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INTRODUCTION

Lethality Assessment and Research (LAR) investigated the hypothesis that the formation and collapse of tiny cavitation bubbles generated in the body by blunt force trauma, small arms, blast and electro-magnetic radiation, cause the start of a biological chain reaction which leads to Post Traumatic Stress (PTS) and other neurodegenerative disorders. The idea is that the shock wave, and ensuing cavitation injury, causes the release of stress hormones that triggers brain inflammation and the resultant PTS as well as other disorders, which may persist for years in a self-reinforcing Brain Inflammation Cycle; Figure 1.

The aim of the research is to be able to predict, prevent and detect shock event cavitation injury; historically known as "*Shell Shock*". This paper details the key outcomes of the initial research to be able to predict and prevent the shock event cavitation injury, including:

a. **Prediction.** Initial numerical modelling was conducted to determine the minimum pressure require to initiate cavitation within the brain and torso. The model was then extended to determine the back of armour pressure from impacts of in-service 5.56mm and 7.62mm projectiles.

b. **Prevention.** An initial design of the concept for Advanced "*Blast Disk*" Body Armour and Helmets that aim to abate the shock event pressure below the cavitation nucleation pressure while still being able to prevent penetration by the small arms projectiles.

The initial findings predicted that shock induced cavitation injury may occur in the brain and torso as a result from the operational events including:

a. Blast overpressure as low as 11 kPa. This may be within the range of weapon system operating overpressures, such as direct fire weapon systems, large calibre rifles, and artillery.

b. Back of armour pressure from impacts of in-service 5.56mm and 7.62mm projectiles to their effective ranges and an impact angle up to 85 degrees.

c. The *Blast Disk* advanced body armour was predicted to be able to abate the shock event pressure below the cavitation nucleation pressure while being able to prevent penetration by the small arms projectiles.

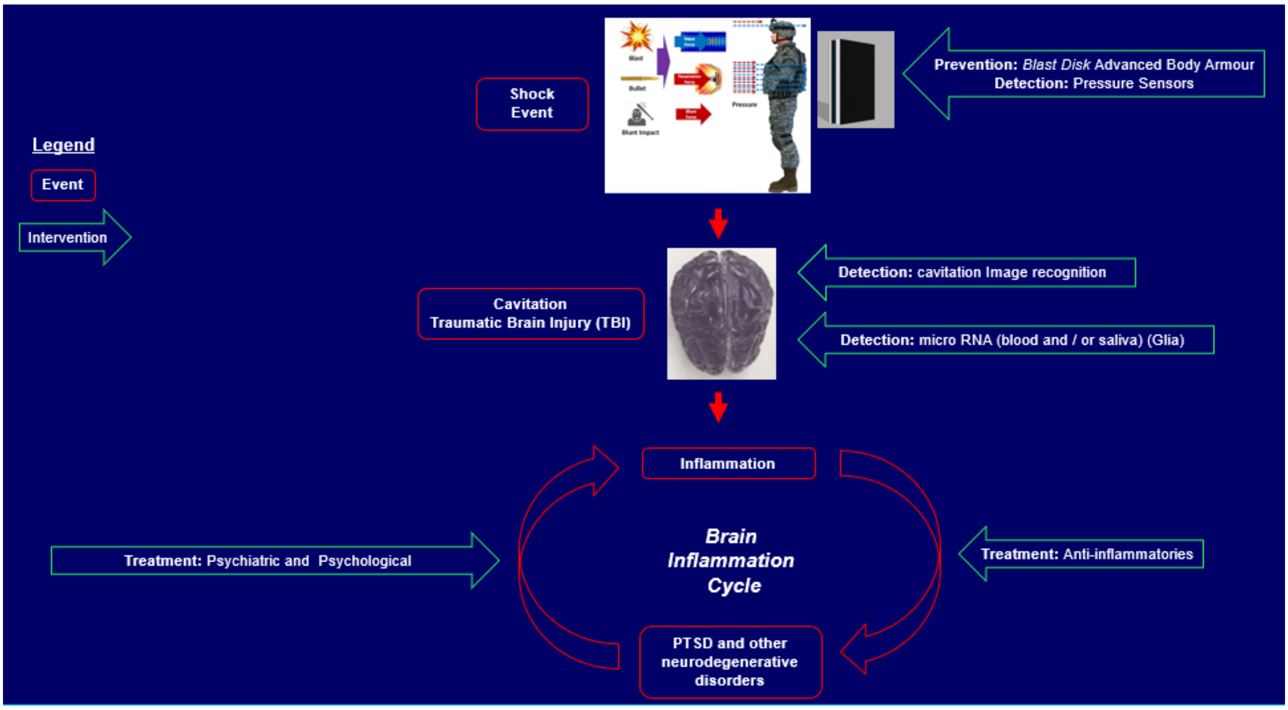

Figure 1. Brain Inflammation Cycle and Potential Interventions

AIM

The aim of the research is to be able to predict, prevent and detect shock event cavitation injury; historically known as "*Shell Shock*".

