THESIS

EFFECTS OF EXPLOSIVE PRESSURE ON CADAVERIC OVINE AUDITORY TISSUE

Submitted by

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ABSTRACT

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The focus of this research centered around two main goals: 1) determine the allowable pressures that people can be exposed to in non-life-threatening situations and 2) determine the pressure required to rupture a sheep eardrum as a representative sample for human ears. For the first goal, blast pressure tests were conducted at a local football stadium using Composition 1 (C1) plastic explosive, 50-grain detonation cord, and the game cannon firing 75% strength shells. The results for each explosive were put into units of TNT equivalency to provide a common unit between explosive types. Based on the recorded pressures, spectators and staff in the vicinity of the game cannon are not at risk of severe ear damage, but should still take precautions and wear hearing protection when in the vicinity.

The second goal, which forms the bulk of this thesis, was investigated through conducting two series of explosive tests on dissected sheep heads and sheep ears as a representative sample for human ears. Through these experiments, the author developed a refined process for preparing and analyzing the eardrum samples under blast conditions. From these two blast tests, eight eardrums were ruptured when exposed to varying explosive pressures and this damage was used to estimate the threshold pressure at which severe damage initially occurs. The threshold pressure for these experiments is within the range of 34 kPa (4.9psi) to 42 kPa (6.1psi), which is substantially refined compared to the range of 8 kPa (1.2psi) to 104 kPa (15.1 psi) listed in other published literature. Presently, this result is only accurate for deceased sheep eardrum ruptures, but further testing could verify that this is also applicable to humans.

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LIST OF SYMBOLS

A, B, C, D, E, F, G = coefficients for Kingery-Bulmash equations
P = instantaneous overpressure at time t
P_0 = maximum or peak overpressure observed when t is 0
RE = relative efficiency of explosive
t = time
t_d = time duration
W_S = weight of sample explosive
W_{TNT} = equivalent weight of TNT
Z = scaled distance
Z_S = distance from explosive to point of interest
α = decay parameter

DEFINITION OF TERMS

Black Powder: a mixture of 75% potassium nitrate, 15% charcoal, and 10% sulfur, also known as gunpowder and used to propel explosives into the air (Chemistry of Gunpowder, 2015)

C1 Explosive: a plastic explosive, also known as Composition C, consisting of 88.3% cyclotrimethylene-trinitramine (RDX) and 11.7% plasticizer (Harris, 2018)

C4 Explosive: a plastic explosive, also known as Composition 4, containing 91% RDX, 5.3% dioctyl sebacate (DOS) as the plasticizer, 2.1% polyisobutylene as a binder, and 1.6% process oil (Pike, 2018)

Deflagration: the action of heating a substance until it burns away rapidly

Detonation: the act of causing a bomb or explosive device to explode

Detonation cord: a waterproof flexible fabric tube containing pentaerythritol tetranitrate (PETN) and often used to initiate other explosives (Johnson, 2015)

Ear pinna: the external part of the ear in humans and other mammals

Explosion: a sudden release of energy that generates light, heat, noise, and pressure, which results in a blast wave

Impulse: a force acting on a body and producing a finite change of momentum

Malleus: the outermost of three bones in the inner ear; this bone is directly attached to the tympanic membrane

Negative phase: the period of time when the properties of an explosion are below the ambient values

Overpressure: the difference between the ambient air pressure and the pressure developed in an explosion

Pars tensa: the thick and taut part of the tympanic membrane

Peak pressure: the maximum pressure achieved by an explosion

Positive phase: the period of time when the properties of an explosion are above the ambient value

Primary Blast Injuries (PBI): injuries related to explosions that occur as a direct effect of changes in atmospheric pressure caused by a blast wave, Relative Effectiveness (RE) factor: a factor assigned to an explosive material that serves to compare its strength to that of TNT

Rise Time: the amount of time it takes for a blast wave to reach peak overpressure

Scaled Distance: a calculated distance in the TNT equivalency formulation that converts an experimental distance to an equivalent distance for TNT using the TNT equivalent weight of a sample explosive

TNT Equivalency: relationship used to standardized the amount and type of explosive used in testing

Tympanic Membrane: a thin membrane that separates the cavity of the middle ear from the outer ear and helps transmit sound to the bones of the middle ear

Chapter 1 – Introduction and Objective

For most people, the idea of being subjected to explosive pressures is an abstract concept. Explosions are often assumed to be only associated with man-made events such as terrorism, and the probability of being exposed to their dangerous effects are correctly assumed to be minimal. Yet there are several instances where the average person could come in contact with these forces with varying levels of intensities. This could include, for example, accidental events such as explosion of an oil refinery, being in close proximity to a fireworks display, or being at a sporting event where the home team celebrates using a cannon or other type of explosive display. In these scenarios, people can suffer from injuries of the same magnitude as a terrorism or criminal related explosion. The determining factor for the amount or type of injuries caused by explosions not involving shrapnel is the created pressure wave.

Currently, very little published research related to the amount of pressure required to cause severe damage to the ear, including rupture eardrums, is available. The data that has been published is very ambiguous and lists wide ranges of pressures that may lead to this injury, but does not give specific threshold pressures between safety and injury. The author set out with two specific goals related to this lack of information: 1) determine the pressures people are exposed to in a common nonthreatening situation and 2) determine what the threshold pressure is that distinguishes between injured and non-injured eardrum tissue.

The testing to determine the pressures people could be exposed to involved the use of pressure probes and a local football stadium that discharges a cannon during home games. Several pressure probes were arrayed in position in and around the cannon enclosure and several shots were fired using Composition 1 (C1) explosive, detonation cord (det cord), and the cannon firing at 75% capacity. The resulting pressures were plotted on a schematic of the cannon alcove and compared with published data regarding potential damage that could occur at the pressures created in the stadium.

The experimentation for pressure damage to tissue involved extensive sample preparation and analysis both before and after the explosive testing was conducted. Since it is inhumane to expose living subjects to explosive blasts, deceased sheep from Colorado State University's Veterinary Teaching Hospital were selected and used for testing. The tissue selected for experimentation was the sheep ear since there is significant research indicating that the anatomy and physiology of the sheep ear is comparable to that of humans. In two separate explosives tests, sixteen ear samples from nine different sheep were exposed to explosive pressures using C1 and TNT explosives. Each ear was visually inspected with the naked eye and, in the second series of tests, with a 3.9mm (.15 in) ear borescope to determine if there was noticeable damage to the tympanic membrane (i.e. eardrum), which is the membrane located at the termination of the external auditory ear canal. After the visual inspection, one set of sample ears was prepared for a histological inspection to determine if there is microscopic damage to the eardrum prior to a full or partial rupture. From these tests, a clearer picture was formed of what pressures average people can be exposed to and at which pressure level damage can be first detected.

In the following chapters, the two primary thrusts of this work are outlined in detail. The main outcomes of this work are levels of shock wave pressure that can be experienced in what are usually assumed to be non-threatening environments, and estimates of the levels of pressure that are associated with full or partial tympanic membrane damage.

Chapter 2 – Background and Review of Literature

2.1 Blast-Related Injuries

Many factors affect air pressure changes that result from explosions, and it is generally considered inhumane to expose living creatures to explosives simply to study their effects. Because of these restrictions, there is limited literature available on the effects of explosives on animal tissue. The majority of research related to explosives and living tissue is centered on categorizing the different types of injuries from explosives. Several studies involving humans have been conducted immediately after an explosion occurred; however, the chaos at the scene made it difficult to reconstruct what happened and how people in the vicinity were arrayed at the time of the blast (Garner and Brett, 2007; Kerr and Byrne, 1975; Wightman and Glasdish, 2001). Only one other similar study in relation to the effects of shock waves on living specimens was available for public access (Cho et al. 2013) but it had distinct differences in methods from those discussed herein to create shock waves.

2.1.1 General Blast Injuries

Wightman and Gladish (2001) categorized the types of injuries that can be sustained as result of an explosion. According to their study, blast injuries can be placed into three different categories. Primary blast injuries (PBI) are caused by the change in atmospheric pressure that accompanies an explosion. This is the category under which eardrum perforation and rupture fall and is the focus of this study. Secondary blast injuries occur when people in vicinity of an explosion are hit by flying debris. Tertiary blast injuries are the result of a person being lifted by the force from an explosion and thrown some distance. The most common category of injuries that people suffer from when explosives are involved is PBI that affect the middle ear, the lungs, and the bowels. For the middle ear, several studies have been conducted and determined that pressures between 8 and 104 kPa (1.2 and 15.1 psi) are required to rupture the human tympanic membrane with the pars tensa being the most commonly injured portion of the ear. The pars tensa is the thick and taut portion of the tympanic membrane. The studies conducted to determine this range of pressures often revolved around studying soldiers and civilians who had survived being exposed to blast pressures. Their ears were examined after exposure to determine the level of sustained damage and the scene of the explosion reconstructed and mathematically modeled to determine pressure at various locations (Garner and Brett, 2007; Kerr and Byrne, 1975; Wightman and Glasdish, 2001). The range of 8 to 104 kPa (1.2psi and 15.1 psi) is a relatively large spread for this type of study, which could be explained by the fact that a wide variety of factors can impact the outcomes of an explosion.

In the Department of Defense (DoD) Directive (England, 2006) two additional categories of blast injuries were defined aside from primary, secondary, and tertiary blast injuries: quaternary and quinary. According to the DoD, quaternary blast injuries include burns, inhalation of toxic gas or other explosive related gases, and injuries resulting from environmental contamination. Quinary blast injuries result from the explosion of dirty bombs or bombs that are contaminated with bacteria or radioactive materials. Though these injury categories do not have direct relation to blast injuries of the ear, it does demonstrate that explosions can have widespread impacts. This report also presented a table, replicated as Table 1 below, listing the types of injuries that can be expected at different peak pressures. These values were determined after analyzing the injuries of service members who had been involved in explosive incidents. The explosions were studied, and the pressure waves reconstructed to determine the pressure at the location of the soldier.

Table 1: Short-duration primary blast overpressure effects on unprotected persons. (Champion, Holcomb, and Young, 2009)

Pressure (psi)	Pressure (kPa)	Effect
2	13.79	Auditory shift
5	34.48	Possible eardrum rupture
15	103.43	50% chance of eardrum rupture
30-40	206.85-275.80	Slight chance of lung injury
80	551.60	50% chance of lung injury
100-120	689.50-827.40	Slight chance of death
130-180	896.35-1241.10	50% chance of death
200-250	1379.00-1723.75	Probable death

2.1.2 Blast-Related Ear Injuries

A diagram of human ear anatomy is shown in Figure 1. The relevant structures of the ear to this experiment include the auditory canal and the tympanic membrane, which is the most commonly injured portion of the ear when exposed to explosive pressures. In addition to ruptures of the tympanic membrane, less severe injuries can also be experienced. These injuries often involve a shock to the receptor organs in the ear, from which most people will fully recover in a relatively short period of time. The symptoms of this include ringing in the ear, also known as tinnitus, and temporary deafness. Exposure to severe blasts or repeated exposure to blasts increased the chances of people developing damage to the cochlea or permanent hearing loss (Wightman and Gladish, 2001).

Kerr and Byrne (1975) studied the different forms of injuries that can occur to the ear and specific information was given related to other injuries caused by explosions. According to the authors, there are three distinct types of injuries that can be caused to the ear because of airborne stimulation. The first is noise-induced deafness, which causes damage to the middle ear through prolonged exposure to high-intensity noise, such as being near speakers at a concert or large-scale sporting event. The second is report trauma, which most frequently occurs in weapons operators who are exposed to repeated short duration sounds. The third form of trauma is blast trauma and results from a single exposure to a stimulus that has duration greater than 1.5 ms.

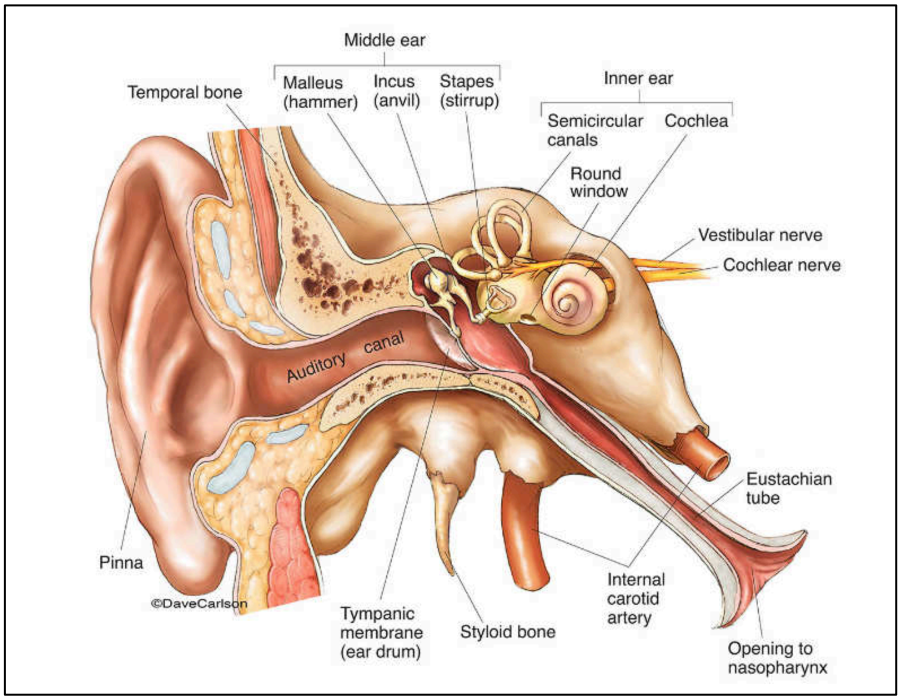

Figure 1: Illustration of the anatomy of the human ear. The pars tensa region is the thick and taut portion of the tympanic membrane and is the focus of study for this research (Carlson, 2010).

In a blast trauma, the rise time, peak pressure, and duration of the positive phase determine the effects of the blast on the ear. The damage caused by a blast can also be affected by the distance from the explosion, the protection offered by walls and other obstacles, and the orientation of the body to the explosion. In Kerr and Byrne (1975), a specific explosive incident was described as well as the effects experienced by people in the vicinity. In March 1972, a 5-pound bomb exploded in the Abercorn Restaurant in Belfast, Northern Ireland. Many people suffered injuries from the explosion and two girls were killed. A key discovery made in the investigation and medical examinations after the explosion revealed that the majority of people present in the restaurant suffered short-term hearing loss. Approximately one-half of the patrons at Abercorn had ruptured eardrums. Half of these were bilateral perforations, meaning both ears had been ruptured. Medical responders discovered that the tympanic membranes of children tended to be stronger than those of adults since several children sitting amongst adults who had ruptured eardrums were unharmed. This could be because the modulus of elasticity of the tympanic membrane decreases with age meaning it becomes more brittle (Gaihede, Liao, Gregersen, 2007). The main problem encountered by researchers was getting a good understanding of how far away different patrons were sitting from the explosion. Lacking this data, there was no way to correlate the amount of damage to the distance from the bomb.

To the author's knowledge, only one study has been completed regarding the effects of shock waves on the ear. Conducted by Cho et al. (2013), the study used living mice placed in a specially designed chamber that would deliver a pressure wave of compressed air to the mice's ears. The simulated blast waves were set at pressures of 94±2 kPa (13.6±0.29 psi), 123±9 kPa (17.8±1.31 psi), and 181±5 kPa (26.3±0.73 psi). Perforated eardrums were observed in all of the mice exposed to the blast wave and always occurred within the inferior aspect of the tympanic membrane. One somewhat surprising result of this study is that larger blast pressures did not produce larger perforations. This means that a similar level of damage was observed any time a blast wave exceeded a certain threshold pressure and was dependent on the properties of the membrane. Further results from Cho et al. (2013) revealed that the blast waves did not cause any noticeable damage to the bones of the middle and inner ear. Since the mice were exposed to the blast waves while they were alive, the researchers were able to observe the healing process of the tympanic membrane. In all of the mice, the tympanic membrane healed without medical intervention, though it was measured that the membrane was thicker after healing most likely because of scar tissue growth. After the membranes healed the researchers conducted hearing tests on the mice to determine if the mice's range of hearing had been affected. They discovered that the blast waves did cause damage to the cochlea, which resulted in sensorineural hearing loss. To confirm that this result was caused by the blast wave and not just perforation of the tympanic membrane, researchers surgically ruptured a group of mice's eardrums and conducted a hearing test on them after their ears had healed. The results showed that only the blast mice suffered from cochlea damage. Overall, this study demonstrated that blast wave damage to the ear is distinctly different and produces more severe injury than other means of ear damage. Clearly more work is needed to understand the process of blast damage.

2.2 Blast Mechanics

According to the article *Explosions Modeling – A Tutorial* (Usmani, 2015), “an explosion is a sudden release of energy that generates light, heat, noise, and most importantly pressure, which results in a blast wave.” (Usmani, 2015) After an explosion has occurred, the gas created expands rapidly in a spherical manner away from the point of detonation. As this gas travels outward from the explosion it pushes into the existing stationary gas, which results in a region of high pressure. It is this region of high pressure that is known as the blast wave (Usmani, 2015). Depending on the level of pressure, this wave is what can lead to injuries in humans and animals, most commonly at air-fluid interfaces in the body.

Though the destructive properties of a blast wave depend on several factors such as presence and distance of obstacles, all explosions have a similar pressure versus time profile. A graphic representation of this is shown in Figure 2. According to this graph, from the point of detonation, the pressure almost instantly reaches a peak pressure that can be significantly higher than the ambient pressure. After reaching the peak pressure, the blast wave then exponentially decays to or below the ambient air pressure. The portion of time that the blast wave has a pressure greater than the existing air pressure is labeled the positive phase and the subsequent phase where the pressure is lower than that of the ambient air is the negative phase. When examining blast-related injuries both the peak pressure and the duration of the positive phase contribute to the severity of injury. The longer the positive phase of an explosion is, the higher the likelihood of injury and the more severe the injuries. Based on data collected by Usmani (2015) the duration of the blast wave increases as it moves away from the point of detonation until it reaches a maximum value before dissipating into a sound wave. Equation 1 can be used to calculate the pressure of an explosion as a function of the time from detonation. In this equation, P is the instantaneous overpressure at time t, P_0 is the maximum or peak overpressure when t is 0, t_d is the time duration, and α is a decay parameter.

$$P = P_0(1 - \frac{t}{t_d})e^{\frac{-\alpha t}{t_d}} \qquad \text{Equation 1}$$

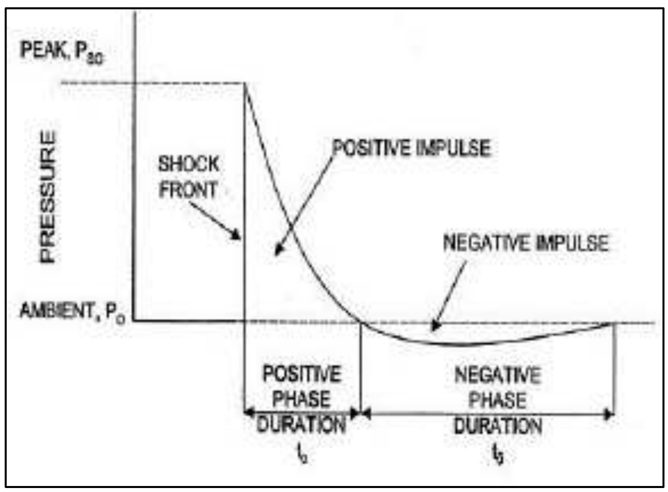

Figure 2: Qualitative pressure-time history diagram of a blast wave. (Usmani, 2015)

Even though all blasts have the same general characteristics in terms of a positive phase and negative phase, there are other factors that affect the way a blast wave travels. In a completely clear area with no obstacles and no change in terrain, the profile of the blast wave will generally follow the pressure-time plot as shown in Figure 2. However, if there are obstacles or changes in the terrain, the profile of the wave will show some variation. When obstacles are present they will cause a portion of the blast wave to be reflected back towards the point of explosion and can result in a pressure-time profile as shown in Figure 3. The measured pressure in this figure peaks and goes into the negative phase in the same manner as the unobstructed wave in Figure 2, but at approximately 0.10 seconds, the wave peaks again as a result of the blast wave reflecting towards the pressure sensor and the source of the explosion after coming into contact with a military style road barricade. The more obstacles and the closer they are to the source of the explosion, the more peaks that will be seen on a pressure-time plot. Reflected waves can pose a greater risk to humans and animals in the vicinity since the overpressure of the reflected wave may be higher than that of the initial wave. It is for this reason that explosions occurring in enclosed spaces can cause substantially more damage than an explosion occurring out in the open.

