uses a thick plastic resin with an embedded thermocouple. The temperature output of the thermocouple was correlated with human injury 120 mm below a living skin surface. A temperature of 44 degree celsius was derived as the threshold for such transdermal injury.

In future tests, thermocouple sensors should be embedded in the dummy skin at the thorax, head and extremities to determine the risk of thermal injuries. This method is especially useful in the unprotected reference tests to provide a baseline for the comparison of the effectiveness of the protective ensemble for burn prevention.

**Conclusions**

Mine blasts are forceful events for which there is significant risk of injury even while wearing protective equipment. To provide the most effective yet practical protection, a procedure must be developed to objectively and systematically evaluate protective demining equipment. Such a procedure is proposed in this study.

To avoid long development and high costs associated with the development of a completely new test procedure, this procedure builds on techniques currently used in the automobile industry to evaluate risk of injury from blast force trauma in automobile crashes. The technique includes the use of Hybrid III dummies in testing with injury criteria adapted from accepted injury risk tolerances. Mine blasts are simulated in repeatable conditions for the rapid and inexpensive evaluation of a wide range of blast conditions.

Injuries modeled in this procedure include blast trauma to the head and chest, neck injuries, blast lung and blast-induced hearing damage and thermal injuries. For these injuries, existing injury criteria may be used with the Hybrid III dummy or injury criteria can be adapted for use with the Hybrid III dummy.

Preliminary tests have been performed that suggest the need for augmented instrumentation and validation using an appropriate physical injury model. These tests suggest that AP mine blasts may be injurious or fatal even with protective headgear and body armor. Further work is needed to characterize the robustness, repeatability and applicability of this promising technique for the evaluation of personal protective systems for demining.

**References**


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