PREDICTION

Small arms

The research was initiated following the observation of cavitation during Defence small arms terminal effects testing, that demonstrated that the small arms impacts generate cavitation remote from the entry site. During small arms terminal effects testing, the impact of a 5.56mm projectile generated cavitation over 500mm from the projectile entry site; Figure 2. Further, it is believed the location and direction of the projectile impact may lead to the formation of the cavitation bubbles in areas outside the brain, and result in nerve and other damage throughout the body.

The hypothesis is that the shock wave may travel and reflect through the body, leading to cavitation injury to the nervous system remote from the wound site. Schmied has commenced creating a series of numerical models of the body; lethality models. These models will be used to predict the behaviour of the shock wave and subsequent cavitation generated for varying calibres, ranges and impact angle.

For the numerical modelling, terminal effects were observed to be as a result of ballistics gelatine acting both as a solid and fluid, and thus require different modelling techniques for each case. As shown in Figure 2:

a. Deformation (green arrows) may be predicted by modelling gelatine as a hyperelastic solid using a Mooney-Rivlin model. Appropriate values for the two-parameter Mooney-Rivlin model under varying strains rates are detailed in Naarayan et. al. (2017) [1].

b. Cavitation may be predicted in ballistics gelatine by modelling as a non-Newtonian (Power Law) shear-thickening liquid, as detailed in Subhash (2012) and Schmied (2019). The terminal effects testing detailed in Brooks et. al. (2017) [2], Figure 1, observed that cavitation was generated between 400 mm and 500 mm from the entry site and in advance of the projectile. Further, whilst cavitation was observed at a range of 50 m, no cavitation was observed at longer ranges.

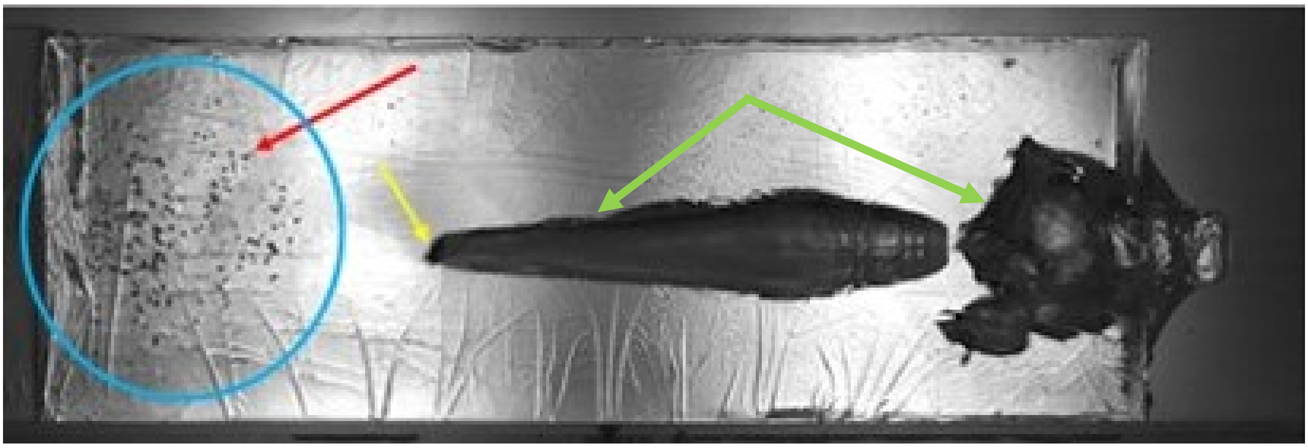

Figure 2. A 5.56mm M55A1 (yellow arrow) at 50m range generated cavitation (red arrow and blue circle) well in front of the projectile, with the gross deformation behind (green arrows). The length of the ballistic gelatine block was 500mm.