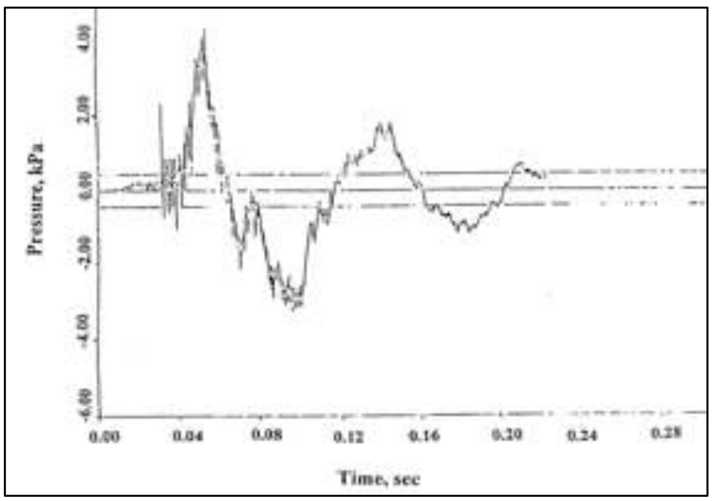

Figure 3: Pressure-time trace recorded behind a barrier after firing a 155mm shell. Complex waveform results from reflections and reverberations. The initial peak overpressure occurs at approximately .05 sec followed by the negative phase of the explosion from .07 seconds to .12 seconds. A second peak in pressure is observed at approximately .15 seconds because of the reflection of the pressure wave back towards the source of the explosion and the pressure sensor (Usmani, 2015).

2.3 TNT Equivalency

When explosives are involved in a study, there are multiple factors in addition to obstacles to consider when describing their effects. The characteristics of the explosives themselves pose a challenge since, for example, a mass of C1 explosive will have a different strength than a similarly massed C4 explosive. In order to put all explosives on a level surface for comparison, equations were developed to put all explosives into common units of TNT equivalency. In Caggiano (1973), the method and background for these equations is described. The equations can be used in all applications of explosives.

Though they were initially derived to assist in the design and placement of barricades for military installations, the TNT airblast standards and the procedure for calculating TNT equivalencies is relevant in the study of biological tissue damage because they are centered around the blast pressure and impulse, the two main factors of concern in blast-related injuries. In developing the equivalency equations, the primary variable in the calculation was the weight of the explosive. Equation 2 is used to convert the weight of the sample explosive to that of TNT using the Relative Effectiveness (RE) factor. In this equation the RE factor is used with the weight of the sample explosive (W_s) to determine the equivalent weight of TNT (W_{TNT}). A comprehensive list of explosive materials and their associated RE factors is located in Appendix A. This factor is a ratio of the relative mass of TNT to which an explosive is equivalent. For example, if a sample explosive has an RE factor of 1.66, then it would take 1.66 kg of TNT to generate the peak pressure from 1 kg of the sample explosive. After the equivalent weight of TNT is determined, the scaled distance (Z) for the explosive blast is calculated using Equation 3. The scaled distance of an explosive is the radial distance of a sample explosive (Z_s) from a point of interest divided by the cubed root of the equivalent weight of TNT (W_{TNT}). This value can then be used in Table B.1 in Appendix B to identify the expected corresponding pressure.

$$W_S * RE = W_{TNT} \qquad \text{Equation 2}$$

$$Z = Z_S/(W_{TNT}^{\frac{1}{3}}) \qquad \text{Equation 3}$$

An alternative method for solving the pressure experienced at a point comes from the Kingery-Bulmash empirical equations. The empirical equations were developed based on four large-scale explosive events where TNT explosions between five and five hundred tons were detonated and the various blast characteristics measured. The main limitation of these equations is the inability to account for variations due to weather, which generally have a greater effect on small-scale explosions. In this method, Equations 2 and 3 are still used to calculate the equivalent weight of TNT and the associated distance, but rather than search the results in Table B.1, the values from these equations can be plugged into Equation 4 and the pressure calculated directly using the coefficients listed in Table 2 (Swisdak, 1994). Both methods result in similar pressures, but the Kingery-Blumash equation allows for a wider range of pressures to be calculated outside of the data that is listed in Table B.1.

$$PI = (A + B(\ln(Z)) + C(\ln(Z))^2 + D(\ln(Z))^3 + E(\ln(Z))^4 + F(\ln(Z))^5 + G(\ln(Z))^6$$

Equation 4

Table 2: Coefficient values for the Kingery-Bulmash equation for incident pressure (i.e. peak pressure) in both kPa and psi (Swisdak, 1994).

Incident Pressure, PI (kPa)							
Range, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.2 - 2.9	7.2106	-2.1069	-0.3229	0.1117	0.0685	0	0
2.9 - 23.8	7.5938	-3.0523	0.40977	0.0261	-0.01267	0	0
23.8 - 198.5	6.0536	-1.4066	0	0	0	0	0

Incident Pressure, PI (psi)							
Range, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.5 - 7.25	6.9137	-1.4398	-0.2815	-0.1416	0.0685	0	0
7.25 - 60	8.8035	-3.7001	0.2709	0.0733	-0.0127	0	0
60 - 500	5.4233	-1.4066	0	0	0	0	0

While these equations are able to equalize different types of explosives into one common intensity scale, other factors can have an effect on the strength of an explosion and are not accounted for in the calculations. The storage and handling of the explosives, the age of the explosive, and environmental factors all play a role in the ultimate intensity experienced during an explosion. It is also important to understand that any material not classified as a high explosive may experience an incomplete explosion where only a part of the total mass is involved in detonation. The remaining mass is usually consumed in deflagration and dissipated as thermal energy. Hence these equations can give a baseline equivalency for different types of explosives, but there are other factors that can ultimately affect the resulting explosions. For these reasons, direct measurements of the pressure were completed for all blast experiments that were performed as part of this study.

Chapter 3 – Methods

This thesis is focused on two primary objectives: 1) determining the levels of sound pressure that can be generated in a common environment other than those generated by rare-event explosive detonations, and 2) attempting to assess more explicit relationships between the level of air pressure and damage to ear tissue as observed via physical experiments.

3.1 Stadium Pressure Testing

A common venue in which people can be exposed to higher than normal air pressure is a college football game. Several stadiums around the country have the tradition of firing a cannon or other similar explosive device for a wide variety of reasons. Tests were conducted in a local stadium using known explosive quantities and the actual cannon fired during games in an attempt to measure typical levels of blast pressure at these sort of events. The cannon, which is a 1918 French 75mm (2.95 in) field gun, is located in a concrete alcove in the southeastern corner of the field as shown in Figure 4 with an AutoCAD drawing shown in Figure 5. There is spectator seating surrounding the concrete alcove which places people as close as 5 feet away from the end of the cannon. Values for the radial distance of each point are listed in Table 3.

Figure 4: Picture of alcove where game cannon is located showing an overhead view and view looking into the alcove from the field.

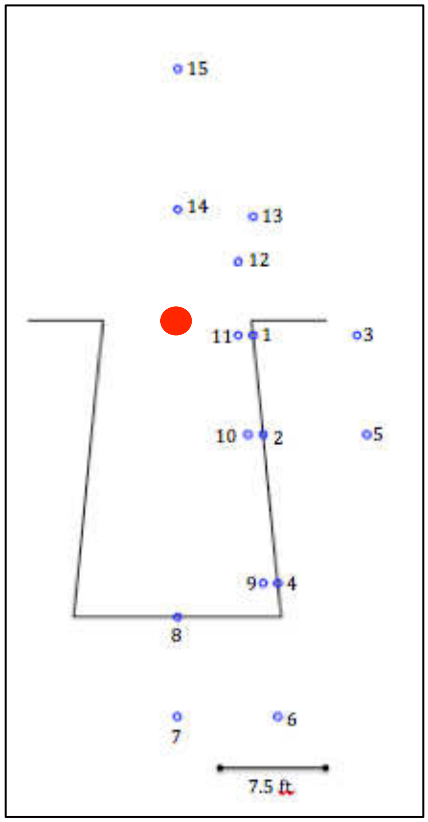

Figure 5: Schematic drawing to scale of cannon alcove with probe locations 1 through 15 labeled. Scale is provided in lower right corner. The red dot in the center is representative of the nose of the cannon.

Table 3: Horizontal, vertical, and radial distance from each probe location to the nose of the cannon.

Point	X distance (ft)	Y distance (ft)	Radial distance from cannon (ft)	Radial distance from cannon (m)
1	5	1	5.10	1.55
2	5.8	7.7	9.64	2.94
3	12.1	1	12.14	3.70
4	6.8	17.7	18.96	5.78
5	12.8	7.7	14.94	4.55
6	6.8	27	27.84	8.49
7	27	0	27.00	8.23
8	20	0	20.00	6.10
9	5.8	17.7	18.63	5.68
10	4.8	7.7	9.07	2.77
11	4	1	4.12	1.26
12	4	4	5.66	1.72
13	5	7	8.60	2.62
14	0	7.5	7.50	2.29
15	0	16.8	16.80	5.12

The first measurement was taken for one trial of six square inches of C1, equivalent to 0.022 pounds (6 g) of TNT with an RE factor of 1.66, followed by several trials each using one foot of 50 grain detonation cord, equivalent to .0118 pounds (3.23 g) of TNT also with an RE factor of 1.66. The explosive charges in each test were hung from a wire that crossed the front opening of the alcove and positioned so they were at the same height that the nose of the cannon is when fired. In each test, the resulting pressure wave was measured using four ICP Free-Field Blast Pressure "Pencil" pressure probes (PCB Piezotronics, 2018) wired to a DAQ computer terminal running LabVIEW software (LabVIEW, 2018). The probes were rotated through various positions in the stands, in the alcove, and on the field near the alcove where the cannon is fired so that at least one reading was recorded at each location. After each test, the probes were moved to a new location and the process repeated until measurements were collected at each probe location. In each test, the pressure probes were oriented in the direction of the source of the blast.

Following the tests for the C1 and detonation cord explosives, the process was repeated with the game cannon being fired at 75% of its capacity due to safety limitations of firing in a public venue. The mechanisms of the cannon explosions differed substantially from the explosions using C1 and detonation cord. When firing the cannon, a cartridge of black powder was fed down the barrel and pressed into the end of the cannon using a rammer. For the stadium cannon tests, the cartridges contained between 3/8 and ½ lb. of black powder. Once the cartridge was loaded, a cardboard imitation round was fed down the barrel until it was completely in contact with the black powder cartridge. At the end of the cannon, there was a small hole that allowed a friction igniter or other ignition system to be inserted into the cartridge. After being given permission to fire, the igniter was rapidly pulled from the cartridge and ignited the black powder in a similar manner to lighting a match. The black powder detonated and, as the pressure built in the barrel, the round was forced out of the muzzle. This was different than the C1 and detonation cord tests because the main explosion occurred in the barrel of the cannon and not in open space. For this reason, the calculations for theoretical pressure did not apply to the stadium tests involving the cannon.

3.2 Specimen Selection and Preparation

The levels of pressure that can cause partial damage to the tissues involved in hearing are still an open question in the literature and can vary from species to species or even within species. To test and further quantify the relationship between blast pressure and damage, appropriate test specimens had to be identified. As discussed previously, small animals such as mice have been used in earlier blast wave experiments, but because of their substantial difference in size (see Table C.1 in Appendix C) they do not give accurate results for comparison with human ear samples. There are several other species that can be used to give a more accurate example of the human ear than mice. Seibel, Lavinsky and Irion (2006) have noted that the most commonly used middle-sized animals for ear related experiments are dogs, cats, and monkeys. Unfortunately, when used as models to develop comparisons with humans, these animals pose substantial anatomical differences. They also tend to be more aggressive over the course of their lives, which could cause damage to the ear prior to testing. Additionally these animals are more prone to developing diseases, which could compromise the health of the ear and thus skew the accuracy of any results. Aside from health and morphologic differences, these animals also require more maintenance and housing before they are viable test subjects.

One species that has been studied and determined to resolve all of the issues associated with dogs, cats, and monkeys is sheep. Several medical and anatomical studies have been conducted on sheep to establish their ability to be used in studies related to humans. Seibel, Lavinsky, and Oliveira (2005) took CT scans of sheep heads to measure key ear anatomy to determine if sheep ears are satisfactory models for human comparison. After analyzing the scans of the sheep heads, the researchers listed their results in two tables comparing the dimensions for external and middle ear anatomy for humans and sheep. Those results are replicated below in Table 4 and Table 5 respectively. In general, the dimensions for the external ear features of sheep tend to be less than those for human ears. The dimensions of the middle ear follow a different pattern and tend to be slightly larger for sheep than for human. Overall, researchers estimated that sheep ear anatomy is related to that of humans by a factor of 2/3. This value is a much closer ratio than that of mice when compared to humans and, when combined with the similar anatomical layout, will give a more accurate representation of what would happen to a human ear under explosive conditions. Though some dog and cat ears can be similar in size to sheep, they have a different ear physiology than humans and sheep meaning the results from dog or cat ears would be inaccurate. Based on these results, Seibel, Lavinsky, and Oliveira (2006) determined that sheep ears have a high degree of similarity to the anatomy of human ears and is one of the most similar models to the human ear in terms of size. Because of these similarities, these researchers concluded that sheep are suitable models to use in surgical training, implantation of hearing aids, and acoustic trauma studies. Additionally, according to Lim (2009), the tympanic membranes of sheep and humans are morphologically similar and contain the same types of cells and cell layers so they have similar mechanical properties.

Using sheep ears for explosive testing proved to be an appropriate specimen in this research not only because of their deemed suitability but also since they are readily available through Colorado State University's Veterinary Teaching Hospital. All specimens were humanely euthanized for research purposes and all excess were tissues disposed of or used for additional research.

Table 4: Comparison between the dimensions of the auris externa (external ear) in sheep and humans. (Seibel, Lavinsky, and Oliveira (2006))

External ear	Humans (mean)	Humans (2/3) of mean	Sheep (mean)	Sheep (lower limit)	LL[a] (% 2/3 mean)
External acoustic meatus					
Length (mm)	15.0	10.0	14.1[b]	13.6	136.0
Horizontal diameter (mm)	4.5	3.0	3.9[c]	3.6	120.0
Tympanic membrane					
Horizontal diameter (mm)	8.5	5.7	5.3[c]	4.2	73.7
Vertical diameter (mm)	9.5	6.3	8.2[b]	7.9	125.4
Surface (mm^2)	65	43	36.4	34.9	81.2
Tympanic membrane angle (°)/external acoustic meatus			47.0[b]	44.9	

[a]LL, lower limit of the mean at 95% confidence interval.
[b]CT in coronal section.
[c]CT in axial section.

Table 5: Comparison between the dimensions of the auris media (middle ear) in sheep and humans. (Seibel, Lavinsky, and Oliveira, 2006)

Middle ear	Humans (mean)	Humans (2/3 of mean)	Sheep (mean)	Sheep (lower limit)	LL[a] (% 2/3 mean)
Length (mm)	15.0	10.0	13.3[c]	12.5	125.0
Height (mm)	15.0	10.0	18.9[b]	18.0	180.0
Width (mm)	3.0	2.0	3.6[b]	3.4	170.0
Tympanic membrane/promontory (mm)	2.0	1.3	2.4[c]	2.2	169.2
Hypotympanic					
Width (mm)	5.0	3.3	10.1[b]	9.3	281.8
Length (mm)	15.0	10.0	17.1[c]	16.3	163.0

[a]LL, lower limit of the mean at 95% confidence interval.
[b]CT in coronal section.
[c]CT in axial section.

After being euthanized, the sheep heads were collected and placed in a freezer at 28°F to prevent decay prior to dissection. During dissection, the skin, muscle, fat and other tissues including the ear pinna were removed from the skull and the mandible dislocated to better expose the ear canal and the portion of the skull containing the inner ear. Once the bone around the ear canal had been cleared, a one and a half inch circular coring drill bit attached to a drill press was used to remove the entirety of the inner ear from the skull. Care was taken to keep the inner ear chamber completely intact. After being removed and properly cataloged, the ears were frozen again to prevent decay before the blast tests. An example of the ear samples prior to explosive testing is shown in Figure 6. The final step of the specimen preparation was to take pictures of the tympanic membrane before the explosive testing to provide a visual comparison for images taken after the blasts. The pictures were taken using a 3.9mm (.15 in) ear borescope inserted into the ear canal. The pre-explosion images for seven ear samples are shown in Appendix D.

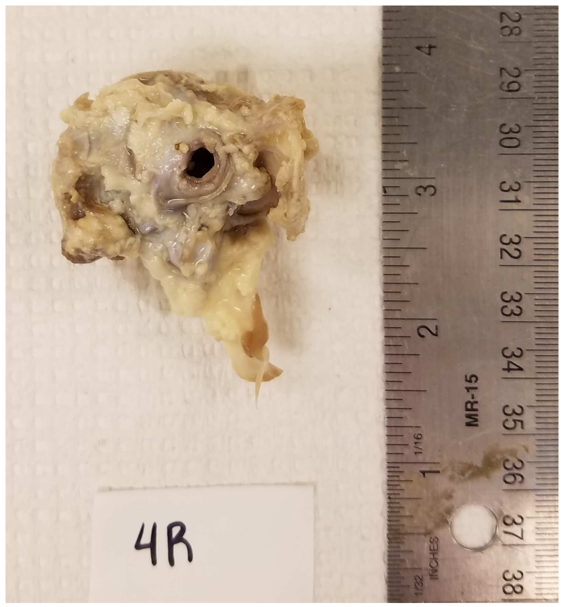

Figure 6: Sheep ear sample after being removed from the skull. The hole in the center of the sample is the ear canal and leads to the tympanic membrane and the inner ear cavity.

3.3 Explosive Test Setup and Procedures

A preliminary blast test involving sheep ears was conducted on February 14th, 2018 at the Colorado State University explosives site in Fort Collins, CO. In this experiment, five sheep heads that had not been fully dissected were used for five trials of explosive testing. The sheep heads were mounted on a vertical piece of rebar and placed directly in front of the blast with either the left or right ear facing the explosive. Three stands for pressure probes were placed around the sheep head at varying distances and a wooden A-frame supported by a metal cart was placed in front of the head mount to hold the explosive. Once all of the stands were in place for each explosion, the sheep heads and the pressure probes were installed on the stands and the explosive charge tied to the A-frame in front of a gallon-sized bag filled with water. The water bag served to direct the blast towards the specimen and away from the research team. The charge used for each test in the experiment was a six square inch piece of C1 explosive detonated with a twelve-inch piece of 50-grain detonation cord. The layout and pressure readings for each of the five trials are shown in Appendix E. In this test, the pressure probes were not positioned at the same distance from the explosive charge as the heads, so the exact pressure experienced at the ear could only be estimated through calculations using Equations 2 through 4. Table 6 lists the radial distances of the sheep head and three pressure probes from the explosive charge as well as which side of the sheep head was facing the blast.

Table 6: Layout of February blast test listing the explosive type used, the distances of probes, and the distance of the specimens from the explosive.

Trial	Charge Used	Radial Distance of Head	Radial Distance of Probe 1	Radial Distance of Probe 2	Radial Distance of Probe 3	Ear Facing the Blast
1	6 in^2 C1 Detasheet and 1 ft 50 grain det cord	0.3 m (1 ft)	0.8 m (2.7 ft)	0.8 m (2.7 ft)	3.7 m (12 ft)	Left
2	6 in^2 C1 Detasheet and 1 ft 50 grain det cord	0.9 m (2.91 ft)	0.4 m (1.3 ft)	0.8 m (2.7 ft)	3.7 m (12 ft)	Left
3	6 in^2 C1 Detasheet and 1 ft 50 grain det cord	0.9 m (2.91 ft)	0.4 m (1.3 ft)	0.8 m (2.7 ft)	3.7 m (12 ft)	Left
4	6 in^2 C1 Detasheet and 1 ft 50 grain det cord	0.3 m (1 ft)	0.4 m (1.3 ft)	0.8 m (2.7 ft)	3.7 m (12 ft)	Right
5	6 in^2 C1 Detasheet and 1 ft 50 grain det cord	0.6 m (2 ft)	.6 m (2 ft)	0.8 m (2.7 ft)	3.7 m (12 ft)	Right

The second blast test occurred on Wednesday September 26th, 2018 at Colorado State University's Maxwell test site located just south of Virginia Dale, Colorado. Upon arrival at the test site, a tripod style rebar stand was emplaced in front of the explosive holding stand. The stand held a mount for one of the ICP Free-Field Blast Pressure "Pencil" pressure probes (PCB Piezotronics, 2018) and a clamp used to hold the ear samples in place was zip-tied directly above the pressure probe. This allowed for a far more accurate pressure measurement at the actual location of the specimen. The final stand configuration used for the ears and pressure probe is shown in Figure 7. The explosives were attached to a wooden A-frame linked to a metal support cart as shown in Figure 8. Both the rebar stand, and the explosives frame were reinforced with several fifty-pound sandbags to keep them from moving during the explosions. The explosives used in this test were one-half pound and three-quarter pound cylinders of TNT approximately.