The numerical lethality model mayl also incorporate:

a. **Sonoluminescence.** Cavitation bubble collapse generates high pressures and temperatures, leading to the breaking down of the water vapour into a variety of species through multiple reactions, some of which cause electron excitation creating a flash of light. The process also causes the release of fuel (such as hydrogen gas) that can combust in the event of a bubble collapse rebound. The process results in cauterising the surrounding material and issuing a high-pressure water hammer shock wave that further damages the surrounding material. Further, an extremely strong electromagnetic pulse is generated during the sonoluminescence event. Interestingly, sonoluminescence occurs during the collapse of a cavitation bubble generated by a 25mm long pistol shrimp; Figure 3.

b. **Dieseling.** May occur at lower pressures and temperatures compared to sonoluminescence. Here the deformation of the hyperelastic soft material (such as ballistics gelatine) leads to a large void sometimes coupled with air entrainment. When the void, collapses, high pressures and temperatures can release volatiles from the gel, which along with the entrained air or released oxygen can explode, cauterising the surrounding material and issuing a high-pressure shock wave that further damages the surrounding material. As an example, dieseling has been observed during small arms testing; Figure 4.

The implications for injury to the human body may be:

a. dieseling may occur as the bubble cools following a sonoluminescence event, including in the brain

b. dieseling in the body may use fat as a fuel source

c. sonoluminescence and dieseling create by-products that may be toxic within the human body

d. as sonoluminescence generates an extremely intense electromagnetic pulse, this pulse may affect the functioning of the brain.

Figure 3. Sonoluminescence (right) occurring during the collapse of a cavitation bubble generated by a 25mm long pistol shrimp (left)

Figure 4. Dieseling in ballistics gelatine generated by the impact of a 5.56mm M855A1 projectile, showing the deformation (top left), dieseling (top right) and smoky by-products (bottom) [3]

Cavitation In The Human Body

Dynamic cavitation in soft materials is becoming increasingly relevant due to emerging medical implications such as the potential of cavitation-induced brain injury. Mechanical stiffness of biological samples is typically much lower than conventional engineering materials and covers a broad range from 0.1 to 10 kPa for brain tissues to 100 kPa for human aorta [4]. One attractive advantage of using gelatine to characterise cavitation properties is that stiffness of gelatine gels may easily be tuned to different soft to hard tissues by controlling concentration of gelatine (c_g); e.g. $0 <= c_g <= 0.075$ corresponded to mechanical stiffness of 0 – 60 kPa [5], $c_g = 0.0125$ equating to brain tissue.

Cavitation behaviour in gelatine is understood to be:

a. Only the water between the filaments of gelatine turns to water vapour. Therefore the vapour pressure is taken to be the same as pure water.

b. Once the vapour bubbles form, the gelatine filaments act to retard both growth and collapse of the bubbles, as detailed in Kang et. al. (2017) [6].

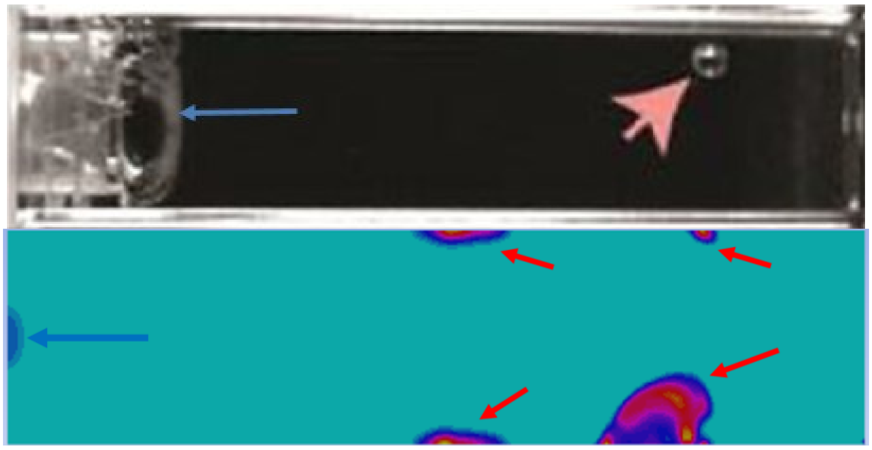

Figure 5. Cavitation (indicated by the arrows) generated in a drop test; experimental (top) and numerical (bottom).