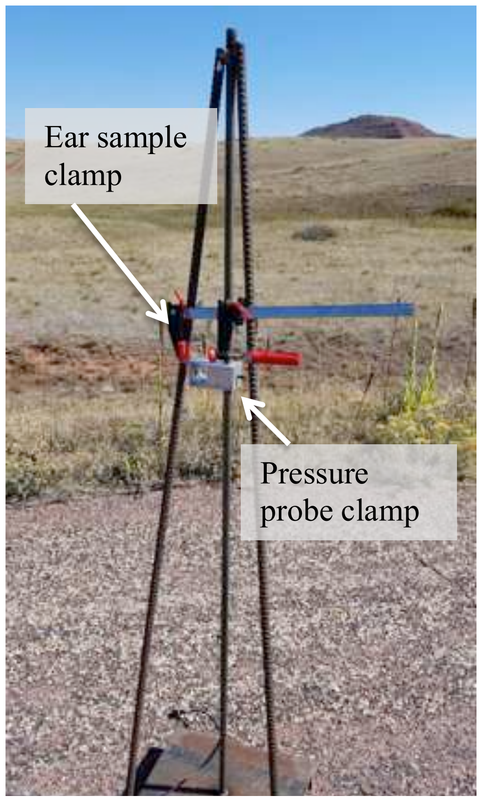

Figure 7: Configuration of stand with pressure probe clamp and clamp for September sheep ear samples.

Figure 8: Picture of the stand used to support the explosive charge during tests.

After the various support components were in position, the pressure probe was secured in place and attached to a computer running LabVIEW analysis software (LabVIEW, 2018). Since the pressure probes and their cables are sensitive to all motion, the cable for the probe was secured directly to the rebar stand with tape to limit the effects of environmental factors on the results.

When all components were in place, the ear was positioned in the clamp with the ear canal facing the explosive. The explosive charge was then attached to the support frame in front of a hanging water bag to direct the blast towards the target. Using an electric detonating system consisting of a blasting cap and electric wire, the explosion was initiated from a safe distance away. After each blast test, the ear sample was removed from the clamp and replaced with a new sample. Overall, six ears were exposed to blasts and one ear served as the control for the series. Table 7 lists the amount of explosives used in each test and the radial distance of the ear specimen and pressure probe from the explosive charge.

Table 7: Summary of explosive amounts used in September testing and the distances between the explosive and specimen for each trial.

Trial	Ear Sample	Mass of TNT	Distance from Charge
1	4R	190.5 g (0.42 lb)	6.22 m (20.42 ft)
2	4L	171.5 g (0.38 lb)	4.72 m (15.50 ft)
3	3L	195.5 g (0.43 lb)	3.20 m (10.50 ft)
4	3R	200.5 g (0.44 lb)	1.68 m (5.50 ft)
5	2R	354.5 g (0.78 lb)	1.68 m (5.50 ft)
6	1L	246.0 g (0.76 lb)	2.74 m (9.00 ft)

3.4 Post-Explosion Analysis

3.4.1 February Blast Test

When the blast tests were completed, the five heads that had been involved in the testing were placed in the freezer set to 28° F at CSU's Orthopaedic Bioengineering Research Laboratory (OBRL) until they could be fully processed. After being removed from the freezer at a later date, the heads were thawed for 24 hours before the skin, muscle, and fat tissues were dissected away from the skull. When all of the tissues were removed, the lower jawbone was dislocated and removed from the skull. With the skull and the ear canal fully exposed, a one-and-a-half-inch diameter coring drill bit was used in a drill press to core out the entire inner ear cavity. Since the tympanic membrane could not be viewed directly in this configuration, the ear cores were trimmed down using a band saw with a diamond tip abrasive blade. Slices were made around the ear core to expose the tympanic membrane entirely. A visual inspection was completed and photographs were taken of each sample. The pictures of the ears after trimming are shown in Appendix F. The relative difficulty of this process made after the actual tests precipitated the introduction of pre-test extraction of the ear region.

3.4.2 September Test Ears

After all blast tests were completed, the ear specimens were brought back to the OBRL for processing. The first analysis of the ears involved a visual inspection of the tympanic membrane using a 3.9mm (.15 in) ear borescope. These images could then be compared to the pictures taken before the explosive testing and any differences identified. Due to the physiology of the sheep ear and the geometry of the borescope, the entire membrane could not be seen or pictured with the ear borescope. The images that were obtained from this inspection are shown in Appendix G. After taking pictures of the eardrums, the ear cores were put in a solution of formalin to fix and preserve the specimen until further processing could begin. The ears were left in formalin solution for four days. On the fourth day, the ear samples were trimmed using a band saw with a diamond tip abrasive blade until the tympanic membranes were completely exposed. These samples were cut down to approximately one square inch pieces, which was a much smaller size than the samples from the February test because they were put through additional histological processing. Pictures were taken of all the samples after trimming and are shown in Appendix G.

Once the visual inspection of the eardrums was complete, the processing for developing histology slides began. The first step of this process involved submerging the ears in an 8% trifluoroacetic acid (TFAA) solution to begin dissolving the calcium in the bones around the eardrum. The TFAA solution was changed approximately every 24 hours and x-rays were taken of the ears once a week in order to determine the amount of calcium remaining in the samples.

After the decalcification process was complete, the ears were placed in a Tissue-Tex machine to begin a chemical bath process that would first dehydrate the samples, then infuse the tissue with paraffin, before a final round of fixing. In total, the ear specimens went through sixteen different stages of chemical baths. Table 8 lists the various steps, what chemicals were used, and their concentrations. The specimens remained in this chemical bath for three days before they were removed and then submerged in melted paraffin wax for twenty minutes. When the embedded samples were removed from the paraffin, the excess wax was cut from around the ear tissue. The remaining block of wax containing the eardrum was then placed on a surgical microtome used to cut 5μm slices of the eardrum specimens. After the slices were cut from the embedded sample, they were mounted on glass slides and put in a low temperature oven to melt off any excess paraffin. The final stage of the histology exam involved staining the slides and then analyzing the samples under a microscope looking for abnormalities in the tympanic membrane. Because of the high density of the skull bone, the ability of the decalcification solution to infiltrate the bone was severely reduced and the process took longer than expected. The results of the histological analysis were not available at the time of submission.

Table 8: Stations and chemicals used to dehydrate and infuse specimens with paraffin in the Tissue Tex machine.

Station	Solution	Concentration
1	Alcohol	70%
2	Alcohol	80%
3	Alcohol	80%
4	Alcohol	95%
5	Alcohol	95%
6	Alcohol	100%
7	Alcohol	100%
8	Alcohol	100%
9	Xylene	100%
10	Xylene	100%
11	Paraffin	n/a
12	Paraffin	n/a
13	Paraffin	n/a
14	Paraffin	n/a
15	Xylene	100%
16	Alcohol	100%

4.1 Stadium Pressure Tests

After the data from the LabVIEW software was sorted and compiled, the pressure results for the stadium test were recorded for each probe location. Since cannon alcove is symmetric, it was assumed that the results on the left side of the enclosure would mirror the results measured on the right side of the enclosure for all tests. The pressures measured at each probe location for the C1, detonation cord, and 75% strength cannon tests are shown in Figures 9, 10, and 11 respectively. Tables 9 and 10 list the measured pressures for each probe during all of the different test series, the radial distance of the probe from the explosive, and the calculated theoretical pressure using Kingery-Bulmash equation. Table 11 lists the measured pressures at the various probe locations and the radial distance of the probe from the blast, but because of the unique nature of the cannon explosions, no theoretical pressures are included. The pressure-time plots for all tests are shown in Appendix G.

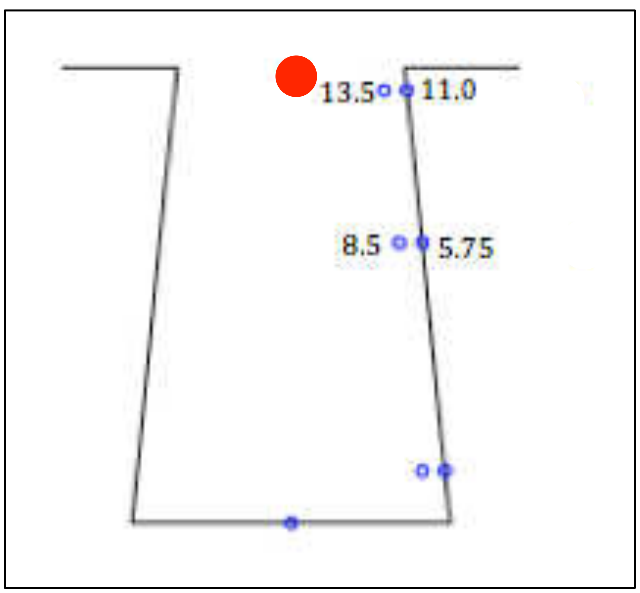

Figure 9: Measured pressure levels in and near cannon enclosure for 6 in^2 of C1 explosive (.022lb TNT, RE=1.66). Only one test was completed using this load because of the high output pressure readings. The red dot denotes the location of the explosive charge and the pressure values are listed next to the location of the respective pressure probes. All values shown are in kPa.

Table 9: Measured and theoretical pressures for explosive test using 6 in^2 of C1.

C1 Test			
Trial 1			
Probe Number	Distance from Charge	Actual Pressure	Theoretical Pressure
1	2.98 m (9.64 ft)	5.75 kPa (0.834 psi)	9.79 kPa (1.42 psi)
2	1.55 m (5.10 ft)	11.0 kPa (1.60 psi)	23.73 kPa (3.44 psi)
3	1.26 m (4.12 ft)	13.5 kPa (1.96 psi)	33.27 kPa (4.83 psi)
4	2.76 m (9.07 ft)	8.5 kPa (1.23 psi)	10.61 kPa (1.54 psi)

Based on the results, the highest-pressure recording occurred during the C1 test at probe location 11 as shown in Figure 5 and had a reading of 13.5 kPa (1.96 psi). This does fall within the range of pressures that could cause damage to the tympanic membrane, but it is on the lower end of the spectrum and since no one should be detonating C1 in the stadium, it is highly unlikely that anyone in the stadium would be exposed to these pressures. Comparing the theoretical pressure levels to the measured pressures, all of the theoretical pressures are substantially higher than the pressures measured by the probes. This discrepancy could be a result of the weather conditions in the stadium, which the Kingery-Bulmash equations do not take into account. It could also be related to certain properties of the explosive material such as age or moisture content.

Similarly, in the detonation cord tests, the greatest pressure reading occurred at location 11 and had a value of 10.4 kPa (1.5 psi), just barely within the pressure limits to possibly cause damage to the ears. Since more trials could be completed using the detonation cord, a pattern of how the pressure traveled through this portion of the stadium could be better understood. The highest region of pressure is clearly the region directly in front of and to the right and left of the charge. This makes sense because the blast was setup in a way that it would mimic the directional explosion of the cannon. What is somewhat surprising is the relatively high pressure reading of 6.5 kPa (.94 psi) experienced behind the charge inside the cannon alcove. This indicates that a portion of the pressure wave is being directed back into the area where cannon operators are working during home games. Though the pressure is outside of the range that could cause serious ear damage, because it is being contained in an enclosed space, there is the potential for reflected waves to propagate through the space taking much longer to diminish than a wave in open space. Aside from that one pressure anomaly in the cannon alcove, the remaining locations show an expected pattern of pressure diminishing as the distance from the blast increased in all directions.

Comparing the theoretical pressure values for the detonation cord tests to the actual pressure measured, there are several instances where the two values are nearly the same. These equivalencies occurred most often when the radial distance between the charge and the probe was greater than 15ft (4.6m). This indicates that for small-scale testing, the Kingery-Bulmash equations can be reasonably accurate for calculating pressures that occur further away from the source of the explosion. The pressures measured at distances closer than 15ft (4.6m) tended to be much lower than the theoretical values calculated at the same distance, similar to the trend observed in the C1 stadium test.

The pressure results for the cannon firing at 75% capacity show a similar pattern to the results of the detonation cord tests. The higher pressures were measured in front of and directly to the right and left of the cannon, but there was still one point of relatively high pressure recorded in the cannon alcove meaning the reflected wave trend exists even for explosions producing lower overall pressure levels. The most noticeable difference between the cannon results and the results from the C1 and detonation cord tests is that the pressures at every location are drastically smaller with 2.7 kPa (0.39psi) being recorded as the maximum pressure created by the cannon. Because the main explosion for the cannon occurs within the barrel, it makes sense that the pressures experienced in locations surrounding the blast point are lower than they were for an open-air explosion.

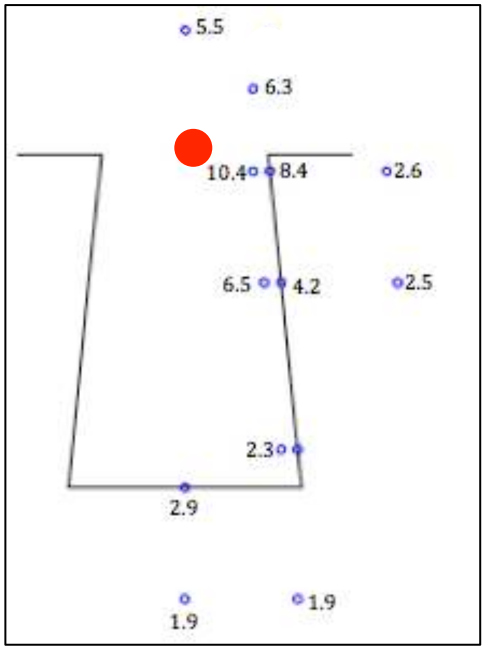

Figure 10: Measured pressure levels in and near cannon enclosure for one-foot pieces of detonation cord (.0118lb TNT, RE=1.66) tests. Three individual tests were completed and the results from the pressure probe at all positions combined. All values shown are in kPa.

Table 10: Measured pressure results and calculated theoretical pressures for stadium blast tests using 1-foot pieces of 50-grain detonation cord.

Detonation Cord			
Probe Number	Distance from Charge	Actual Pressure	Theoretical Pressure
Trial 1			
1	3.70 m (12.14 ft)	2.6 kPa (0.38 psi)	5.65 kPa (0.82 psi)
2	8.49 m (27.84 ft)	1.9 kPa (0.28 psi)	1.89 kPa (0.27 psi)
3	1.26 m (4.12 ft)	10.4 kPa (1.51 psi)	23.93 kPa (3.47 psi)
4	2.76 m (9.07 ft)	8.5 kPa (1.23 psi)	10.61 kPa (1.54 psi)
Trial 2			
1	5.68 m (18.63 ft)	2.3 kPa (0.33 psi)	3.18 kPa (0.46 psi)
2	8.23 m (27.0 ft)	1.9 kPa (0.28 psi)	1.94 kPa (0.28 psi)
3	1.73 m (5.66 ft)	6.3 kPa (0.91 psi)	15.09 kPa (2.19 psi)
4	2.29 m (7.5 ft)	5.5 kPa (0.80 psi)	10.37 kPa (1.50 psi)
Trial 3			
1	1.55 m (5.10 ft)	8.4 kPa (1.22 psi)	17.47 kPa (2.53 psi)
2	2.98 m (9.64 ft)	4.2 kPa (0.61 psi)	7.55 kPa (1.10 psi)
3	4.55 m (14.94 ft)	2.5 kPa (0.36 psi)	4.32 kPa (0.63 psi)
4	6.10 m (20.0 ft)	2.9 kPa (0.42 psi)	2.87 kPa (0.42 psi)

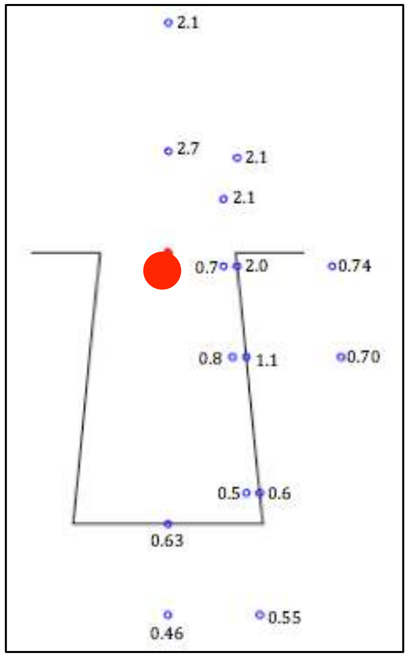

Figure 11: Measured pressure levels in and near cannon enclosure for the 75% cannon tests. All values shown have units of kPa.

Table 11: Measured pressure results from stadium test using cannon at 75% capacity.

Cannon		
Probe Number	Distance from Charge	Actual Pressure
Trial 1		
1	1.55 m (5.10 ft)	2.0 kPa (0.29 psi)
2	5.68 m (18.63 ft)	0.5 kPa (0.07 psi)
3	6.10 m (20.0 ft)	0.63 kPa (0.09 psi)
4	2.98 m (9.64 ft)	1.1 kPa (0.16 psi)
Trial 2		
1	N/A	N/A
2	5.12 m (16.8 ft)	2.1 kPa (0.30 psi)
3	2.29 m (7.5 ft)	2.7 kPa (0.39 psi)
4	8.49 m (27.84 ft)	0.55 kPa (0.08 psi)
Trial 3		
1	1.26 m (4.12 ft)	0.7 kPa (0.10 psi)
2	3.70 m (12.14 ft)	0.74 kPa (0.11 psi)
3	4.55 m (14.94 ft)	0.7 kPa (0.10 psi)
4	2.76 m (9.07 ft)	0.8 kPa (0.12 psi)
Trial 4		
1	8.23 m (27.0 ft)	0.46 kPa (0.07 psi)
2	5.78 m (18.96 ft)	0.6 kPa (0.09 psi)
3	1.73 m (5.66 ft)	2.1 kPa (0.30 psi)
4	2.62 m (8.6 ft)	2.1 kPa (0.30 psi)

Even though the pressures for the cannon blasts were substantially smaller than those of the C1 or detonation cord, the noise level associated with the blast pressure had to be taken into consideration since this is the actual explosion experienced in the stadium. According to the Occupational Health and Safety Administration (OSHA), the calculated sound level pressure associated with 2 kPa is 160 dB. This sounds level falls between the level of noise one would experience from a jet engine from 100 yards away (100 dB) and being at an extremely loud rock concert (200 dB). OSHA has set standards for the duration people can be exposed to certain sounds levels before irreversible damage occurs to the ear. Starting with being exposed to 90 dB sounds level for 8 hours, the acceptable exposure duration is cut in half for every increase of 5 dB. For the cannon at 160 dB, the acceptable exposure duration is 1.75 seconds (OSHA, 2018). The cannon blasts only maintain the peak pressure for approximately 1 ms, so it is unlikely that irreversible damage would be caused. This is still a substantial sound level, so proper people in the vicinity of the cannon should wear hearing protection.

There were a number of practical constraints that limited the number, duration, and level of charge that could be explored in the time allowed for these tests. To obtain more accurate and refined results, the tests should be repeated several times and a statistical analysis conducted to determine the average, minimum, and maximum pressures as well as the variance and standard deviation.

4.2 February Blast Test

With the results of the stadium testing complete, the first round of sheep test results were analyzed to determine at what pressure damage could be identified. The data collected from the pressure probes was compiled and resulted in the pressure time plots shown in Appendix H. Since there were instances in several of the trials where the pressure probes were not at the same distance from the explosive as the ear samples, the pressure of the blast wave at the ear had to be calculated using the blast equivalency equations from Chapter 2. The C1 detasheet used in the tests had an RE factor of 1.66. The results from these equations as well as the identified damage to the ears are listed in Table 12 and sample calculations are shown in Appendix I. A graphic representation of the pressure versus damage is shown in Figure 12. The pressure experienced by the ear facing the opposite direction from the blast could not be calculated since the head itself provided protection to the eardrum by acting as a shield for the specimen. Without a pressure probe located at that point, the exact pressure was unknown, though based on the results in Table 12, it was enough of a shield to prevent all of the eardrums facing away from the explosion from rupturing. The values for the pressure experienced by the ears facing the explosion are rough estimates based on the data available and the TNT equivalency equations. For comparison of the effectiveness of the TNT equivalency equations, Table 13 lists the calculated theoretical pressure values for the three probes in each test that were estimated by the Kingery-Bulmash equations.

Table 12: Pressure results from February blast test showing measured pressures at each probe location, the calculated pressures at the ear, and the resulting damage to the ear. Highlighted cells in the ear sample column represent the ears that were facing the explosion.