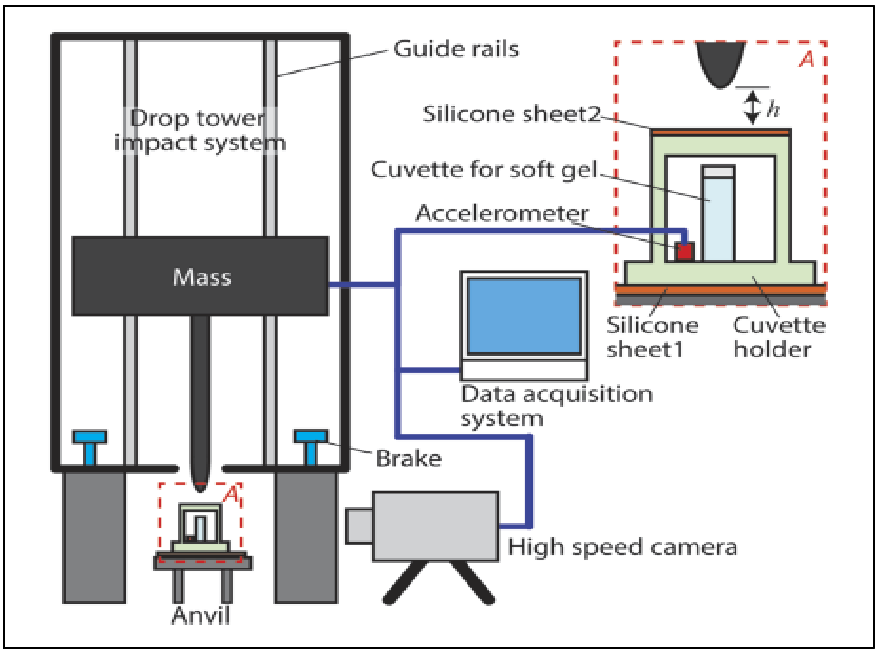

Figure 6. Drop test rig [6]

Small Arms

Prediction of small arms terminal effects generated cavitation injury were then modelled. The model was increased in complexity over three iterations to determine the parametric limits for P_{cr}^{*}, including:

a. c_g

b. projectile calibre

c. range (R)

d. entry angle relative to the lateral (α) and vertical (β) planes.

The in-service projectile calibres modelled were:

a. **5.56 mm x 45 mm** M855A1. STANAG 4172 specifies the 5.56mm NATO ammunition family [7]

b. **7.62 mm x 52 mm M80**. STANAG 2310 specifies the 7.62 mm NATO ammunition family [8]

The key findings were:

a. It is believed that the model is sufficient to predict cavitation nucleation and collapse resulting from shock events, as the cavitation nucleation in terms of P_{cr}^{*} were predicted to be conservative compared to the experimental results.

b. The numerical model predicted a Power-Law relationship between P_{cr}^{*} and c_g, potentially indicating that cavitation is more likely to occur at lower pressures in fluids that shown shear thickening rheological behaviour, such as the materials that make up the human body.

c. The numerical model predicted that P_{cr}^{*} may be exceeded for ranges out to the effective firing range for both calibres fired from in-service weapons.

d. The pressure inlet model results may indicate that cavitation may occur in cases without projectile penetration, as such as behind body armour and helmets. In these cases, the projectile may be prevented from penetrating, however, sufficient pressure may be transmitted for cavitation nucleation to be initiated. Further, by spreading the projectile impact over a wider area, the skull, helmets and body armour may contribute to cavitation nucleation, even though there may be a decrease the total pressure applied to the brain and/or body. Finally, the results may indicate that blunt force trauma may be a significant cavitation injury event.

e. Deformation behind the projectile was predicted, however, it was not a wide as observed experimentally in the small arms terminal effects testing documented in Brooks et. al. (2017). It is believed a hyperelastic Mooney-Rivlin solid model may accurately predict the deformation.

f. P_{cr}* was predicted for the 50th percentile body as 3e7 Pa. At P_{cr}*, cavitation occurred adjacent to the top and bottom of the inlet, equating to the shoulders and hips. As the inlet pressure was increased, the cavitation area was predicted to increase and extend rearwards and towards the centre of the domain.

g. P_a* = 997 was predicted as a result of the impact by an in-service 5.56 mm x 45 mm on in-service Tier IIIA SiC armour plate, in accordance STANAG 2920 Fragmentation Test (V50 Test) F6 (u_0 = 650 m.s^-1). The model results may indicate that cavitation may occur in cases without projectile penetration, as such as behind body armour and helmets.

h. From the initial numerical predictions of the advanced body armour performance, P_a* may be reduced to below P_{cr}* by using the burst bladder advanced body armour.

It is recommended:

a. Yaw of the projectile be considered in future developments of the numerical lethality model.

b. Using the lethality model, predict the pressure transferred through the skull, and in-service body armour and helmets to the body to determine if cavitation may occur for non-penetrating impacts and blunt force trauma.

c. Extend the lethality model to prediction cavitation nucleation in the human brain with and without a skull, especially given the preference for the cavitation to nucleate on the surface.

d. Validate the numerical predictions through experimental blunt force, small arms and blast testing, including using c_g = 0.1 gelatine models of the brain.

e. A hyperelastic Mooney-Rivlin solid model be developed to more accurately predict the deformation caused by the projectile impact that in turn may generate dieseling as the deformation collapses.

PREVENTION

Advanced Body Armour And Helmets

To prevent shock induced cavitation injury in the body, the research developed the concept for the *Blast Disk* advanced body armour using empirical analysis and numerical modelling approach, including:

a. an empirical analysis of armour performance required to prevent cavitation nucleation

b. numerical modelling of the 50th percentile human torso [9] to predict the critical pressure for cavitation nucleation (P_{cr}^*) and behaviour in the torso

c. P_a* = 997 was predicted as result of the impact by an in-service 5.56 mm x 45 mm on in-service Tier IIIA Silicon Carbide (SiC) armour plate, in accordance STANAG 2920 Fragmentation Test (V50 Test) [10] F6 (u_0 = 650 m.s^-1). The model results may indicate that cavitation may occur in cases without projectile penetration, as such as behind body armour and helmets.

d. the behaviour of the liquid filled burst bladder and the ability to reduce P_a* to below P_{cr}^*.

By reviewing Eq. 1, P_a* may be decreased to less than P_{cr}* by increasing effective armour thickness (T_a) and/or armour frontal area (A_a):

$$P_a = \frac{u_0^2 . m_p}{2. T_a . A_a .} \quad (1)$$

where m_p is the projectile mass.

To achieve an increased effective T_a and/or A_a, the *Blast Disk* advanced body armour concept was proposed. The *Blast Disk* advanced body armour aimed to abate P_a* to below P_{cr}* whilst still preventing penetration by the projectile. A desirable requirement was for the advanced body armour to lighter and more flexible than the in-service SiC armour plate. The Critical Operational Issues (COIs) for the advanced body armour are:

a. Does the system reduce P_a* to less than P_{cr}^* for STANAG 2920 Fragmentation Test (V50 Test) F6 for a SS109 projectile?

b. Does the system prevent projectile and fragment penetration of the torso for STANAG 2920 Fragmentation Test (V50 Test) F6 for an SS109 projectile?

The initial design concept for the armour consists of a number of different layers (left to right); Figure 7:

a. **Ballistics cloth.** Protection of ceramic plate, and retard the velocity and spin of the bullet.

b. **Plate armour.** Slow and break up the bullet.

c. **Ballistics cloth.** Further retards the velocity and spin of the bullet.

d. **Liquid filled burst bladder.** The incompressible liquid to provide effective full thickness T_a and full area A_a, whilst also providing pressure abatement by the edges of the bladder bursting (acting as a pressure outlet) at a pressure below P_{cr}*.

e. **Crushable high-density foam.** Further pressure abatement.

f. **Ballistics cloth.** Prevent penetration by bullet fragments.

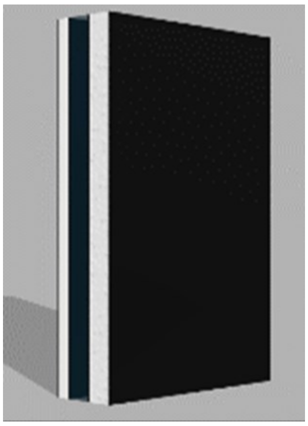

Figure 7. *Blast Disk* Advanced Body Armour Concept

The burst bladder aided the dissipation the pressure wave laterally. A thicker burst bladder and/or a different liquid may further reduce P_a*. Future armour optimisation may include, but not limited to:

a. the thickness of the bladder

b. bladder burst pressure

c. materials for the ballistics cloth, plate, liquid and foam

d. thickness of layers

e. lay-up angles of the ballistics cloth

f. potentially use of non-Newtonian liquids (shear thinning).

NEXT PHASE

The next phase of the research aims to extend the *Prediction* and *Prevention* capabilities, and commence development of the *Detection* capabilities:

Prediction

a. maturing numerical lethality model, including the incorporation of sonoluminescence and dieseling, and the modelling a full-size brain; Figure 8.

b. drop testing rig to validate the relationships of c_g to:

   i. P_{cr}*

   ii. bubble growth and collapse (P_g*)

   iii. sonoluminescence (P_s*)

   iv. dieseling (P_d*)

c. initial drop tests of ballistics gelatine brain models, with and without skull and skull & helmet; Figure 8.