Trial	Ear Samples	Pressure at Probe 1	Pressure at Probe 2	Pressure at Probe 3	Pressure at ear sample	Status of Eardrum
1	1R	75.9 kPa (11.01 psi)	53.67 kPa (7.78 psi)	6.42 kPa (.931 psi)	N/A	Intact
	1L				311.8 kPa (45.22 psi)	Ruptured
2	3R	75.9 kPa (11.01 psi)	40.4 kPa (5.86 psi)	6.24 kPa (.905 psi)	N/A	Intact
	3L				34.02 kPa (4.93 psi)	Ruptured
3	2R	65.72 kPa (9.53 psi)	21.90 kPa (3.18 psi)	5.16 kPa (.748 psi)	N/A	Intact
	2L				34.02 kPa (4.93 psi)	Intact
4	4R	75.9 kPa (11.01 psi)	37.94 kPa (5.50 psi)	5.75 kPa (.834 psi)	311.8 kPa (45.22 psi)	Ruptured
	4L				N/A	Intact
5	5R	51.27 kPa (7.44 psi)	53.17 kPa (7.71 psi)	6.94 kPa (1.01 psi)	70.83 kPa (10.27 psi)	Ruptured
	5L				N/A	Intact

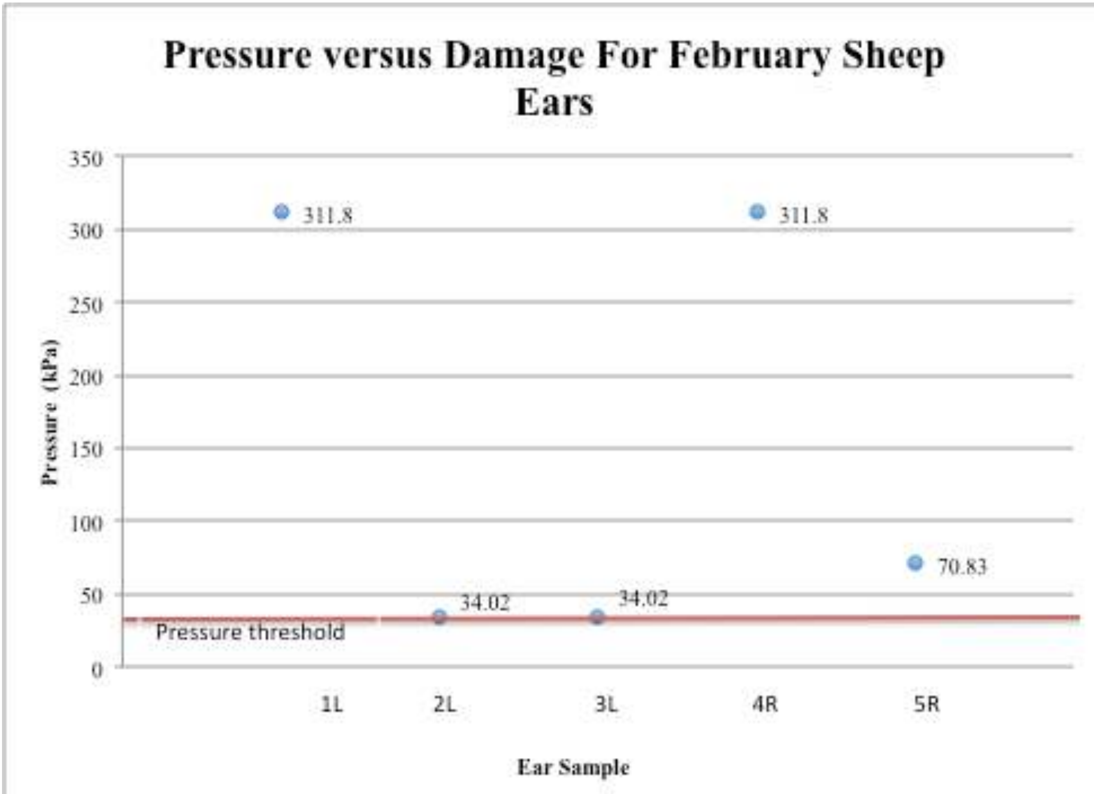

Figure 12: Plot of pressure experienced by the five samples that were directly subjected to blast testing on 14 February 2018. The red line on the plot indicates the threshold pressure value for this test and is set at a value of 34.02 kPa (4.9 psi).

Table 13: Theoretical pressures of February blast tests calculated using Kingery-Bulmash equations.

Trial	Pressure at Probe 1	Pressure at Probe 2	Pressure at Probe 3
1	74.75 kPa (10.84 psi)	74.75 kPa (10.84 psi)	7.33 kPa (1.06 psi)
2	335.65 kPa (49.70 psi)	74.75 kPa (10.84 psi)	7.33 kPa (1.06 psi)
3	335.65 kPa (49.70 psi)	74.75 kPa (10.84 psi)	7.33 kPa (1.06 psi)
4	335.65 kPa (49.70 psi)	74.75 kPa (10.84 psi)	7.33 kPa (1.06 psi)
5	135.13 kPa (19.61 psi)	74.75 kPa (10.84 psi)	7.33 kPa (1.06 psi)

The limitations in the calculations become apparent when comparing the setup and results of trials 2 and 3. In both tests, the probes and sheep head were kept at the same distances and the same size explosive charge was used. Despite the identical setup of each trial, the pressures measured by the probes in trial 2 were greater than those in trial 3, up to a nearly 20 kPa (2.9 psi) difference at probe 2. This pattern is not reflected in the calculation for the pressure experienced at the ear samples as both have the same calculated pressure of 34.02 kPa (4.9 psi). Further evidence that there are limits to the equations is related to the ear damage experienced in these two trials. In trial 2, the ear facing the explosion suffered a full rupture of the tympanic membrane, but the ear in trial 3 had no visible damage. To prevent this error in future tests, more trials should be conducted to calculate averages and outliers in the data. In this situation, it is possible the two pieces of C1 used had been stored under different conditions or one was much older than the other, both of which are factors that impact the effectiveness of the explosives.

Based on the results listed in Table 12 and shown in Figure 12, the threshold pressure for this series of test is approximately 34 kPa (4.9 psi). At this pressure the first instance of damage was observed even though a second charge at the same weight and distance did not cause damage.

4.3 September Blast Test

After adjusting the procedure for preparation of the ear samples and placing a pressure probe at the same location as the ear samples, the September test gave a much more accurate set of results. The peak pressures recorded for each explosive test, the calculated theoretical pressures, as well as the physical damage to the ears are listed in Table 14 and the individual pressure-time plots for each test are shown in Appendix J. A graphic representation of this data is shown in Figure 13 with a threshold line drawn at the value that distinguishes between clear damage to the ear and the point of no visible damage. The threshold value for this set of tests was 42 kPa (6.1psi) since this is the lowest pressure at which damage was seen in the ears. Since there was no need to calculate any of the pressures experienced by the ears, the results for this test are more reliable than those collected in February. The theoretical values that were calculated for comparison fall both above and below the measured pressures indicating that outside factors, such as weather, had a greater influence on the measured results for this test. The theoretical pressures calculated for comparison to the measured pressures between 23 kPa

(3.36psi) and 42 kPa (6.13psi) tended to be less than the actual pressure, while those calculated for the higher pressures were typically much higher.

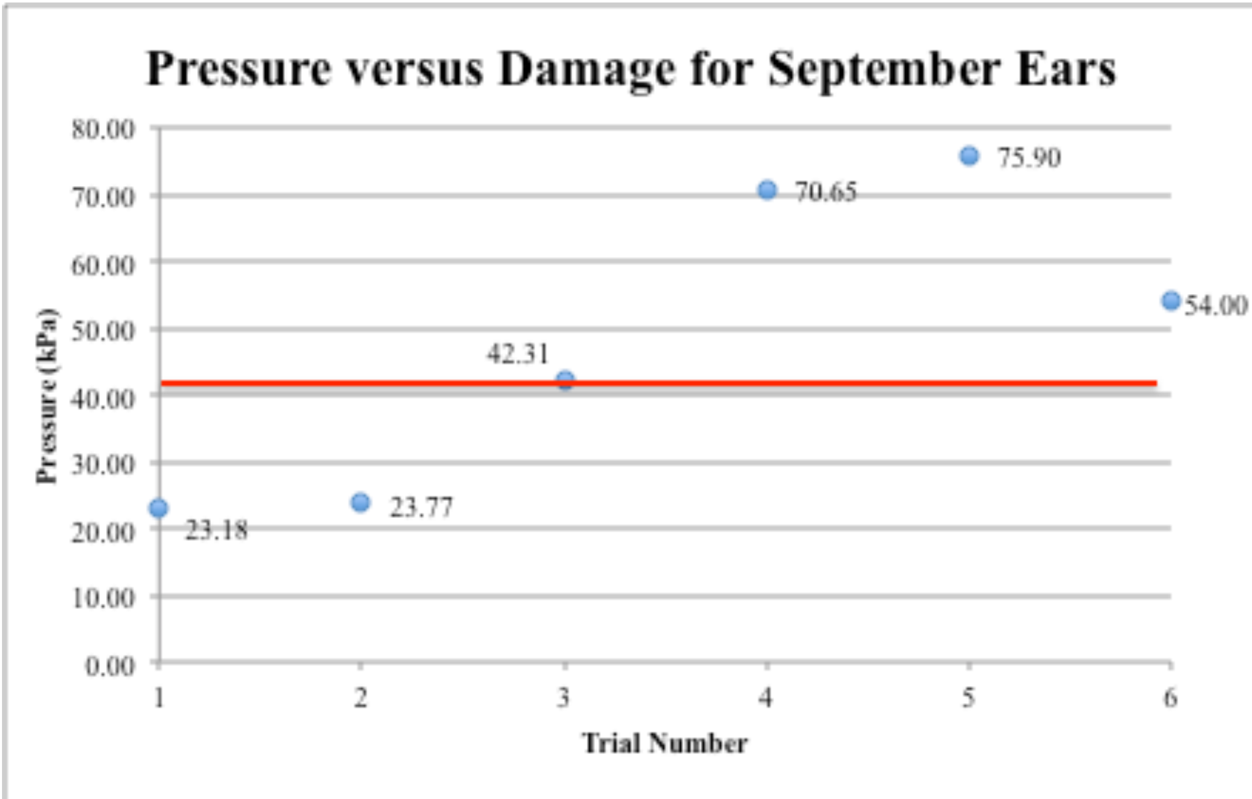

Figure 13: Plot of pressure experienced by the six samples that were directly subjected to blast testing on 26 September 2018. The red line on the plot indicates the threshold pressure value for this test and occurs at a value of 42.31 kPa (6.13 psi).

Table 14: Pressure and damage results for September test ears with theoretical pressures calculated using Kingery-Bulmash equations.

Trial	Ear Sample	Pressure	Theoretical Pressure	Status of Ear
1	4R	23.18 kPa (3.36 psi)	13.3 kPa (1.93 psi)	Intact
2	4L	23.77 kPa (3.44 psi)	18.66 kPa (2.71 psi)	Intact
3	3L	42.31 kPa (6.13 psi)	36.46 kPa (5.29 psi)	Ruptured
4	3R	70.65 kPa (10.24 psi)	127.19 kPa (18.45 psi)	Ruptured
5	2R	75.90 kPa (11.00 psi)	193.19 kPa (28.12 psi)	Ruptured
6	1L	54.00 kPa (7.83 psi)	67.72 kPa (9.82 psi)	Ruptured

4.4 General Points of Discussion

At the beginning of the tests involving sheep ears, there was no set procedure as to how to prepare the ears and no information about how different steps of the preparation process would ultimately affect the end results. In the first test where the entire sheep head was taken out to the firing range, there was no way to know going into the test what the ears looked like or if they had any preexisting damage. Had there been damage to the ear before testing, it could lead to skewed results. The chance for impacting results continued in the post-explosion preparation of the ears as they were cored and then trimmed down to size. The vibrations of the drill or saw may have affected the amount of damage that could be seen on the eardrum, or, as it happened in one case, a misplaced cut with the saw could completely destroy the tympanic membrane and force it to be taken out of the study.

The errors in preparation were noted and the process improved for the September test by using an ear borescope to image the ears before testing and removing the ears from the skull prior to exposing them to blasts. These corrections reduced the chance of causing further damage to the ears and also allowed an opportunity to see the eardrum and ensure there was no existing damage or infection in the ears.

Though these adjustments allowed for better acquisition of results, there are still a variety of factors that can affect how the ears react to blast pressures. All of the samples were frozen at least once during processing, but there is no concrete information about how the tympanic membrane is affected by drastic repeated temperature changes. The sheep themselves and their health when alive could also have an impact on the health of the tissue after death. An older animal will generally have a more brittle tympanic membrane resulting in a lower pressure required to rupture (Gaihede, Liao, Gregersen, 2007). For domesticated animals it can be near impossible to get an accurate medical history; however, any information known about the animal before death is worth noting as it can have an effect on results. A final factor important to the legitimacy of the results is the fact that the tissue was deceased. After death the membrane in the ear was no longer getting lubrication and moisture from the body so there is a possibility that the elasticity of the material was altered due to the substantial reduction in collagen fibers. Future testing should continue to study how these factors affect results until a confirmed procedure for processing and analyzing deceased tissue is developed.

Chapter 5 – Summary and Conclusions

Explosive related testing was completed to provide information supporting two main research goals: 1) determine the pressures an average person can be exposed to in a nonlife-threatening situation and 2) determine at what pressure damage can be observed in sheep ear samples. In a local stadium, explosion testing with C1, detonation cord, and the game cannon revealed the pressure levels that spectators and staff could be exposed to.

- The maximum pressure that people will be exposed to in the stadium from the game cannon is approximately 2kP (0.3 psi).
- Based on limited existing research, 2 kPa is outside of the range of pressures that can cause severe ear damage.
- The associated noise level developed by the cannon is 160 dB which could be a risk to people's hearing if exposed to for a duration longer than 1.75 sec.

Though the pressures experienced in the stadium is not associated with severe ear damage, there is still a potential for minor damage such as tinnitus or temporary hearing loss to occur, so appropriate ear protection should still be worn when in the vicinity of the cannon.

The second focus of testing using sheep eardrums provided a substantial amount of information both related to the pressures that can cause eardrum rupture, but also to the processing procedure for tissue undergoing explosive testing.

- The threshold pressure for ruptured eardrums due to explosive pressures is between 34 kPa (4.9 psi) and 42 kPa (6.1 psi)
- Ears should be visually inspected during all stages of preparation and any changes noted so as not to impact the results.

- The majority of preparation of the ears should be completed prior to explosive testing in order to avoid causing or increasing the level of damage to the ears after the blast tests.

The information and data collected during this experiment provided a more reasonable range of pressures that could serve as the threshold pressure, but there are still many factors that ultimately determine the likelihood of ears being injured. The way a sample is stored prior to blast testing, the age of the tissue, living tissue versus deceased tissue, and the health of the animal are all variables that may affect the value for threshold pressure. Future tests should use the results from this experiment as a baseline and work towards refining the pressure level that initiates severe ear damage.

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APPENDIX A: Relative Effectiveness Values for Explosive Materials

Table A.1: Relative effectiveness for a variety of explosive materials and chemicals. Pertinent equivalencies for this research are highlighted (Maienschein, 2002).

Explosive, Grade	**Density (g/ml)**	**Detonation Vel. (m/s)**	**R.E.**
Ammonium nitrate (AN + <0.5% H2O)	1.72	2550	0.42
Mercury(II) fulminate (AN + <0.5% H2O)	4.42	4200	0.51
Black powder (75% KNO_3 + 19% C + 6% S)	1.65	600	0.55
Tanerit Simply® (93% granulated AN + 6% red P + 1% C)	0.9	2750	0.55
Hexamine dinitrate (HDN)	1.3	5070	0.6
Dinitrobenzene (DNB)	1.5	6025	0.6
HMTD (hexamine peroxide)	0.88	4520	0.74
ANFO (94% AN + 6% fuel oil)	0.92	5270	0.74
TATP (acetone peroxide)	1.18	5300	0.8
Tovex® Extra (AN water gel) commercial product	1.33	5690	0.8
Hydromite® 600 (AN water emulsion) commercial product	1.24	5550	0.8
ANNMAL (66% AN + 25% NM + 5% Al + 3% C + 1% TETA)	1.16	5360	0.87
Amatol (50% TNT + 50% AN)	1.5	6290	0.91
Nitroguanidine	1.32	6750	0.95
Trinitrotoluene (TNT)	1.6	6900	1
Hexanitrostilbene (HNS)	1.7	7080	1.05
Nitrourea	1.45	6860	1.05
Tritonal (80% TNT + 20% aluminium)*	1.7	6650	1.05
Amatol (80% TNT + 20% AN)	1.55	6570	1.1
Nitrocellulose (13.5% N, NC; AKA guncotton)	1.4	6400	1.1
Nitromethane (NM)	1.13	6360	1.1
PBXW-126 (22% NTO, 20% RDX, 20% AP, 26% Al, 12% PU's system)*	1.8	6450	1.1
Diethylene glycol dinitrate (DEGDN)	1.38	6610	1.17
PBXIH-135 EB (42% HMX, 33% Al, 25% PCP-TMETN's system)*	1.81	7060	1.17
PBXN-109 (64% RDX, 20% Al, 16% HTPB's system)*	1.68	7450	1.17
Triaminotrinitrobenzene (TATB)	1.8	7550	1.17
Picric acid (TNP)	1.71	7350	1.2
Trinitrobenzene (TNB)	1.6	7300	1.2
Tetrytol (70% tetryl + 30% TNT)	1.6	7370	1.2
Nobel's Dynamite (75% NG + 23% diatomite)	1.48	7200	1.25
Tetryl	1.71	7770	1.25

Torpex (aka HBX, 41% RDX + 40% TNT + 18% Al + 1% wax)*	1.8	7440	1.3
Composition B (63% RDX + 36% TNT + 1% wax)	1.72	7840	1.33
Composition C-3 (78% RDX)	1.6	7630	1.33
Composition C-4 (91% RDX)	1.59	8040	1.34
Pentolite (56% PETN + 44% TNT)	1.66	7520	1.33
Semtex 1A (76% PETN + 6% RDX)	1.55	7670	1.35
RISAL P (50% IPN + 28% RDX + 15% Al + 4% Mg + 1% Zr + 2% NC)*	1.39	5980	1.4
Hydrazine mononitrate	1.59	8500	1.42
Mixture: 24% nitrobenzene + 76% TNM	1.48	8060	1.5
Mixture: 30% nitrobenzene + 70% nitrogen tetroxide	1.39	8290	1.5
Nitroglycerin (NG)	1.59	8100	1.54
Octol (80% HMX + 19% TNT + 1% DNT)	1.83	8690	1.54
Nitrotriazolon (NTO)	1.87	8120	1.6
DADNE (1,1-diamino-2,2-dinitroethene, FOX-7)	1.77	8330	1.6
Ballistite (92% NG + 7% nitrocellulose)	1.6	7970	1.6
Plastics Gel® (in toothpaste tube: 45% PETN + 45% NG + 5% DEGDN + 4% NC)	1.51	7940	1.6
Composition A-5 (98% RDX + 2% stearic acid)	1.65	8470	1.6
Erythritol tetranitrate (ETN)	1.6	8100	1.6
Hexogen (RDX)	1.78	8700	1.6
PBXW-11 (96% HMX, 1% HyTemp, 3% DOA)	1.81	8720	1.6
Penthrite (PETN)	1.71	8400	1.66
Ethylene glycol dinitrate (EGDN)	1.49	8300	1.66
TNAZ (trinitroazetidine)	1.85	8640	1.7
Octogen (HMX grade B)	1.86	9100	1.7
HNIW (CL-20)	1.97	9380	1.8
Hexanitrobenzene (HNB)	1.97	9400	1.85
— (AFX-757)	N/A	N/A	1.85
MEDINA (Methylene dinitroamine)	1.65	8700	1.93
DDF (4,4’-Dinitro-3,3’-diazenofuroxan)	1.98	10000	1.95
Heptanitrocubane (HNC)	1.92	9200	N/A
— (AFX-777)	N/A	N/A	1.97
— (PAX-28)	N/A	N/A	2.16
Octanitrocubane (ONC)	1.95	10600	2.38

APPENDIX B: Blast Equivalency Table

Table B.1: Blast equivalency table used to determine the peak pressure of an explosion based on the equivalent weight of TNT and the scaled distance (Caggiano, 1973).