Prevention

d. develop the advanced armour design, including:

   i. the thickness of the SiC plate to be optimised to be as thin as possible whilst preventing projectile penetration

   ii. addition to the model of ballistics cloth with various layup directions, especially to reducing projectile spin

e. initial small arms (5.56mm and 7.62mm) testing of the prototype advanced body armour panels, to determine:

   i. P_a* for both the in-service and advanced body armours

   ii. the ability of the advanced body armour to reduce the behind armour pressure to below P_{cr}* whilst preventing projectile penetration

Detection

f. initial cavitation image recognition system.

Figure 8. Numerical (left) and 3D printed (right) models of a full-size human brain

Image recognition

Cavitation injury may create areas of injury from the high pressures and temperatures (upward of 10,000 K) generated during the collapse of the cavitation bubbles. However, whilst numerous, the scarring volume may be very small. To aid radiologists to detect the scarring, it is proposed to develop medical imagery software. The software would search for the characteristic shape of the cavitation injuries and highlight the areas on the image:

a. creating a digital library of images at various stages of damage

b. identification of key image markers defining the deterioration caused by cavitation and adapting the software to recognise these

c. validate the software through blind tests against scans with known cavitation scarring

d. adapt the software for public use.

The image recognition software may also be used to identify cavitation in ballistics gelatine targets in still and high-speed video using weapons testing.

BENEFITS

The key benefit is the prediction, prevention and detection of shock-induced cavitation injury. This research aligns with current ADF projects and Australian Army efforts, including Land 125 and Land 159. Implications and Applications for the research may include:

a. **Lethality Modelling of small arms, blast and blunt force.** Land 159 Survivability

b. **Advanced body armour and helmets.** Land 159 Survivability

c. **Lethality modelling of small arms.** Land 159 Lethality

d. **Concussion modelling.** Land 159 Survivability.

e. **Risk Assessments and operational recommendations.** Cavitation Injury from overpressure for artillery, armoured main weapons, direct fire (e.g. 84mm), 50 cal. sniper rifles and alike

f. **Risk Assessments and operational recommendations.** Cavitation Injury from electromagnetic sources – Naval, Land radars, etc.

g. **Cavitation Modelling.** In-service and future SEA1000 submarines.

The research may contribute to Australia's Defence industry capability and/or capacity by developing new technologies, including:

a. develop a comprehensive lethality model, including cavitation, sonoluminescence and dieseling

b. techniques to use the lethality model to predict the site of potential cavitation injury based on injury location, blast direction and projectile calibre, entry location and entry angle

c. advanced shock attenuating body armour and helmets

d. advance shock sensors, either wearable and/or embedded into the body armour and helmets

e. develop cavitation image recognition software to be able to detect cavitation in medical imagery and during weapons testing in ballistics gelatine

f. support Capability stakeholders, including defensive against small arms and offensive capabilities against small arms.

United States Army Research Laboratory

Finally, this research appears to align with the recommendations of the Center for a New American Security (CNAS) in the 2018 dismounted soldier survivability study conducted for the United States Army Research Laboratory (ARL) [11]:

a. "*The Army should increase its efforts to protect soldiers against blast-induced brain injury, with increased resources for testing, experimentation, and combat helmet development*."

b. accelerating computational modelling and experimental research

c. wearing of pressure sensors

d. development of improved helmets

e. introducing weapon exposure limits (including artillery, shoulder-launched weapons and sniper rifles) and modifying firing procedures to reduce blast overpressure exposure

f. "*Primary blast pressure waves are an important mechanism for brain injury, but the specific causal mechanism is unclear. Multiple theories exist, each with varying degrees of support*"

The team believes that cavitation injury may be the answer.

CONCLUSION

In conclusion, the aim of the research is to be able to predict, prevent and detect shock event cavitation injury; historically known as "*Shell Shock*". This paper detailed the key outcomes of the initial research to be able to predict and prevent the shock event cavitation injury, including:

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d. The Advanced *Blast Disk* Body Armour was predicted to be able to abate the shock event pressure below the cavitation nucleation pressure while being able to prevent penetration by the small arms projectiles.

Recommendation

The next phase of the research is recommended to extend the prediction and prevention capabilities and commence development of the detection capabilities.

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