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
2.0	320.71	2211.22
2.2	262.98	1813.18
2.4	218.47	1506.3
2.6	183.61	1265.95
2.8	155.95	1075.24
3.0	135.71	935.688
3.2	115.64	797.31
3.4	100.81	695.061
3.6	88.51	610.255
3.8	78.24	539.446
4.0	69.58	479.737
4.2	62.24	429.13
4.4	55.96	385.831
4.6	50.57	348.668
4.8	45.90	316.469
5.0	41.84	288.477
5.2	38.29	264
5.4	35.17	242.489
5.6	32.42	223.528
5.8	29.98	206.705
6.0	27.82	191.812
6.2	25.88	178.436
6.4	24.14	166.44
6.6	22.58	155.684
6.8	21.16	145.893
7.0	19.89	137.137
7.2	18.73	129.139
7.4	17.67	121.83
7.6	16.71	115.211
7.8	15.82	109.075
8.0	15.01	103.49
8.2	14.27	98.3882
8.4	13.58	93.6308
8.6	12.95	89.2871
8.8	12.36	85.2192
9.0	11.82	81.4961
9.2	11.31	77.9797
9.4	10.84	74.7392
9.6	10.41	71.7745
9.8	10.00	68.9476
10.0	9.61	66.2586

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
10.2	9.26	63.8455
10.4	8.92	61.5013
10.6	8.60	59.2949
10.8	8.31	57.2955
11.0	8.03	55.3649
11.2	7.77	53.5723
11.4	7.52	51.8486
11.6	7.28	50.1939
11.8	7.06	48.677
12	6.85	47.2291
12.2	6.65	45.8502
12.4	6.46	44.5401
12.6	6.28	43.2991
12.8	6.11	42.127
13	5.94	40.9549
13.2	5.79	39.9207
13.4	5.64	38.8864
13.6	5.5	37.9212
13.8	5.36	36.9559
14	5.23	36.0596
14.2	5.11	35.2322
14.4	4.99	34.4049
14.6	4.88	33.6464
14.8	4.77	32.888
15	4.67	32.1985
15.2	4.57	31.5091
15.4	4.47	30.8196
15.6	4.38	30.199
15.8	4.29	29.5785
16	4.2	28.958
16.2	4.12	28.4064
16.4	4.04	27.8548
16.6	3.96	27.3032
16.8	3.89	26.8206
17	3.82	26.338
17.2	3.75	25.8554
17.4	3.68	25.3727
17.6	3.62	24.959
17.8	3.55	24.4764
18.0	3.49	24.0627
18.2	3.44	23.718

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
18.4	3.38	23.3043
18.6	3.32	22.8906
18.8	3.27	22.5459
19.0	3.22	22.2011
19.2	3.17	21.8564
19.4	3.12	21.5117
19.6	3.07	21.1669
19.8	3.03	20.8911
20.0	2.98	20.5464
20.2	2.94	20.2706
20.4	2.90	19.9948
20.6	2.86	19.719
20.8	2.82	19.4432
21.0	2.78	19.1674
21.2	2.74	18.8916
21.4	2.71	18.6848
21.6	2.67	18.409
21.8	2.63	18.1332
22	2.6	17.9264
22.2	2.57	17.7195
22.4	2.53	17.4437
22.6	2.5	17.2369
22.8	2.47	17.0301
23	2.44	16.8232
23.2	2.41	16.6164
23.4	2.38	16.4095
23.6	2.36	16.2716
23.8	2.33	16.0648
24	2.3	15.8579
24.2	2.28	15.7201
24.4	2.25	15.5132
24.6	2.22	15.3064
24.8	2.2	15.1685
25	2.18	15.0306
25.2	2.15	14.8237
25.4	2.13	14.6858
25.6	2.11	14.5479
25.8	2.08	14.3411
26	2.06	14.2032
26.2	2.04	14.0653
26.4	2.02	13.9274

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
26.6	2.00	13.7895
26.8	1.98	13.6516
27.0	1.96	13.5137
27.2	1.94	13.3758
27.4	1.92	13.2379
27.6	1.90	13.1
27.8	1.89	13.0311
28.0	1.87	12.8932
28.2	1.85	12.7553
28.4	1.83	12.6174
28.6	1.82	12.5485
28.8	1.80	12.4106
29.0	1.78	12.2727
29.2	1.77	12.2037
29.4	1.75	12.0658
29.6	1.74	11.9969
29.8	1.72	11.859
30.0	1.71	11.79
30.2	1.69	11.6521
30.4	1.68	11.5832
30.6	1.66	11.4453
30.8	1.65	11.3764
31.0	1.63	11.2385
31.2	1.62	11.1695
31.4	1.61	11.1006
31.6	1.59	10.9627
31.8	1.58	10.8937
32	1.57	10.8248
32.2	1.56	10.7558
32.4	1.54	10.6179
32.6	1.53	10.549
32.8	1.52	10.48
33	1.51	10.4111
33.2	1.5	10.3421
33.4	1.48	10.2042
33.6	1.47	10.1353
33.8	1.46	10.0663
34	1.45	9.9974
34.2	1.44	9.92845
34.4	1.43	9.85951
34.6	1.42	9.79056

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
34.8	1.41	9.72161
35	1.4	9.65266
35.2	1.39	9.58372
35.4	1.38	9.51477
35.6	1.37	9.44582
35.8	1.36	9.37687
36	1.35	9.30793
36.2	1.34	9.23898
36.4	1.33	9.17003
36.6	1.32	9.10108
36.8	1.31	9.03214
37	1.3	8.96319
37.2	1.29	8.89424
37.4	1.28	8.82529
37.6	1.27	8.75635
37.8	1.27	8.75635
38	1.26	8.6874
38.2	1.25	8.61845
38.4	1.24	8.5495
38.6	1.23	8.48055
38.8	1.22	8.41161
39	1.22	8.41161
39.2	1.21	8.34266
39.4	1.2	8.27371
39.6	1.19	8.20476
39.8	1.19	8.20476
40	1.18	8.13582
40.2	1.17	8.06687
40.4	1.16	7.99792
40.6	1.16	7.99792
40.8	1.15	7.92897
41	1.14	7.86003
41.2	1.14	7.86003
41.4	1.13	7.79108
41.6	1.12	7.72213
41.8	1.11	7.65318
42	1.11	7.65318
42.2	1.1	7.58424
42.4	1.09	7.51529
42.6	1.09	7.51529
42.8	1.08	7.44634

Scaled Distance (ft/lb)	Pressure (psi)	Pressure (kPa)
43	1.08	7.44634
43.2	1.07	7.37739
43.4	1.06	7.30845
43.6	1.06	7.30845
43.8	1.05	7.2395
44	1.04	7.17055
44.2	1.04	7.17055
44.4	1.03	7.1016
44.6	1.03	7.1016
44.8	1.02	7.03266
45	1.01	6.96371
45.2	1.01	6.96371
45.4	1	6.89476
45.6	1	6.89476
45.8	0.99	6.82581
46	0.99	6.82581
46.2	0.98	6.75686
46.4	0.98	6.75686
46.6	0.97	6.68792
46.8	0.97	6.68792
47	0.96	6.61897
47.2	0.96	6.61897
47.4	0.95	6.55002
47.6	0.94	6.48107
47.8	0.94	6.48107
48	0.93	6.41213
48.2	0.93	6.41213
48.4	0.93	6.41213
48.6	0.92	6.34318
48.8	0.92	6.34318
49	0.91	6.27423
49.2	0.91	6.27423
49.4	0.9	6.20528
49.6	0.9	6.20528
49.8	0.89	6.13634
50	0.89	6.13634

APPENDIX C: Anatomical Dimensions of Four Species of Mice Ears

Table C.1: Anatomical dimensions of four species of mice (Keiler and Richter, 2001).

	CBA/CaJ	C57BL/6J	129/CD1	129/SvEv	*F*-statistic
Width					
Basilar membrane (arcuate zone)	40.6 ± 1.9	40.6 ± 0.4	38.7 ± 1.3	35.8 ± 1.2	n.s.
Basilar membrane (pectinate zone)	95.7 ± 3.3	88.0 ± 1.3	94.9 ± 1.7	93.2 ± 3.5	n.s.
Tectorial membrane	117.7 ± 5.5	131.8 ± 1.5	144.0 ± 10.3	130.6 ± 7.0	n.s.
Height					
Inner pillar cell	46.3 ± 2.5	45.1 ± 0.4	40.8 ± 2.0	42.5 ± 1.8	n.s.
Outer pillar cell	45.6 ± 1.7	50.7 ± 1.3	45.4 ± 2.8	50.0 ± 1.3	n.s.
Outer hair cell 1	14.7 ± 0.5	15.0 ± 0.4	12.5 ± 0.7	14.8 ± 1.1	n.s.
Outer hair cell 2	13.9 ± 0.6	15.8 ± 0.5	15.2 ± 1.4	16.3 ± 0.9	n.s.
Outer hair cell 3	13.8 ± 0.8	14.5 ± 0.8	15.5 ± 0.9	14.1 ± 0.9	n.s.
Deiters' cell 1	22.4 ± 1.6	24.7 ± 2.1	29.5 ± 1.7	31.5 ± 1.8	$F(3,18) = 6.099$; $P < 0.05$
Deiters' cell 2	21.9 ± 0.6	28.1 ± 2.3	30.5 ± 2.3	29.6 ± 2.1	$F(3,19) = 5.966$; $P < 0.05$
Deiters' cell 3	25.1 ± 1.2	29.5 ± 1.7	32.7 ± 1.4	33.7 ± 1.4	$F(3,18) = 9.108$; $P < 0.05$
Thickness					
Tympanic cover layer cells	6.5 ± 0.4	7.6 ± 0.5	7.0 ± 0.4	6.7 ± 0.4	n.s.
Boettcher cells	18.3 ± 1.5	14.5 ± 1.2	15.2 ± 0.6	16.5 ± 1.1	n.s.
Claudius cells	42.4 ± 5.3	46.9 ± 2.0	38.5 ± 7.5	43.5 ± 5.4	n.s.
Hyaline matrix	13.3 ± 0.5	11.0 ± 0.4	14.1 ± 0.5	12.1 ± 0.4	$F(3,29) = 6.187$; $P < 0.05$
Tectorial membrane	30.3 ± 1.3	27.5 ± 1.1	30.6 ± 2.8	29.7 ± 2.1	n.s.
Area					
Basilar membrane	1266 ± 51.2	1082 ± 89.6	1388 ± 87.3	1217 ± 58.5	n.s.
Hyaline matrix	878 ± 42.9	670 ± 58.2	876 ± 50.1	655 ± 66.7	$F(3,25) = 5.141$; $P < 0.05$
Tectorial membrane	2507 ± 340.2	2034 ± 118.4	2405 ± 496.8	2163 ± 263.8	n.s.
Organ of Corti	2832 ± 349.9	2612 ± 166.4	2487 ± 253.4	2662 ± 138.2	n.s.
Tunnel of Corti	467 ± 34.7	471 ± 91.5	461 ± 33.3	464 ± 70.7	n.s.
Angle					
RL/OP	63.8 ± 1.6	67.7 ± 1.3	61.6 ± 2.7	69.3 ± 1.9	n.s.
OP/BM (arc)	65.5 ± 2.1	54.7 ± 4.7	62.6 ± 4.2	62.5 ± 3.4	n.s.
IP/BM (arc)	56.5 ± 2.6	72.0 ± 6.0	67.2 ± 8.2	68.3 ± 2.0	$F(3,15) = 5.875$; $P < 0.05$

Linear measures are provided in µm, area measurements in μm^2.

APPENDIX D: Pre Explosion Images of Ears for September Test

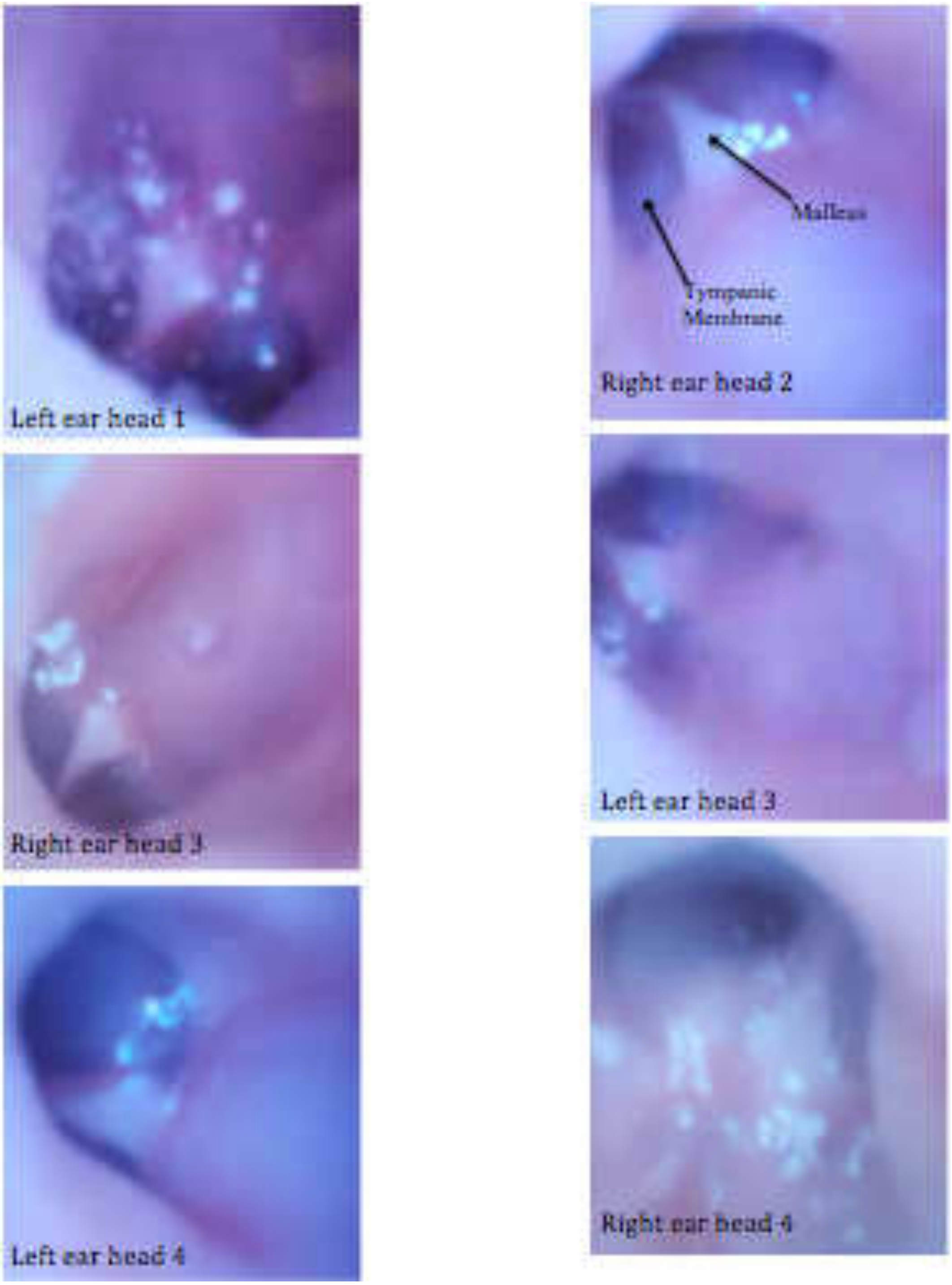
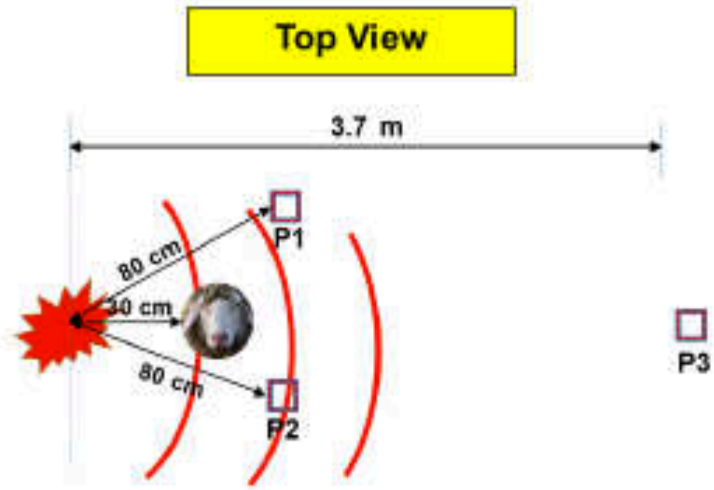


Figure D.1: Pre-explosion images of the tympanic membranes for the six ears tested in the September blast test. Part of the tympanic membrane of each ear is shown as well as the malleus bone of the inner ear as labeled in one image above. The entire tympanic membrane could not be viewed with the borescope due to the camera geometry and the physiology of the ear.

APPENDIX E: Preliminary Sheep Explosive Test Configuration and Results

These plots were created and collected by Mr. Assal Hussein of the CIVE Department.



Probe #	Distance from the charge -m(in.)	Peak pressure (kPa)
P1	0.8(32)	75.9
P2	0.8 (32)	53.67
P3	3.7(12 ft.)	6.42

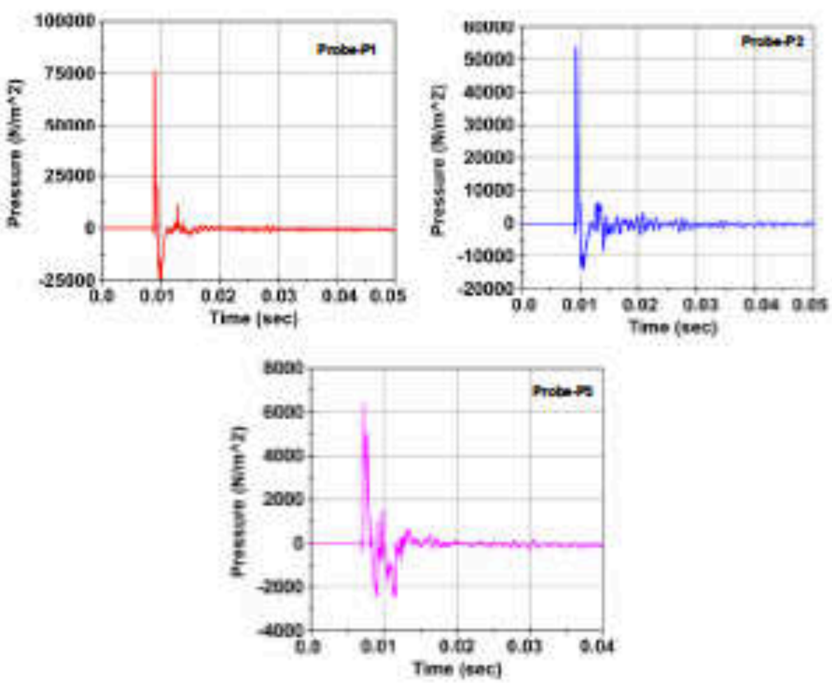
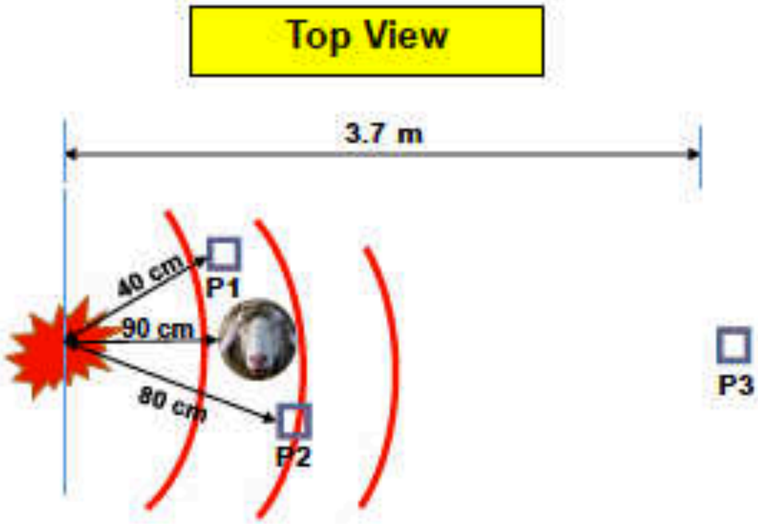


Figure E.1: Depiction of trial 1 layout and resulting pressures measured by three probes shown in tabular and graphic form.



Probe #	Distance from the charge -m(in.)	Peak pressure (kPa)
P1	0.4(32)	75.9
P2	0.8 (32)	40.4
P3	3.7(12 ft.)	6.24

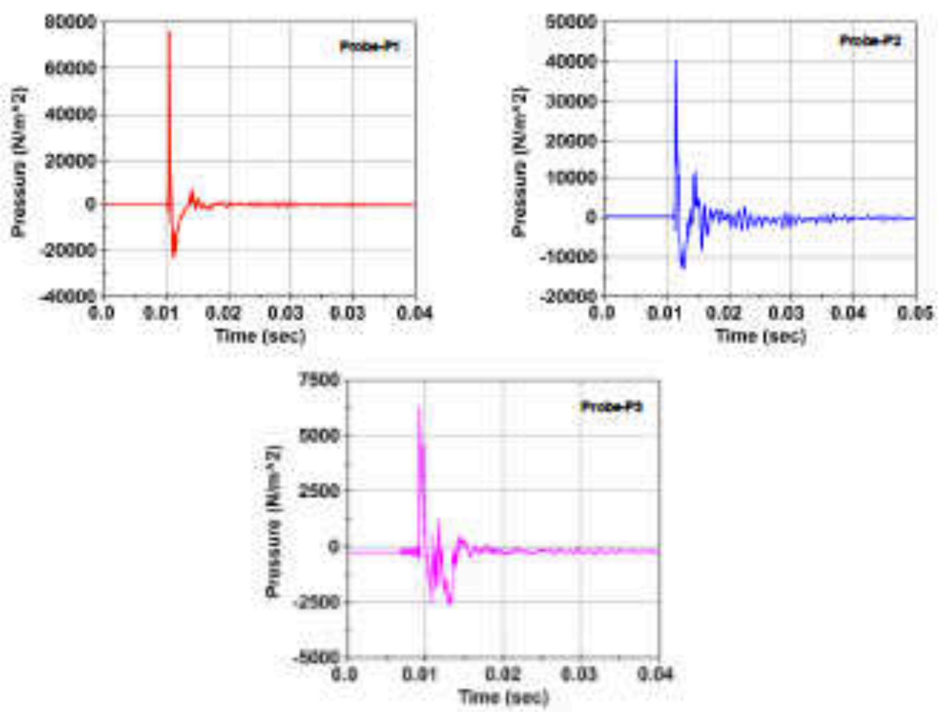
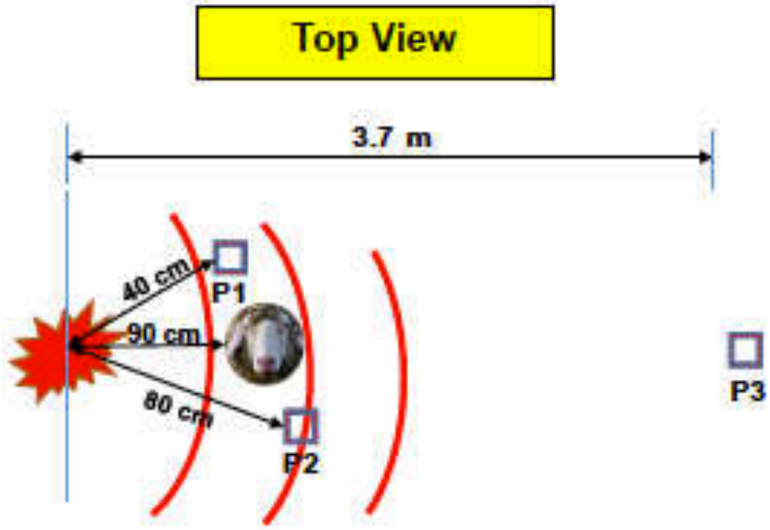


Figure E.2: Depiction of trial 2 layout and resulting pressures measured by three probes shown in tabular and graphic form.



Probe #	Distance from the charge -m(in.)	Peak pressure (kPa)
P1	0.4(32)	65.72
P2	0.8 (32)	21.9
P3	3.7(12 ft.)	5.16

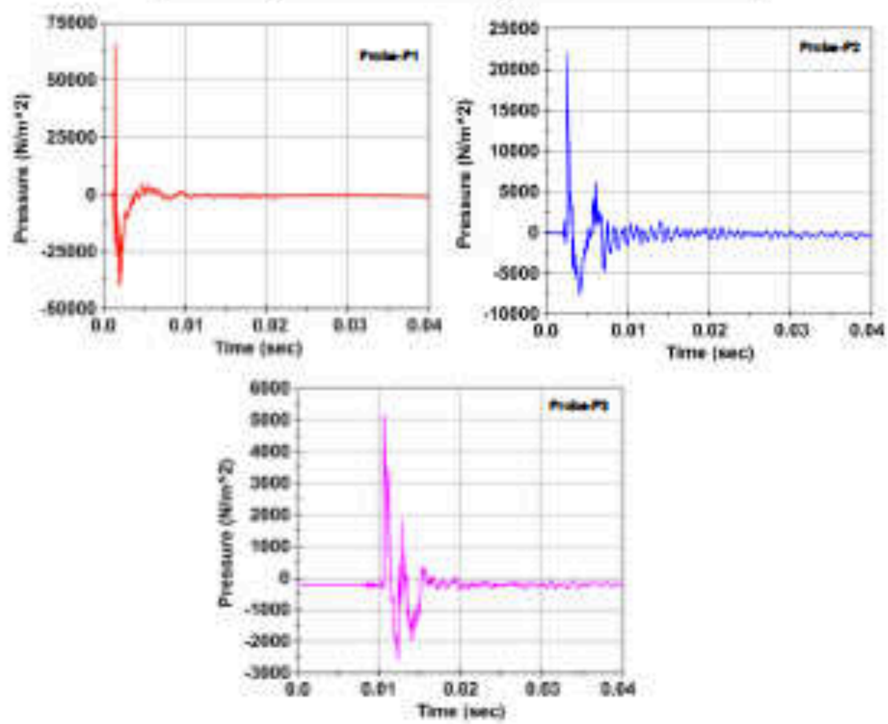
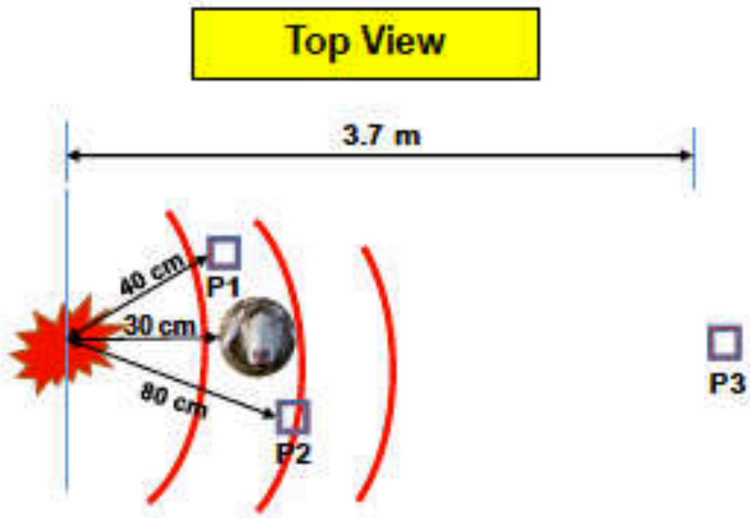


Figure E.3: Depiction of trial 3 layout and resulting pressures measured by three probes shown in tabular and graphic form.



Probe #	Distance from the charge -m(in.)	Peak pressure (kPa)
P1	0.4(32)	75.9
P2	0.8 (32)	37.94
P3	3.7(12 ft.)	5.75

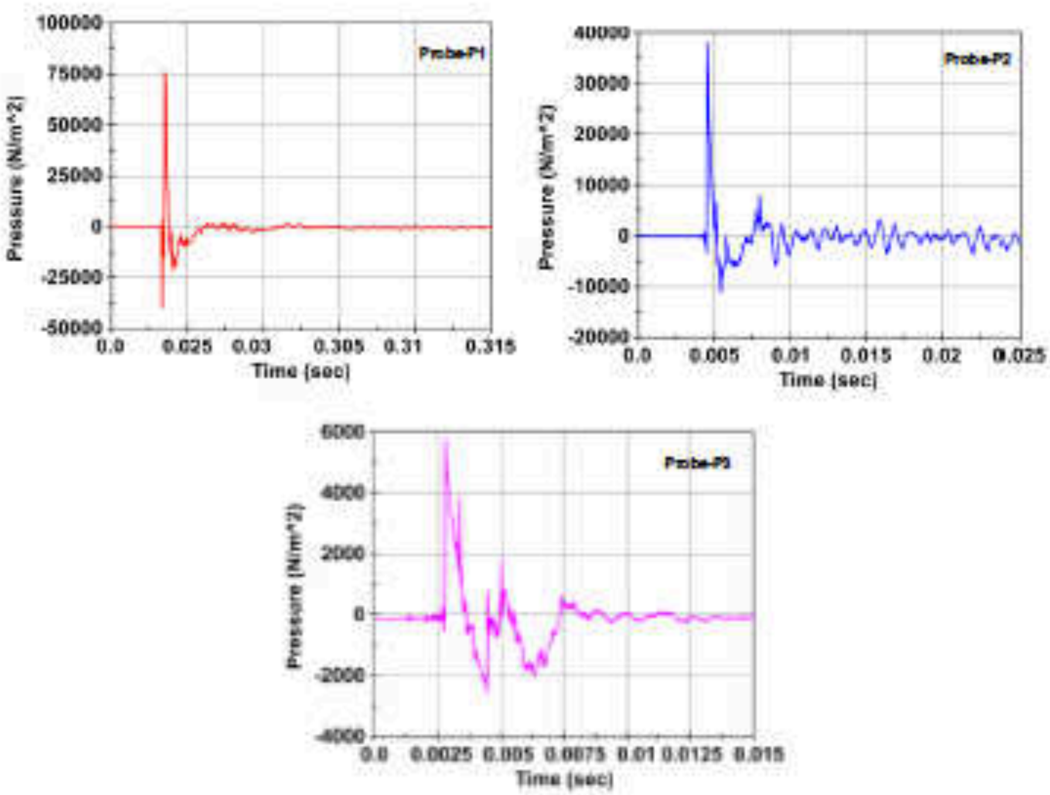
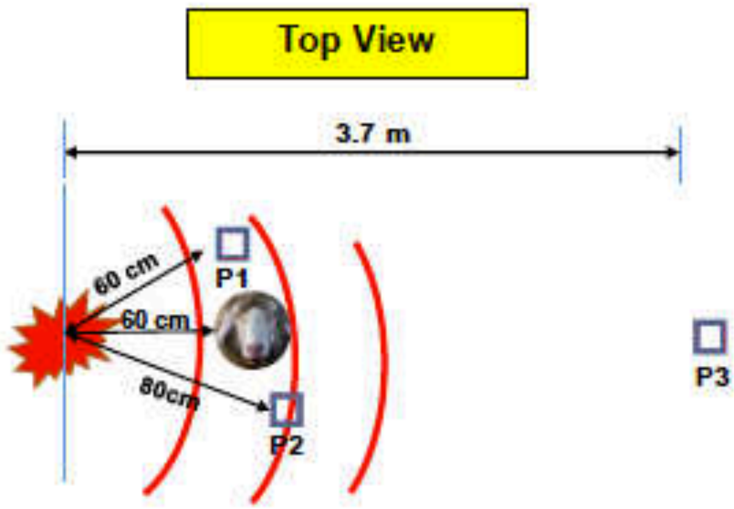


Figure E.4: Depiction of trial 4 layout and resulting pressures measured by three probes shown in tabular and graphic form.



Probe #	Distance from the charge -m(in.)	Peak pressure (kPa)
P1	0.6(32)	51.27
P2	0.8 (32)	53.17
P3	3.7(12 ft.)	6.94

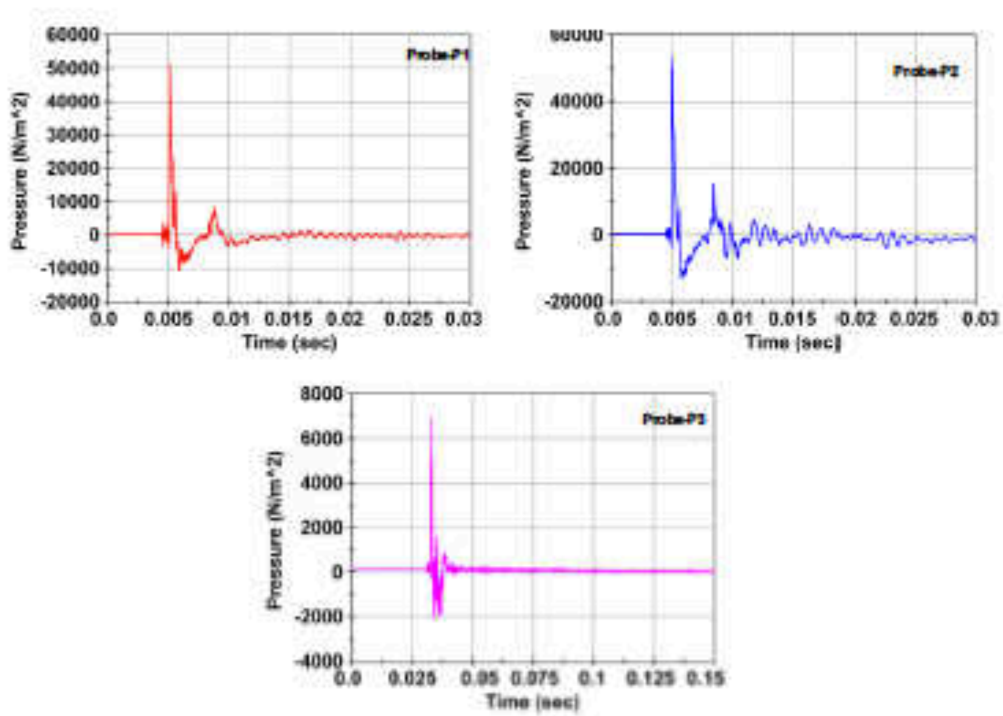
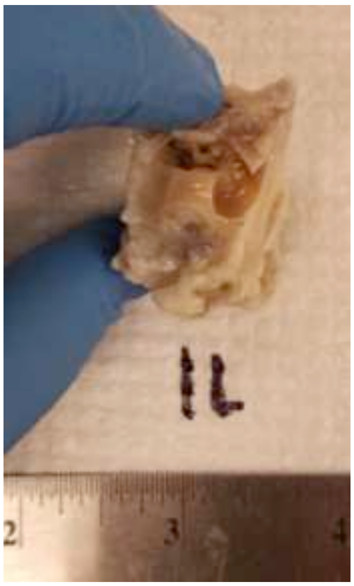
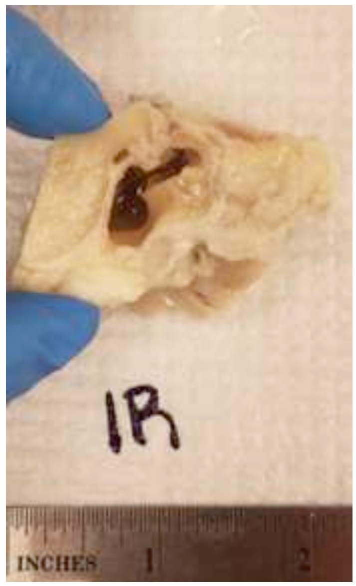


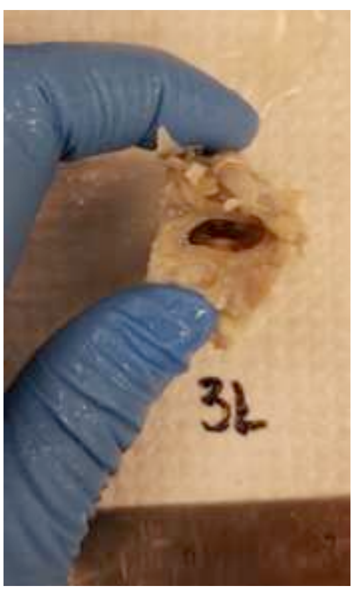
Figure E.5: Depiction of trial 5 layout and resulting pressures measured by three probes shown in tabular and graphic form.

APPENDIX F: Post Explosive Imaging for February Test

February Blast Test Ears:
Due to the fact that the ear borescope was not available to use during the February test or analysis, the only images available are regular camera pictures taken after the ears had been fully processed. The left ear from head two was damaged during the post explosion analysis and could no longer be considered in the results.







Continued on next page

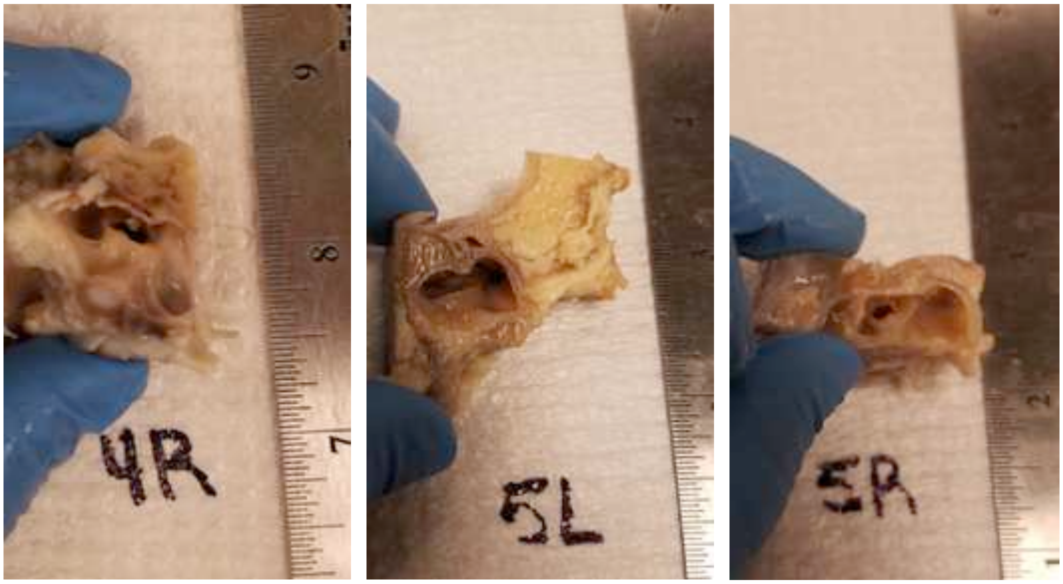


Figure F.1: Post explosive pictures of six ears from the February 14th blast test. The number in the label corresponds to the head the ear was taken from and the letter denotes the left or right ear. The bones supporting the tympanic membrane are shown in each image. The membranes of ears 1L, 3L, 4R and 5R have been ruptured.

APPENDIX G: Post Explosive Imaging for September Test

Ear 1R was not used in the testing because it was infected prior to the sheep's death. Ear 2L served as the control ear for histology analysis and is not shown here.

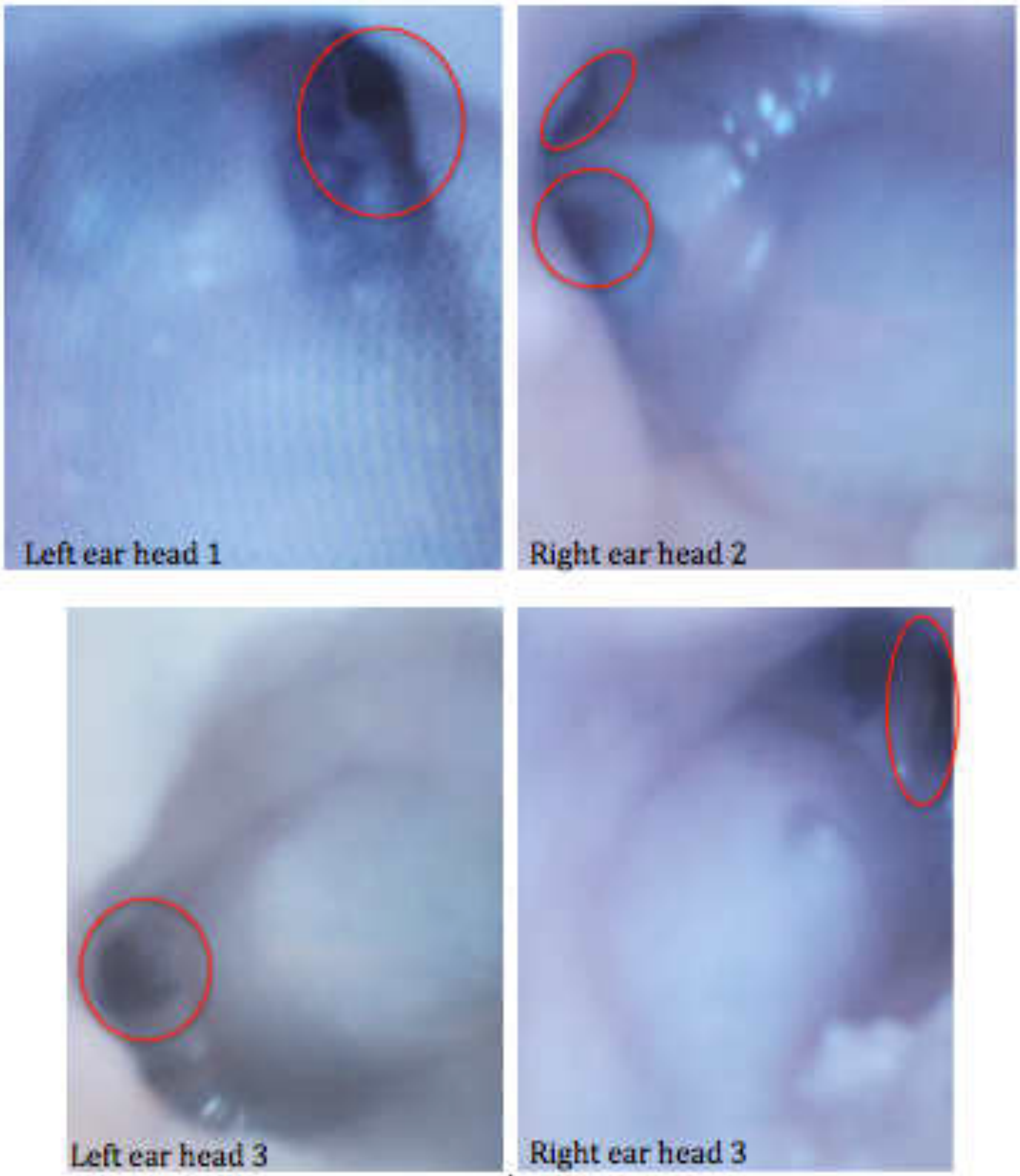


Figure G.1: Ear borescope pictures of the September 26th blast test. The tympanic membrane and malleus of the ear are shown in each image; however, due to the geometry of the camera and the physiology of the ear canal the full membrane could not be photographed. The red circles on the pictures show regions of ruptured membrane due to the explosions.

Figure G.2: Remaining two ears from September blast test. Based on visual analysis of the eardrum with the borescope, there were no signs of rupture or other damage.

September Blast Test Ears Standard Photography:

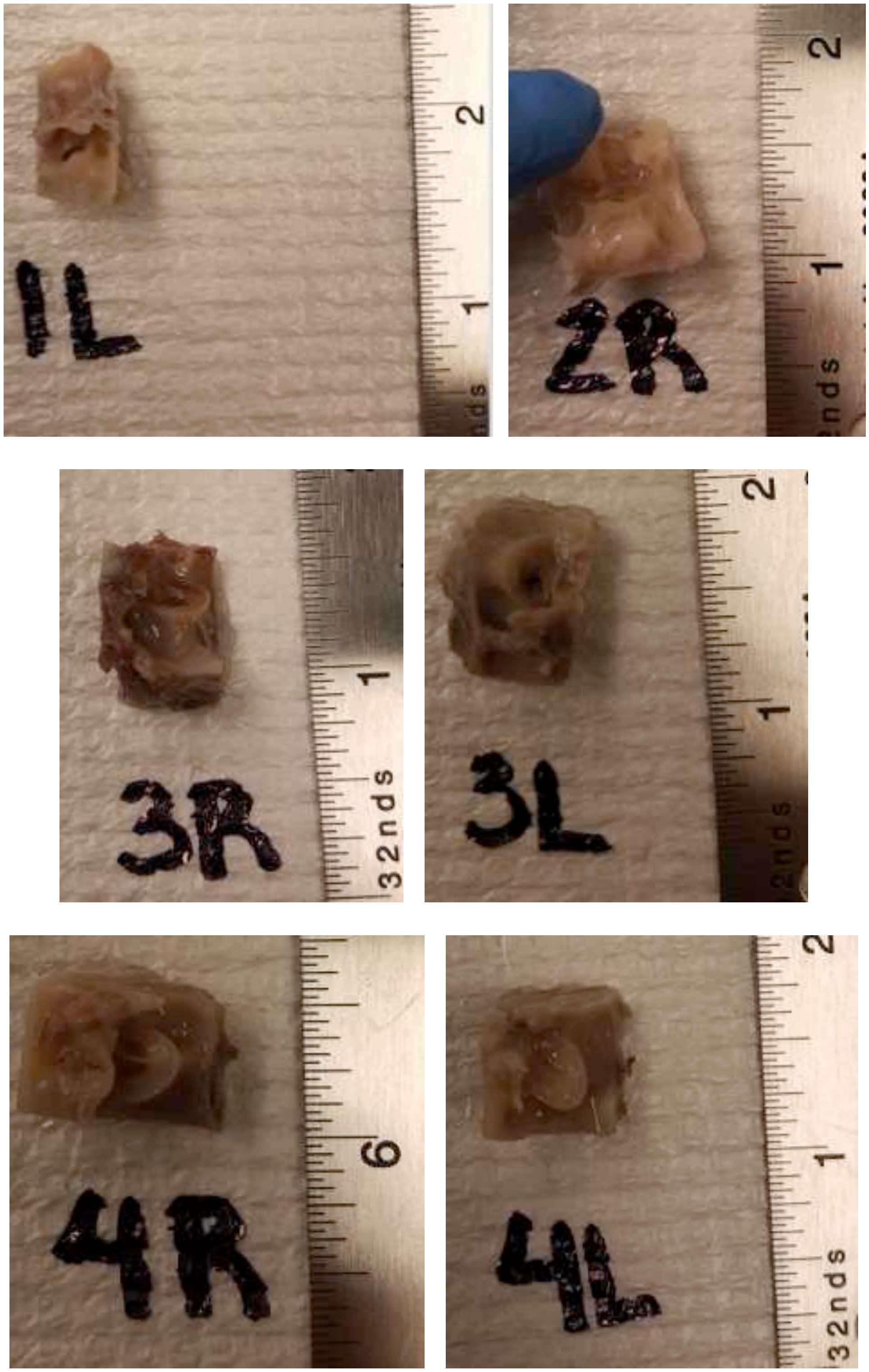


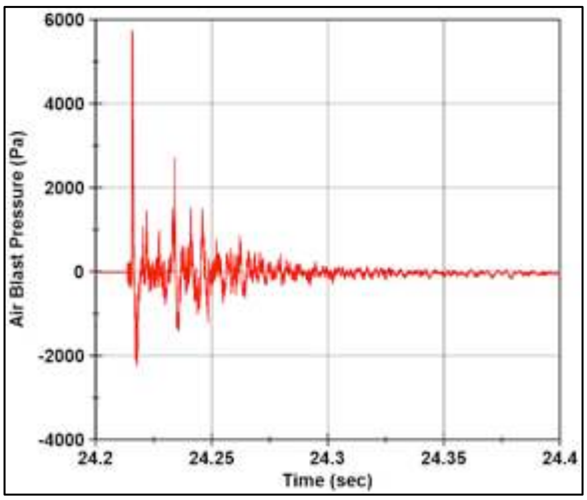
Figure G.3: Standard photography of September 26th eardrums after processing. Of the six samples tested, 1L, 2R, 3L and 3R showed clear signs of rupture thus confirming the images collected with the borescope.

APPENDIX H: Pressure time plots for stadium tests

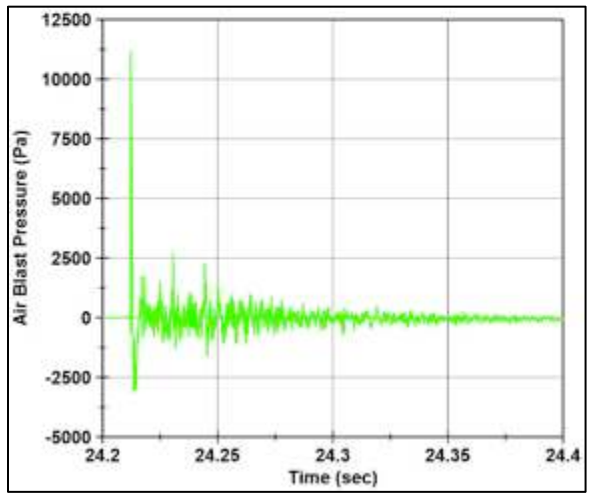
These plots were provided by Mr. Assal Hussein, who was responsible for pressure probe data collection during these tests.

H.1: C1 Pressure-time plots

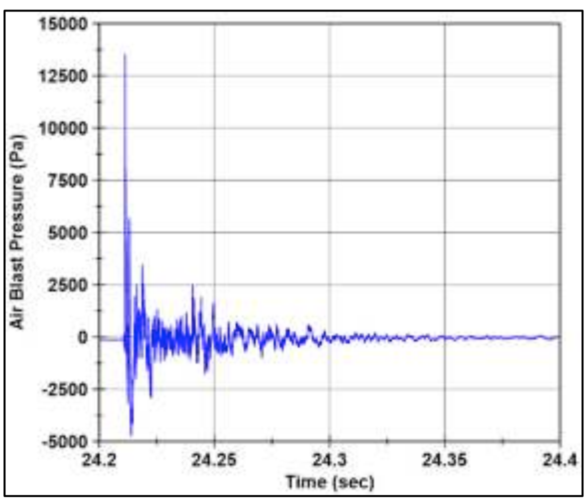
RE = 1.66, W_{TNT} = .022 lb (6g)



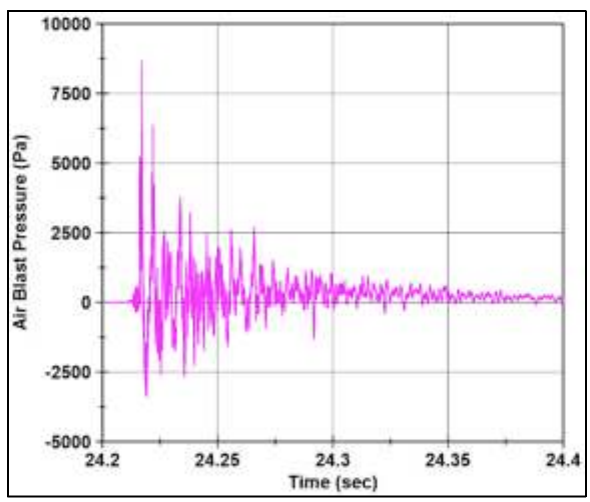
A Distance from charge: 9.64ft (2.94m)



B Distance from charge: 5.1ft (1.55m)



C Distance from charge: 4.12ft (1.26m)

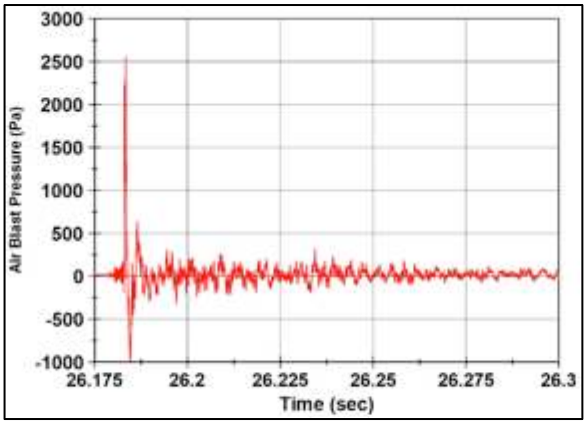


D Distance from charge: 9.07ft (2.77m)

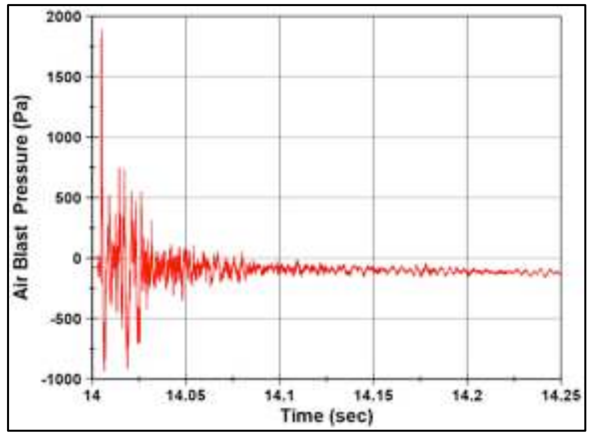
Figure H.1: Pressure time plots for C1 test displaying results for probes 1 through 4 in frames A through D respectively.

H.2: Detonation cord pressure time plots

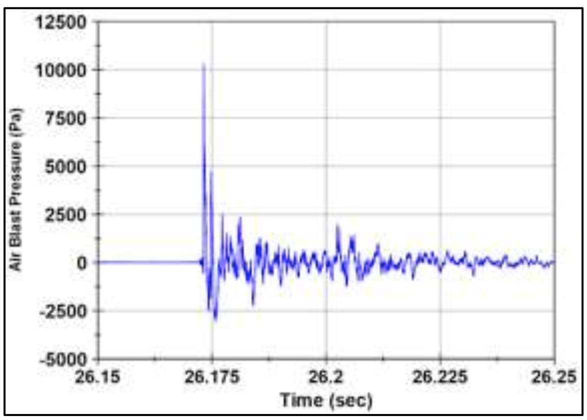
RE = 1.66, W_{TNT} = .0118lb (3.23g)



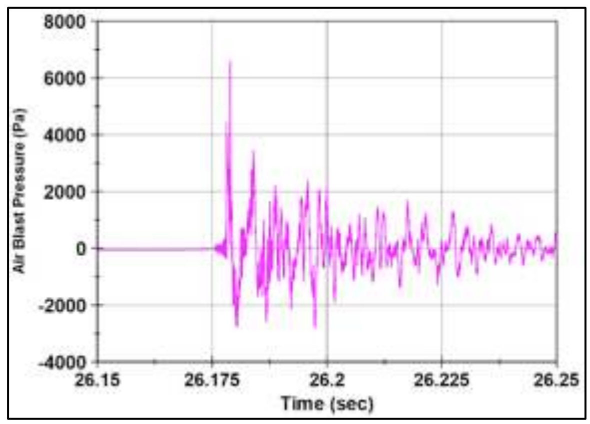
A Distance from charge: 12.14ft (3.70m)



B Distance from charge: 27.84ft (8.49m)



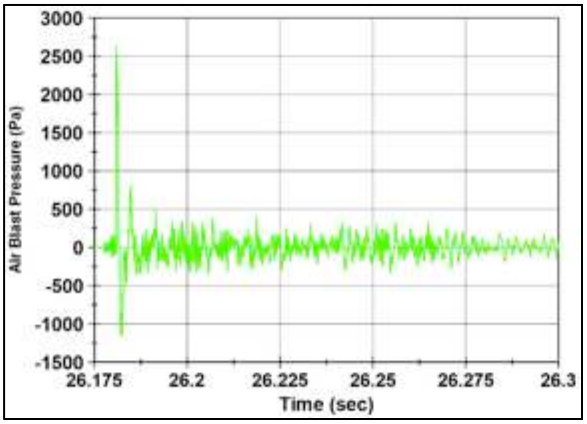
C Distance from charge: 4.12ft (1.26m)



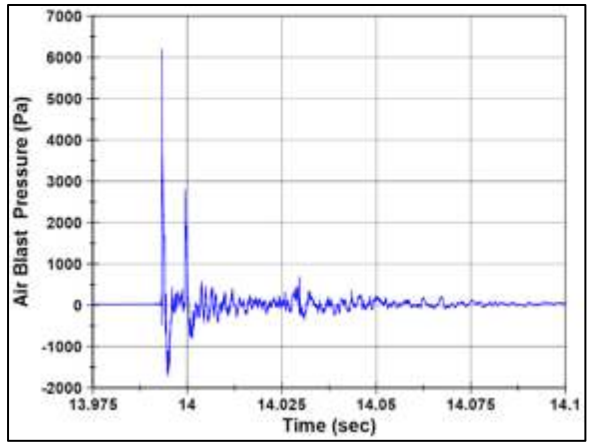
D Distance from charge: 9.07ft (2.77m)

Figure H.2: Pressure time plots for the first detonation cord explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

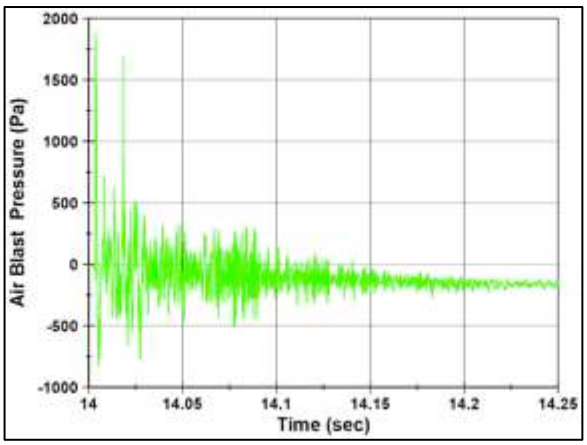
RE = 1.66, W_{TNT} = .0118 (3.23g)



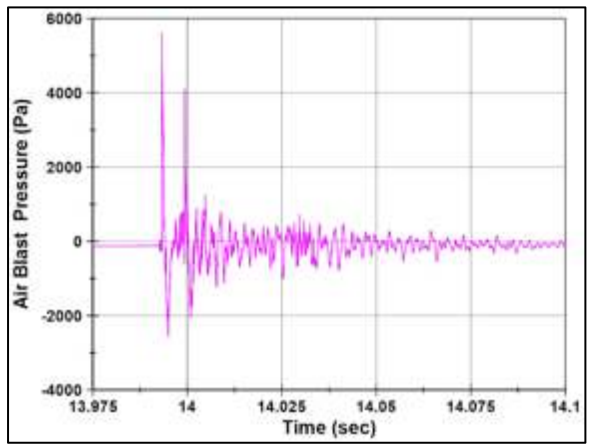
A Distance from charge: 18.63ft (5.68m)



B Distance from charge: 27.00ft (8.49m)



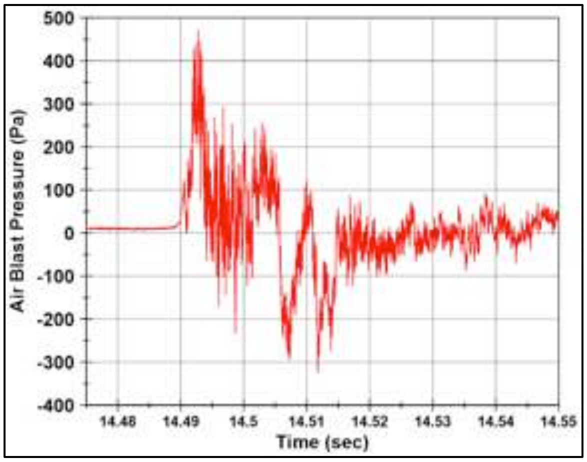
C Distance from charge: 5.66ft (1.72m)



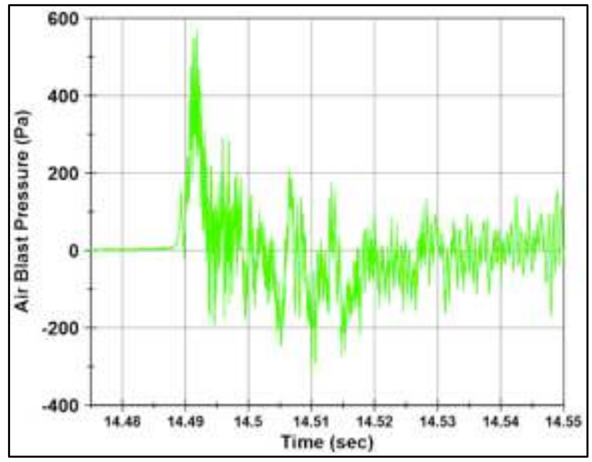
D Distance from charge: 7.50ft (2.29m)

Figure H.3: Pressure time plots for the second det cord explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

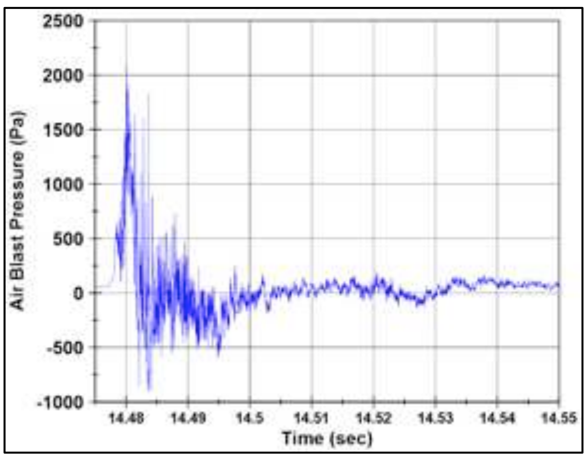
RE = 1.66, W_{TNT} = .0118lb (3.23g)



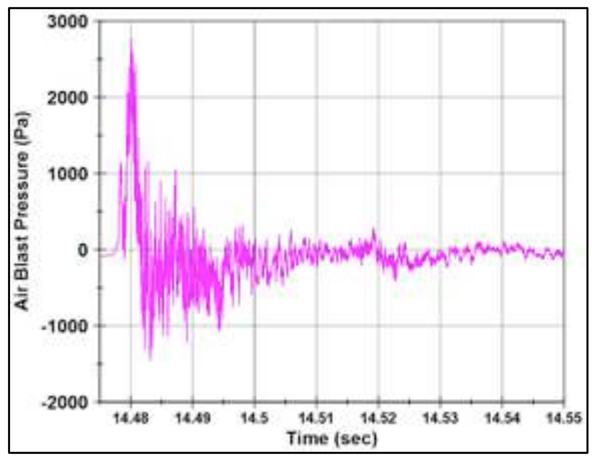
A Distance from charge: 5.10ft (1.55ft)



B Distance from charge: 9.64ft (2.94m)



C Distance from charge: 14.94ft (4.55m)

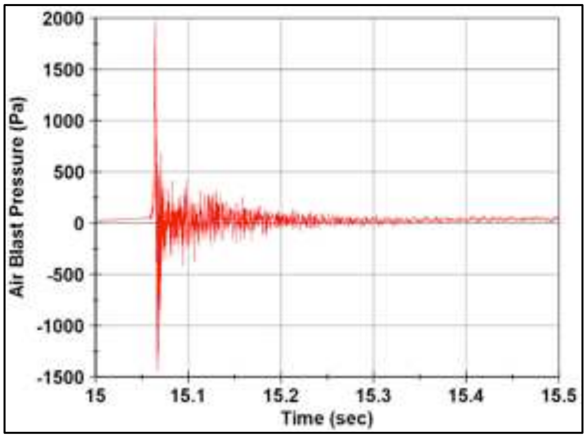


D Distance from charge: 20.00ft (6.10m)

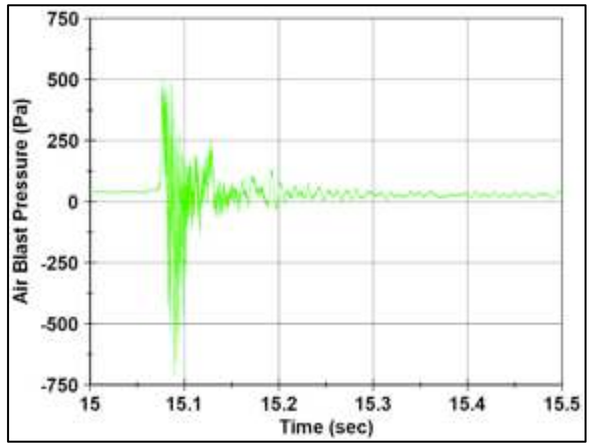
Figure H.4: Pressure time plots for the third detonation cord explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

H.3: 75% cannon pressure time plots

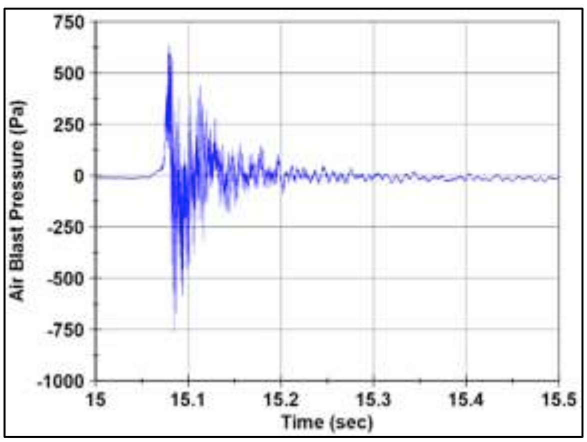
RE = 0.55



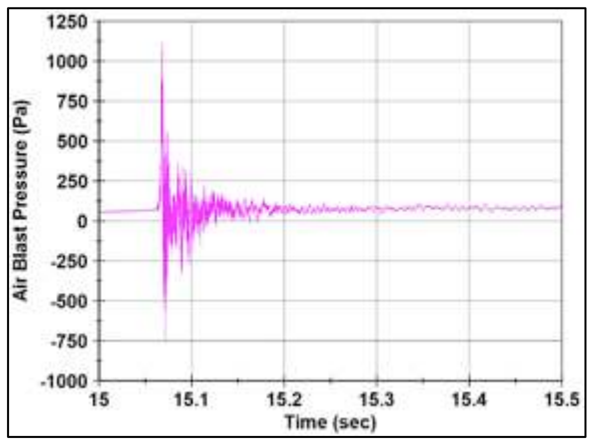
A **Distance from charge: 5.10ft (1.55m)**



B **Distance from charge: 18.63ft (5.68m)**



C **Distance from charge: 20.00ft (6.10m)**



D **Distance from charge: 9.64ft (2.94m)**

Figure H.5: Pressure time plots for the first 75% capacity cannon explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

RE = 0.55

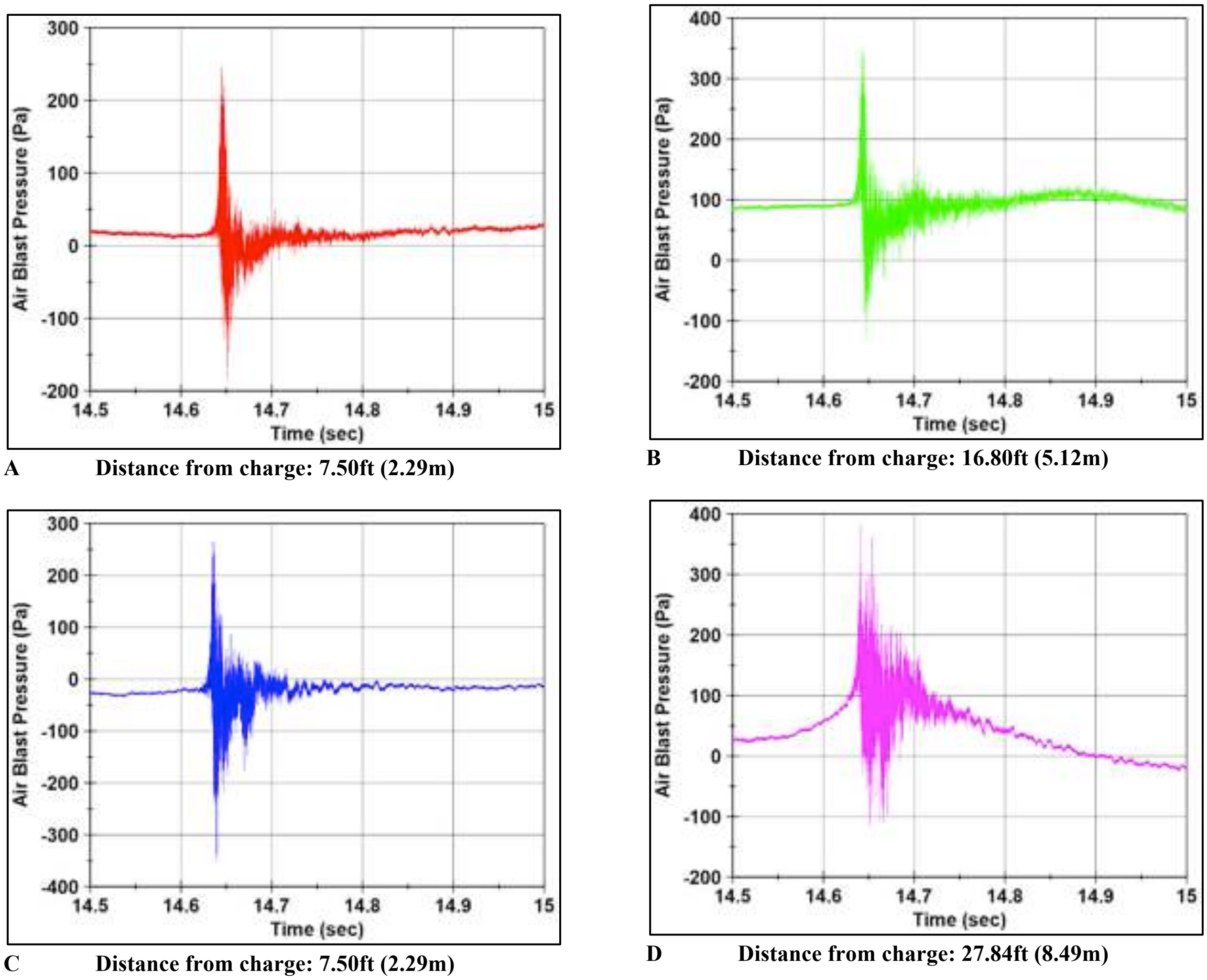
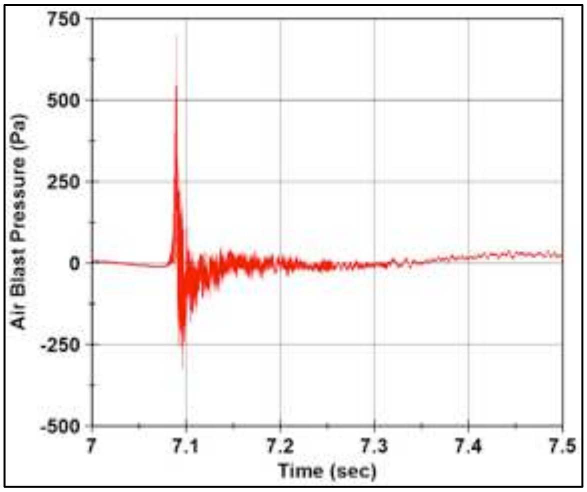
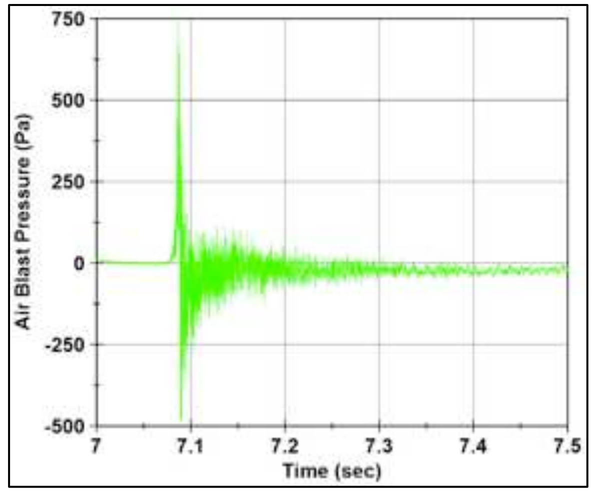


Figure H.6: Pressure time plots for the second 75% capacity cannon explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

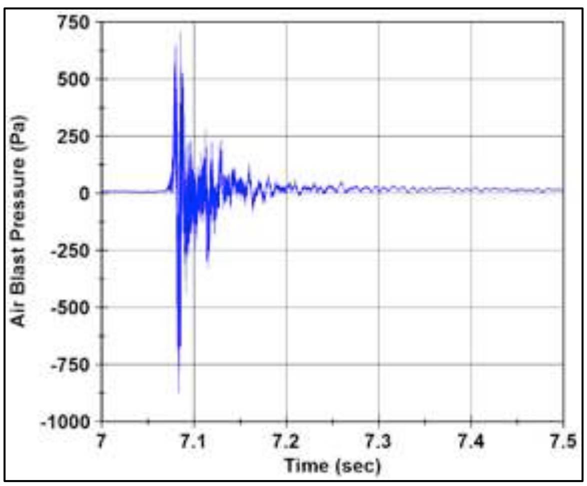
RE = 0.55



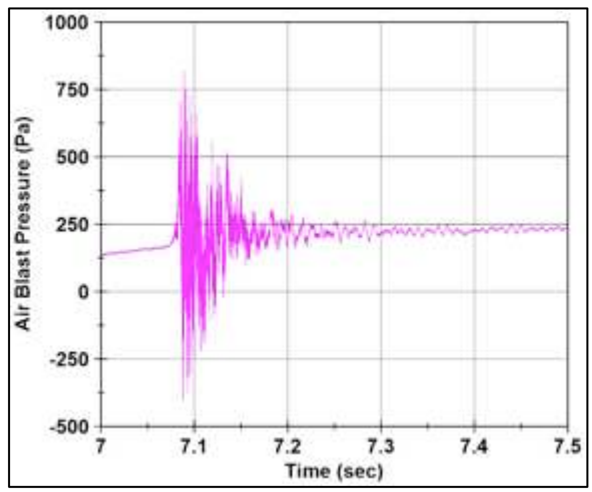
A Distance from charge: 4.12ft (1.26m)



B Distance from charge: 12.14ft (3.70m)



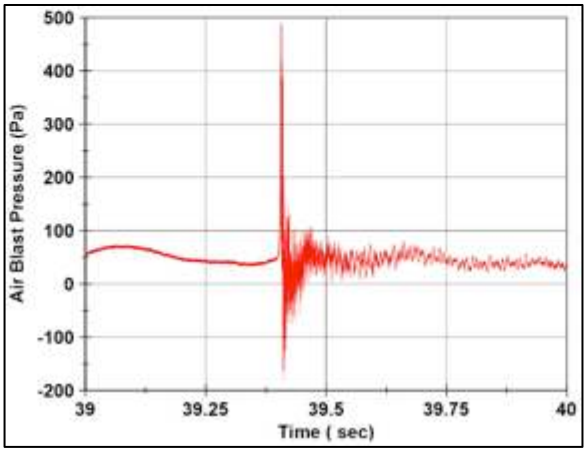
C Distance from charge: 14.94ft (4.55m)



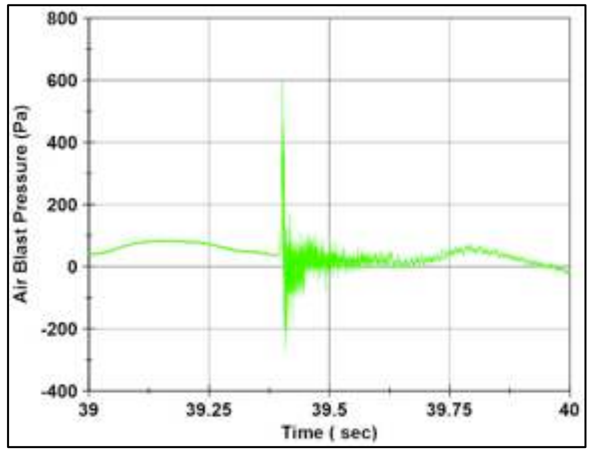
D Distance from charge: 9.07ft (2.77m)

Figure H.7: Pressure time plots for the third 75% capacity cannon explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

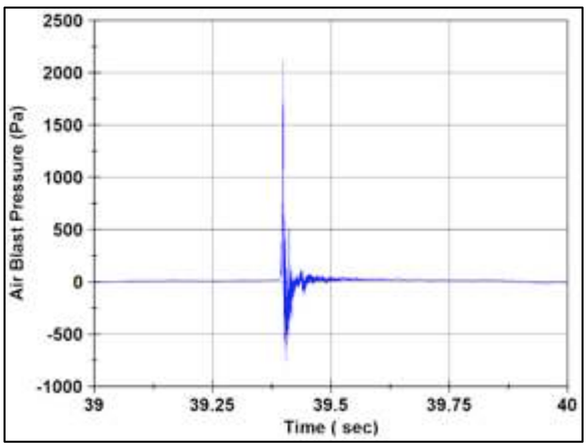
RE = 0.55



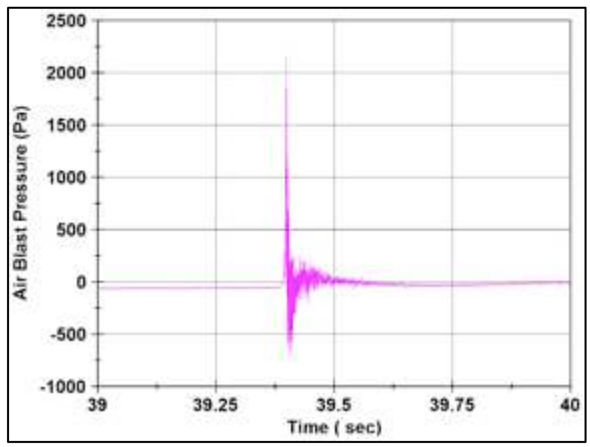
A Distance from charge: 27.00ft (8.23m)



B Distance from charge: 18.96ft (5.78m)



C Distance from charge: 5.66ft (1.72m)



D Distance from charge: 8.60ft (2.62m)

Figure H.8: Pressure time plots for the fourth 75% capacity cannon explosive test. Results for probes 1 through 4 are shown in frames A through D with the distance from the explosive listed below each plot.

APPENDIX I: Sample Pressure Calculations for February Ears

1. For four of the 5 tests, probe one was located at the same distance (.4m or 1.312ft) from the explosive charge. Take average of the four recorded pressures.

Pressure measured at Probe 1 from .4m (1.312ft) from explosive	
75.9	
75.9	
65.72	
75.9	
73.355	**Avg. Pressure**

2. From Table B.1, find the two pressures that are on either side of the average pressure from step 1 and interpolate to get the exact Z value for the average pressure.

Z	Pressure (kPa)
9.4	74.7392
9.6	71.7745

Interpolated data	
9.493	73.355

3. Plug the Z values and the sample distance (Z_S) from the explosive to the ear into Equation 3 and solve for W_{TNT}.

$$Z = Z_S/(W_{TNT}^{\frac{1}{3}}) \qquad \text{Equation 3}$$

$$9.493 = 1.312/(W_{TNT}^{\frac{1}{3}}) \rightarrow W_{TNT} = \left(\frac{1.312}{9.493}\right)^3$$

W_{TNT} = .00264 lbs.

4. Repeat steps 1 through 3 for the two other probes as long each probe was set up at the same distance for each test included in the average.

5. Take the average of the three W_{TNT} values then plug that value back into Equation 3 along with the known Z_s and solve for Z for each trial. This value can then be used in Table B.1, to determine the corresponding pressure value for each trial.

	W_{TNT} (lbs.)
Probe 1	0.00264
Probe 2	0.00838
Probe 3	0.01431
Average	**0.00844**

Trial	Z_S (m) (distance of head from explosive)	W_{TNT} (lbs.)	Z (ft/lb)	Pressure (kPa)
1	0.984	0.00844	4.83	**311.80**
2	2.953	0.00844	14.50	**34.02**
3	2.953	0.00844	14.50	**34.02**
4	0.984	0.00844	4.83	**311.80**
5	1.969	0.00844	9.67	**70.83**

APPENDIX J: Pressure-Time Plots for September Blast Tests

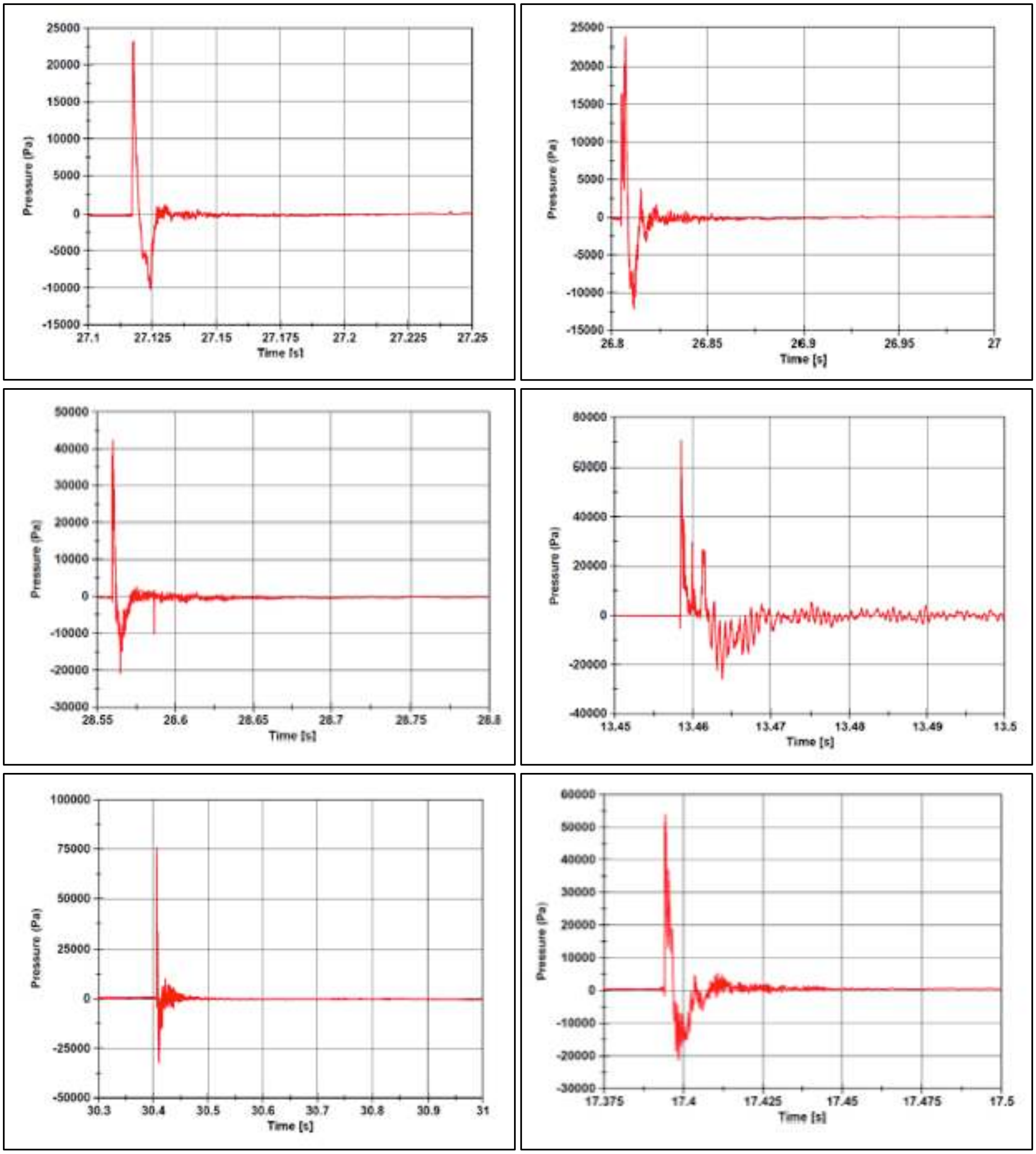


Figure J.1: Pressure-time plots for September blast tests. Plots are in order of trial from left to right, top to bottom. The peak pressures are reported in Chapter 4.